

EDGE WEAR MECHANISMS OF WOODCUTTING TOOLS

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DEDICATION

To my wonderful wife, Qing, for her love and support.

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ABSTRACT

EDGE WEAR MECHANISMS OF WOODCUTTING TOOLS

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Edge deterioration of woodcutting tools causes low productivity, poor wood surface finish, high power consumption, sawing variation and kerf losses. It is a continual problem in every wood machining operation, yet the mechanisms are not fully understood. A good understanding of the mechanisms and their relative magnitude would lead to a better selection of existing tool materials and the development of new materials, and ultimately a higher yield/cost ratio.

A study was performed on various commercial woodcutting tools from several sawmills, emphasizing surface characteristics to examine the deterioration phenomena. The knowledge gained from the field study was then applied towards the development of a laboratory woodcutting test which mimicked the field behavior. Four types of cutting edge materials, a steel, high speed steel, cemented carbide and Stellite™ were used to cut Douglas fir, western red cedar and Oregon white oak, with various moisture contents. Interrupted tests were performed to monitor the progression of edge wear, and edge width and weight loss measurements were used to evaluate the degree of wear.

Abrasion and corrosion were found to be the two major edge wear mechanisms. Either one could be dominant depending on cutting edge materials, wood species and moisture content. For example, abrasion was dominant when Douglas fir was cut, and dry fir caused greater wear than green fir. Green cedar, however, caused more wear to the steel and the cemented carbide,

and corrosion was found to be the predominant mechanism. Dry cedar, nevertheless, resulted in little wear to the same carbide. The Stellite™ exhibited superior overall performance than the steel, high speed steel and cemented carbide, and showed no sign of wear cutting green cedar. Fracture and thermal effects were found only in very specific conditions, and are believed to have little effect on the overall cutting edge deterioration.

The edge width measurement was found to be an effective and reliable method for evaluating the degree of edge wear, and was particularly useful for interrupted tests. The weight loss measurement, however, was not reliable since weight loss from areas other than the cutting edge also contributed to the total measured results.

CHAPTER 1. INTRODUCTION

Edge degradation of woodcutting tools is a continual problem in every wood machining operation. The mechanisms, however, are still not fully understood. This is partially due to the difficulty in monitoring the edge deterioration process with cutting edges typically moving at high speeds. The complexity and variability of wood chemistry and wood macro- and microstructure also contributes to the difficulty of understanding the edge wear mechanisms.

Depending on the end use, a number of types of woodcutting tools can be used to turn raw logs, or composite wood products, into desired geometries and sizes. These tools can be divided into three groups according to the cutting speed at the cutting edges: debarker tools such as canters, abrasive planers such as veneer knives and planer knives, and edgers such as circular saws and band saws. Figure 1.1 illustrates examples of some woodworking tools.

The geometry and pertinent measurements of a typical cutting edge are displayed in Figure 1.2. At the business end of a cutting tool, where chips are being formed, the tool geometry can be described in terms of a cutting edge formed by its intersecting face and back surfaces or planes. The critical geometry of the cutting edge is usually defined in terms of its direction of motion:

- α = the rake angle (also called the cutting angle, the hook angle, the chip angle and the angle of attack) is the angle between the tool face (called the rake face) and a line perpendicular to the direction of travel of the edge.
- β = the sharpness angle, the angle between the face and back (called the clearance face) of the tool edge.
- γ = the clearance angle, the angle between the back of the knife and the direction of travel of the edge.

During a typical cutting process, the sharpness angle tends to be progressively enlarged as the materials at the tip are worn out (dulling) while the clearance angle becomes negative (Figure 1.3). A blunt saw or knife edge in service has several results including:

- 1) sawing accuracy deterioration;
- 2) lumber grade drops due to increasing surface roughness (Figure 1.4) and number of surface defects;
- 3) power consumption increases because of greater tool-wood friction; and
- 4) productivity decreases due to downtime for tool resharpener.

The problem caused by tool dulling could become even more serious in the case of thin-kerf sawing when a thin blade could overheat and thus lose its stiffness due to increased cutting forces. Ultimately, all these problems will lead to increased manufacturing costs. Due to a continuous decline of timber resources and an increase in environmental concerns, the driving force for high operation efficiency has increased. Competition will eventually be so fierce that only those sawmills with highest yields and lowest production costs will survive.

The industry has long been aware of cutting edge wear problems and many attempts have been made to improve the situation. For instance, cutting improvements have been made by mechanical engineers through designing tools with optimum geometry. Design engineers typically used those materials that have been successfully utilized as wear resistant materials in the metal machining industry. For example, tipping with harder and more wear resistant materials than traditional steels have proved to be a successful way to tackle some problems. Nevertheless, edge deterioration still persists and the mechanisms are not fully understood.

Several cutting edge degradation mechanisms have been either demonstrated or proposed; namely corrosion, abrasion, thermal effects and fracture. In most wood cutting operations, the relative magnitude of each of these mechanisms has not been established, especially given the context of wood species and condition. The aim of this research is to establish the edge degradation mechanisms, and their relative magnitude.

The ultimate objective is to improve wear resistance and performance of woodcutting tools by a better selection of existing materials, designing new materials or applying surface engineering technology. As timber resources become scarce, thinner blades, which produce higher yield, are in strong demand. This further requires development of tools with a good combination of strength and wear resistance.

To achieve the goal of this research, a two-step experimental program was conducted. In the first step, a field study was performed, emphasizing surface characteristics of commercial tools from the field to establish a wear pattern database. During this study, a number of woodcutting tools, band saws, circular saws, canters, chipper knives and planers, were obtained for analysis. The cutting edges of these tools were made of steel (with 2%Ni), tool steel (with Cr, Mo and Si), high speed steel (with Cr, W, Mo, and V), cemented carbide (WC-Co) and Stellite™ (Co-Cr-W-C). A laboratory test was then developed such that when cutting wood under conditions similar to those in the sawmill, the worn cutting edge exhibited features which mimicked the cutting tools obtained from the field. A circular saw, with an inserted tooth blade with 7 sockets, was obtained for the laboratory cutting test. Bits with different cutting edge materials, a steel (with Ni), high speed steel (with W, Cr, V and Mn), cemented carbide (tipped, WC-Co) and Stellite™ (tipped, Co-Cr-W-C), were used. Douglas fir, western red cedar and Oregon white oak were cut at various conditions, green, wet (water soaked), laboratory-dried or oven-dried. By performing interrupted cutting tests and post test analysis, cutting edge wear was evaluated both quantitatively, with weight loss, edge width change and cross-section examination; and qualitatively, with examination of edge appearances, wood chips and sawdust.

Additionally, a modified dry sand rubber wheel (DSRW) test was used to study the nature of soft abrasives against hard steel samples. Dry soft abrasives, such as walnut shells, were used to replace the dry silica sand in the testing. By examining steel sample surfaces, with both surface roughness and topography prior to, during and after the test, the grooving effect of soft abrasives on steel samples was studied.

This thesis is divided into 7 chapters. A brief and overall introduction to this research project is given in the current chapter, followed by background which describes the details of wood with emphasis on structure and chemistry, wood cutting tool materials and a literature review on the present understanding of edge wear mechanisms (Chapter 2). Testing tool and wood materials, equipment used and experimental procedures are explained in Chapter 3. Experimental results and discussions are presented into two Chapters, 4 and 5 respectively. Finally, conclusions are listed in Chapter 6 and recommended future work is given in Chapter 7.

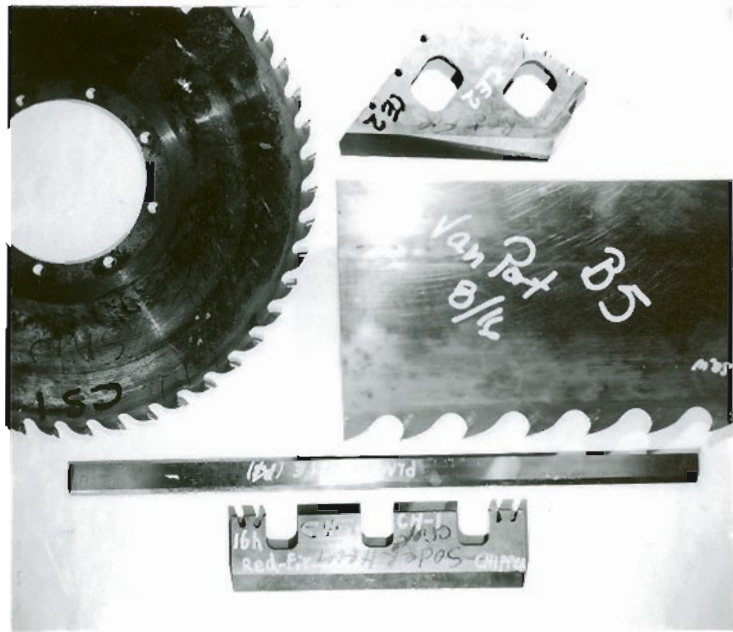


Figure 1.1 Parts of a circular saw (A), canter knife (B), band saw (C), planer knife (D) and chipper knife (E).

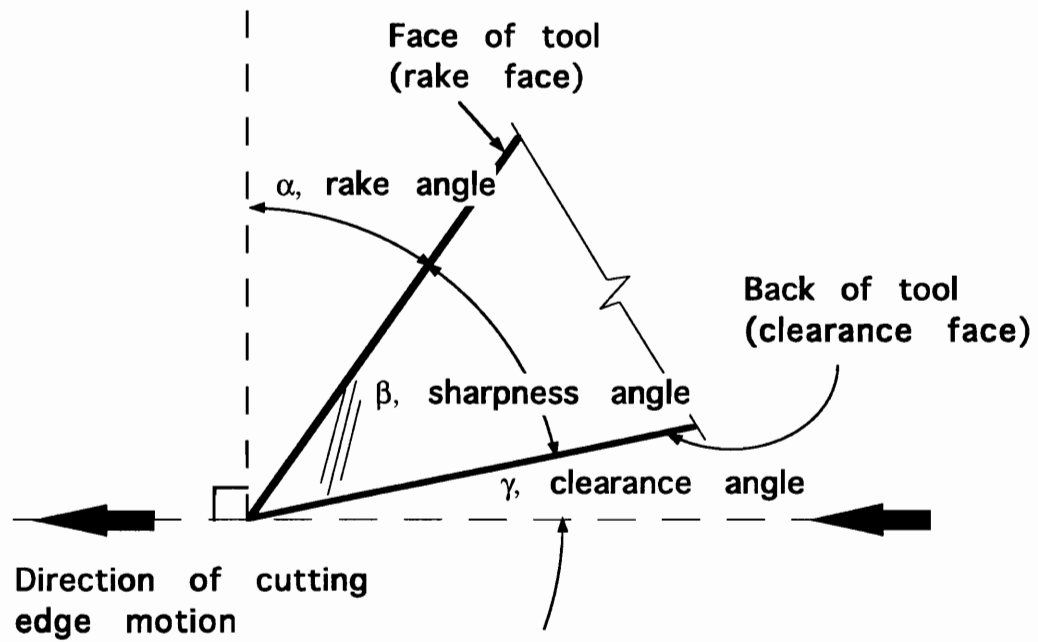


Figure 1.2 Schematic cutting edge geometry of woodcutting tools.

Stages of dulling

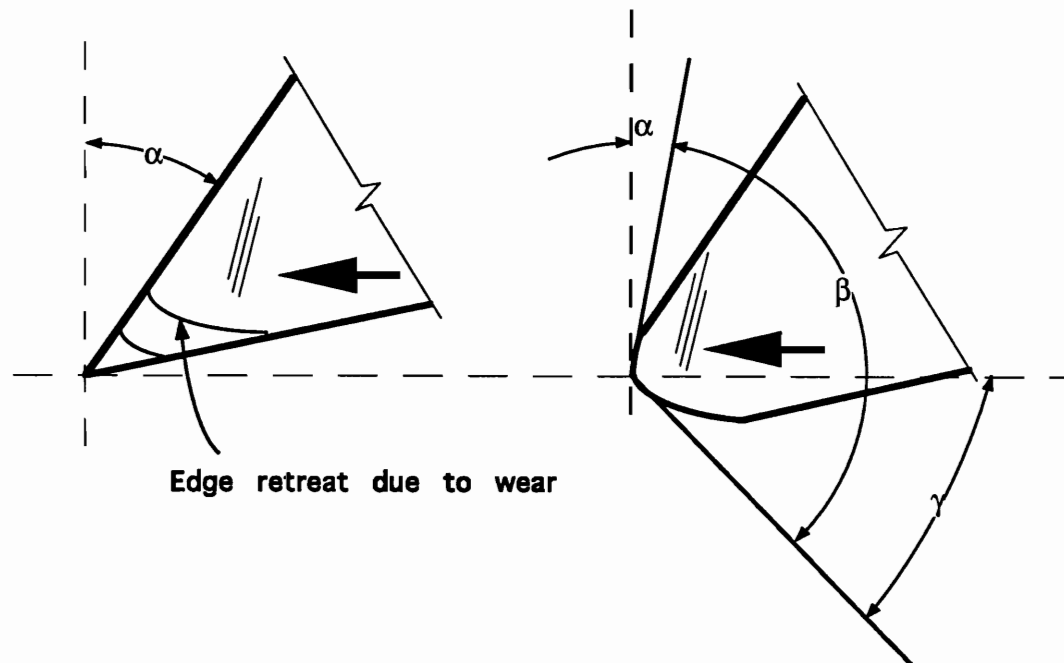


Figure 1.3 Change of edge profile or edge retreat (dulling) due to wear.

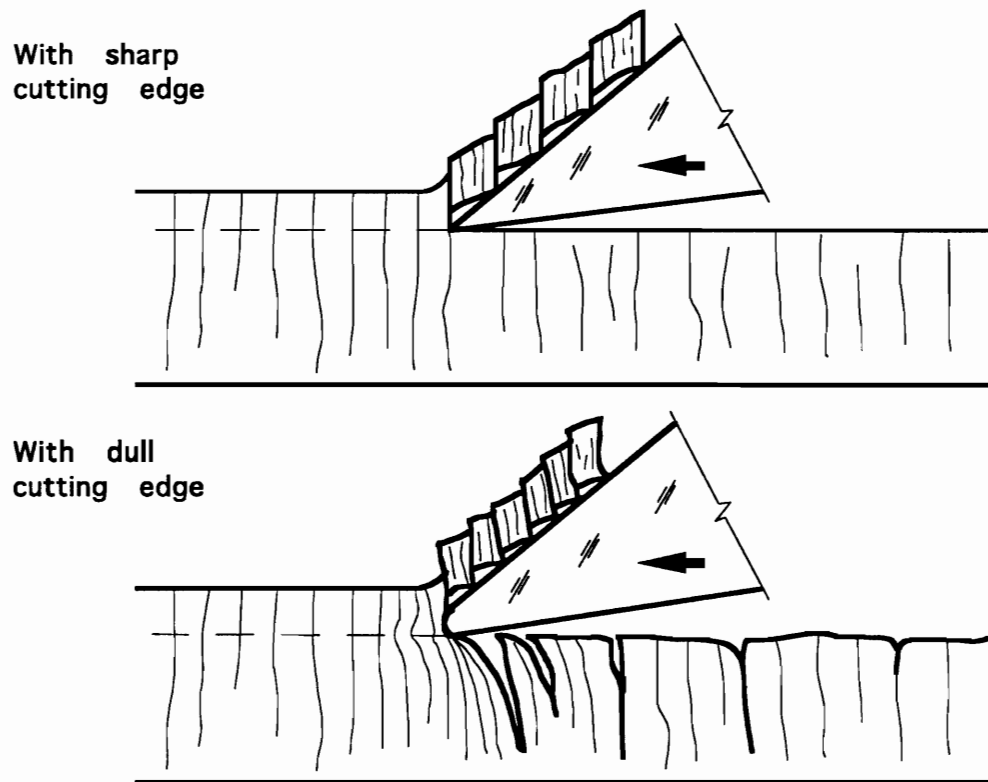


Figure 1.4 Effect of blunt edge on wood surface finish.

CHAPTER 2. BACKGROUND

2.1 Understanding Wood

2.1.1 Classification

The plant kingdom comprises several major divisions. One that includes all seed plants, Spermatophytes, is further divided into two broad groups, gymnosperms and angiosperms, separated according to how the seeds are born. The gymnosperms (naked seeds, i.e., seeds are not enclosed in the ovary of the flower) include all trees producing the lumber known as 'softwood', and the angiosperms (covered seeds, i.e., seeds are enclosed in the ovary of the flower) include all trees yielding the lumber, known as 'hardwood'. These groups are subdivided into orders, families, genera (singular genus) and species (singular species) [1].

The term 'conifer' is also used to indicate softwood trees. Usually softwoods are cone-bearing plants with needlelike or scalelike evergreen leaves or foliage (Figure 2.1). The hardwoods are plants typically with broad leaves that, with few exceptions in the temperate region, are deciduous; i.e., they lose their leaves in fall or during the winter [2]. Familiar softwoods are pines, spruces, firs, hemlocks and cedars while yellow birch, oaks and alders, are hardwoods.

The terms hardwood and softwood have little relevance to the softness or hardness of wood. For example, such softwoods as southern pine and Douglas-fir produce woods that are typically harder than the hardwoods basswood and aspen [3].

2.1.2 Timber Resource

There are approximately 600 species of softwoods and 12,000 species of hardwoods worldwide [2]. Among them, 35% of forest growing stock is in the form of conifers (softwoods) and 65% in hardwoods [4]. Table 2.1 [4] indicates the location of the 323 billion cubic meters resource by regions and countries. It is notable that the former Soviet Union has more than half of the world's coniferous resource, about 2.5 times as much as contained in North America. The vast majority of the hardwood resource exists in the tropics, particularly Africa and Latin America.

The largest trees in the world today are gymnosperms (softwood). The largest commercial trees come from the northwestern U.S. and Canada. The widest conifer is reported to be the giant cypress of Tule, in Mexico, 16 m at its base. However, the tallest trees are the California coastal redwoods. One such tree, at 110 m, is reportedly the largest living thing, plant or animal [2].

In the United States more than 100 woods are available to the prospective user, but it is very unlikely that all are available from any one locality. About 60 native woods are of major commercial importance. Another 30 woods are commonly imported in the form of logs, cants, lumber, and veneer for industrial uses, the building trades, and crafts [3]. Major resources of softwood species are spread across the United States, except for the Great Plains where only small areas are forested. Softwood species are often loosely grouped in three general producing areas: Western softwoods, Northern softwoods and Southern softwoods. With some exceptions, most hardwoods occur east of the Great Plains area. Table 2.2 illustrates the classification and distribution based on the principal region for each wood [2].

2.1.3 Wood Application

Softwood lumber and plywood are used in construction for forms, scaffolding, framing, sheathing, flooring, ceiling, trim, paneling, cabinets, and many other building

components. Softwoods may also appear in the form of shingles, sash, doors, and other millwork, in addition to some rough products such as round treated posts. Hardwoods are used in construction for flooring, architectural woodwork, trim, and paneling. These items are usually available from lumberyards and building supply dealers. Most hardwood lumber and dimension stock are remanufactured into furniture, flooring, pallets, containers, dunnage, and blocking [3]. Wood residual chips, after the extraction of highest value lumber and plywood, are either utilized as the basic raw materials for pulp and paper, or burned off for energy generation [4].

2.1.4 Structure

2.1.4.1 Tree

Wood comes from trees. Whatever qualities or shortcomings wood possesses are traceable to the tree whence it came. To understand wood, trees must be considered at all scales—from the entire plant down to the individual cell, the basic structural unit of plant material. Trees can be considered to have three general parts: (1) the crown, composed of leaves (foliage) and branches; (2) the stem or trunk or bole; (3) the root system. The trunk is the principal source of wood used by woodworkers. The trunk has limbs, which in turn branch and eventually subdivide into twigs.

2.1.4.2 Structural Arrangement (Planes of Orientation)

The structure of wood can be considered in three dimensional terms. One plane, perpendicular to the stem axis, is termed the transverse plane, or cross-sectional plane, typically observed at the end of a log or stump. A plane passing through the pith of the wood (as radius of the circle) is called a radial plane or surface. A plane parallel to the pith, but not passing through it, forming a tangent to the circular growth-ring structure, is termed a tangential plane or surface. These planes or sections are often designated

simply by the letters X, R and T respectively (Figure 2.2) [1].

2.1.4.3 Anatomy of Wood

Bark, Wood, Pith and Cambium

A cross section (Figure 2.3) of a tree trunk shows the following features in succession from the outside to the center. At the periphery of the log surface, the 'bark' layer can be recognized easily. It may be divided into the outer, corky, dead parts and the thin, inner living parts ('cambium'). Within the bark, and comprising the bulk of the stem, is the 'wood', which is characterized by its many rings concentrically arranged around the central 'pith'. Between the bark and the wood is the 'cambium', a microscopically thin layer of living cells (i.e., having protoplasm in their cavities).

Growth Ring, Earlywood and Latewood, Heartwood and Sapwood

In most trees, the nature of wood formation is similarly cyclic, resulting in visible growth layers. These increments are also called 'growth rings', or annual rings when formed in association with yearly growth (Figure 2.3). The age of a tree at the stump or the age at any cross-section of the trunk may be determined by counting these rings. The inner part of the ring formed first in the growing season is called 'earlywood' and the outer part formed later in the growing season, 'latewood'.

The wood part is also visible as consisting of two parts: the central part, concentrated around the pith, is called 'heartwood', usually identified by its dark color; and 'sapwood', located between the bark and the heartwood (Figure 2.3).

Rays

Scattered through the wood are groups of horizontal lines, visible by eye in some wood species. These groups extend radially outward from the pith toward the bark and are therefore called 'rays'.

Grain

The word 'grain' is employed to indicate the degrees of contrast between earlywood and latewood. If a pronounced difference exists, the wood is said to have uneven grains (e.g., southern yellow pine). If little contrast is evident the wood is evengrained, as in basswood. Intermediates can be indicated by compound modifiers such as fairly even (e.g., eastern white pine) or moderately uneven (e.g., eastern hemlock) [1].

The term 'grain' is also used customarily to describe the direction of the dominant longitudinal cells in the tree [1].

Cell, Fiber and Tracheid

The tree stem is an accumulation of countless cells which are of various sizes and shapes and quite firmly cemented together (Figure 2.4). The 'cell' is the basic structural unit of plant material. Each cell consists of an outer cell wall surrounding an inner cell cavity. Within some cells, there is living protoplasm, while others are nonliving and contain only sap or even some air space. The majority of wood cells are considerably elongated and pointed at the ends; they are customarily called 'fibers' or 'tracheids'. The proportion of length to diameter varies widely among cell types, however, from short barrel to long needlelike cells. Cells are arranged either parallel to each other along the trunk of a tree, or scattered horizontally (such as rays). However, the majority of wood is composed of longitudinal cells. The largest cells, as in woods such as chestnut and

mahogany, are visible to the unaided eye, but most are too small to be seen without magnification [1].

Cell Wall Structure

Cellulose molecules are aggregated laterally to form threadlike structures called "microfibrils" (Figure 2.5). The length of microfibrils is not well defined, but their diameters are reported to measure about 10-20 nm. Whether the microfibril is the basic unit of structure in the fiber wall or there exists a smaller, filamentous molecular aggregate called "protofibrils" or "elementary fibrils" and even "sub-elementary fibrils" is still being debated [2].

Another schematic of the structure of the plant woody cell wall, often cited in the literature, is shown in Figure 2.6 [5]. Plant cell walls are shown as being built up of cellulose microfibrils variously oriented, and encrusted with a number of other compounds. They are subdivided into primary walls and secondary walls, according to their time of formation. The primary wall develops first and is often stretched during the differentiation of the cell. It is the only wall found in some cells. The secondary wall is laid down on the inside of the primary wall, usually after elongation of the cell has ceased, and is a characteristic feature of almost all wood cells. The primary or outer wall of a wood cell consists of a thin network of cellulose microfibrils, irregularly and loosely arranged and encrusted with hemicellulose, lignin, and other compounds. The secondary wall is laid down inside the primary wall and in most xylem cells is considerably the thicker of the two. It can be subdivided into three layers according to the orientation of the microfibrils within it. The layer nearest the primary wall is termed the S1 layer and the microfibrils in it are orientated nearly perpendicular to the long axis of the cell. The middle, or S2 layer is by far the thickest and is built up of microfibrils running at a small angle to the long axis of the cell. The S3 layer, lying nearest to the cell lumen, is a thin layer with the microfibrils again orientated in a nearly transverse direction. There may be a gradual transition in microfibril orientation from one layer

to the next. The secondary wall is also encrusted with hemicellulose, and deposits of lignin and other substances. The S3 layer may be overlaid inside the cell lumen by a covering termed the warty layer. This layer when present, so named on account of its small protrusions, is laid down just prior to the death of the cell protoplast and covers the entire S3 layer, pit cavities and any other wall sculpturings.

Individual cells are joined together by intercellular material between their primary walls. This middle lamella is an amorphous mass, rich in lignin and low in cellulose, composed largely of pectin compounds. It is readily dissolved away by macerating solutions [5].

Prosenchyma and Parenchyma

The functions of conduction and support of the tree are carried out by the nonliving (prosenchymatous) tracheids. 'Prosenchyma' refers to those cells whose function is to support the tree, and in some cases conduct sap. A small percentage of the cells, principally those found in the rays, which retain their living protoplasm and can assimilate and store food, are termed 'parenchyma'. In earlywood the tracheids are larger in diameter and thin-walled, well suited for conduction; in latewood the thicker-walled, smaller-diameter tracheids are less suited to conduction but give more support to the tree.

2.1.4.4 Softwood Structure

The general arrangement of softwood structures is shown in Figure 2.7a. The structure of softwoods is relatively simple compared to that of hardwoods. Most of the cells found in coniferous wood are tracheids, which comprise 90% to 95% of the volume of the wood. In an average coniferous species, a cubic inch of wood contains some four million tracheids.

Tracheids are fiberlike cells about 100 times longer than they are in diameter. Among different species their average lengths range from about 2 mm to about 6 mm. Average tracheid diameter ranges from 20 to 60 μm .

Some coniferous species also have resin canals, tubular passageways lined with living parenchyma (epithelial) cells, which exude resin or "pitch" into the canals. Resin canals are the largest and most numerous in pines, usually distinct to the naked eye. In other species, magnification may be necessary to locate them.

2.1.4.5 Hardwood Structure

The general arrangement of hardwood structures is shown in Figure 2.7b. In comparing the anatomy of the hardwoods with that of the softwoods, several general differences are immediately apparent. Most of hardwoods lack resin canals (although some tropical hardwoods have gum ducts). Rays in hardwoods vary widely in size, well into the range of visibility with the unaided eye. Many more types of cells are present in hardwoods, and there is more variation in their arrangement. It is believed that the hardwoods evolved much later than the softwoods. The noteworthy difference in this respect is the degree to which the functions of conduction and support are accomplished by the evolution of specialized cells; vessel elements represent the ultimate in functional specializations.

Vessel elements are extremely large in diameter but have relatively thin walls. They form in the tree in end-to-end arrangement and their end walls have been lost, thus forming continuous pipelines ideal for sap conduction. Vessels vary in size among and within species. Some are seen easily with the naked eye. Others require hand-lens magnification but are distinguishable from other cell types because they are slightly larger. Fibers, by contrast, are smaller in diameter, with closed ends and thick walls, and therefore poorly suited for conduction. They make the tree strong. Vessel elements range in size from 0.2 to 1.3 mm in length, and 20 to 300 μm in diameter [2]. When vessels are cut transversely (across the end grain), the exposed open end is referred to

as a pore. Because all hardwoods possess vessels they are sometimes called porous woods (softwoods are therefore called nonporous woods). The size, number and distribution of vessels and fibers are determining factors in the appearance and uniformity of hardness of a particular wood. In some species (oak, ash, elm, etc.) the pores are concentrated in the earlywood. Such woods are said to be ring-porous. Other hardwoods (cherry, maple, birch, etc.) have pores distributed fairly evenly and are termed diffuse-porous woods. In some woods the pores are large in the earlywood and get smaller toward the latewood, but with no distinct zoning. These woods are called semi-ring-porous or semi-diffuse porous. Examples are black walnut and butternut. Besides the vessels, the other types of longitudinal cells in hardwoods (fibers, tracheids and parenchyma cells) are of uniformly small diameter, so even that they can only be seen with a microscope.

Fiber cells occupy an average volume in hardwood xylem of about 50%, but different species range from about 25 to 75%. On a weight basis, they probably range up to about 85%. The volume ratio of fibers to vessels and average fiber wall thickness are both major influences on hardwood density, compared to softwoods where wall thickness is the primary factor. Figure 2.8 compares the size and shape of various hardwood fibers and vessel elements to those typical of softwood fibers, all at the same magnification [2].

2.1.5 Chemistry

Wood is markedly nonuniform in chemical composition. Within a single tree, the composition varies with height in the stem and the distance from the pith. The compositions of twigs and roots differ from those of the stem. Moreover, characteristic differences are observed in sapwood and heartwood, earlywood and latewood, and, on a microscopic scale, within the individual cells [6]. However, all wood can be considered to be composed of building blocks of cellulose, hemicellulose and lignin [3,4,7].

Cellulose

The skeletal or framework substance of all wood cell walls is cellulose. It is the major constituent, comprising approximately 50 percent of wood substance by weight (dry wood) [3]. Cellulose molecules are long-chain polymers, that is, multiples of simpler molecules (monomers) linked end-to-end. Cellulose is a carbohydrate, meaning that it is composed of carbon, hydrogen and oxygen, with the latter two elements in the same proportion as in water [4].

The structure or chemistry of cellulose is schematically shown in Figure 2.9 [2]. The recurring unit is actually two consecutive glucose ($C_6H_{12}O_6$) anhydride units, known as a cellobiose unit. The polymeric linkages during cellulose synthesis are such that the chains form in an extended manner. As a consequence, cellulose molecules fit snugly together over long segments, giving rise to powerful associative forces that are responsible for the great strength of cellulosic materials [4].

Cellulose has the general formula $(C_6H_{10}O_5)_n$, the subscript n indicating the number of monomer units linked together to form the polymer. In wood cellulose, n may be as high as 10,000, which would produce polymer lengths up to 1/100 mm. The orientation of the long-chain cellulose molecules with the long axis of the cells accounts for many of the basic properties of wood [1]. The properties of cellulosic materials are related to the DP (degree of polymerization) of the cellulose molecules. For example, decreasing the molecular weight below a certain level will cause deterioration in strength [4].

During photosynthesis, water (H_2O) from the soil is combined with carbon dioxide (CO_2) from the atmosphere, catalyzed by chlorophyll and energized by sunlight. This process adds oxygen to the air while removing carbon dioxide, and produces a basic sugar ($C_6H_{12}O_6$) for the tree's own use. The sap (i.e., the water in the tree plus any dissolved nutrients or other materials) carries this sugar down through the inner living bark to where it is used to build new cells in the cambium layer (a thin layer of living cells, having protoplasm in their cavities). Comparison of the chemical formulas

suggests that the sugar produced by photosynthesis ($C_6H_{12}O_6$) is converted to the basic monomer of cellulose by the elimination of a water molecule (H_2O) per monomer [1].

Hemicellulose

Hemicelluloses are relatively low molecular weight, non-cellulosic polysaccharides which occur in plant cell walls together with lignin and cellulose [7]. By contrast to cellulose which is a polymer only of glucose, the hemicelluloses are composed of combinations of five-carbon (pentoses: xylose, arabinose) and six-carbon (hexoses: glucose, mannose, galactose) ring sugars, possess side groups on the chain molecule, and are amorphous in the fiber wall.

Depending on the plant species, these sugars along with uronic acids form various polymeric structures; some are associated with the cellulosic portion of the plant, while others are more closely associated with lignin [4]. Many hemicelluloses have numerous, short side chains, but are otherwise linear [7]. The DP of these sugars is in the range of only 50-300. The hemicelluloses are therefore easily degraded and dissolved (compared with cellulose).

Softwood hemicelluloses are largely galactogluco-mannans while those in hardwoods are mostly xylan. In both cases, they serve as a supportive matrix for the cellulose microfibrils and appear to have a relatively uniform distribution across the fiber wall. The hemicelluloses play an important role in fiber-to-fiber bonding in the papermaking process [2]. In quantity, hemicellulose constitutes 25% of softwoods and 35% of hardwoods based on a moisture free weight [4].

Lignin

In addition to cellulose and hemicellulose (both are carbohydrates), woody plant materials contain an amorphous, highly polymerized substance called lignin. Lignin comprises 25 to 35 percent of softwoods, and 15 to 25 percent of hardwoods [2]. The

chemistry of lignin is extremely complex, and is not fully understood, principally because isolating it from the wood changes it chemically. Figure 2.10 shows the formulation for the repeating unit of spruce lignin [4]. Lignin occurs in the wood throughout the cell wall, but is concentrated toward the outside of the cells and between cells. It is a three dimensional phenylpropane polymer. Lignin structure and distribution in wood are still not fully understood. To remove lignin from wood on a commercial scale may require vigorous reagents or high temperatures or high pressures (as during pulping operations) [3].

Extraneous Materials

In addition to its major structural components, cellulose, hemicelluloses and lignin, wood also contains a large number of other compounds, low and high molecular weights, organic and inorganic [6-25]. The organic component includes fats, waxes, sterols, terpenoids, and phenolic compounds such as lignans, tropolones and polyphenols [2]. The phenolics component contribute to wood properties such as color, odor, taste, decay resistance, density and flammability. The organic components are generally termed extractives, since they can be removed from wood by extraction with such solvents as water, alcohols, acetone, benzene, ethers, and others [3].

The types and amount of wood extractives vary with tree genetics, tree age, position within the tree, and with the environment. They generally constitute only up to a few percent of the wood's dry weight, but amounts up to 20% to 40% have been reported [2]. Many North American wood species have less than 1% extractive content [4].

The inorganic component of the extraneous material generally comprises 0.2 to 1.0 percent of the wood substance, although higher values are occasionally reported. Calcium, potassium, and magnesium are the more abundant elemental constituents. Trace amounts (< 100 p/m) of phosphorus, sodium, iron, silicon, manganese, copper, zinc, and perhaps a few others are also usually present [3].

2.1.6 Water and Wood

Wood in trees is hydrated. The cell structure contains excessive water (sap) and is fully swollen. But under conditions where wood is being shipped, stored and used, the water content in the wood will change. Eventually a fluctuating moisture balance between the dryness of the wood and the humidity of its environment will be reached. The water content within the wood has influence on wood strength which in turn has an effect on the ease of the wood machining process.

Moisture Content

The moisture content (MC) of wood is measured as the ratio of the weight of water in a given piece of wood to the weight of the wood when it is completely dry. The water-free weight of wood is usually referred to as the oven-dry weight, because drying in an oven is a common method of obtaining it. This ratio is traditionally expressed as percent moisture content. Suppose a piece of wood weighs 30 lb, if after drying in an oven it weighs only 25 lb, 5 lb of water have been driven off. The moisture content would be $5/25 = 0.20$, usually expressed as 20% moisture content.

Equilibrium Moisture Content

Wood remains hygroscopic - it responds to changes in atmospheric humidity and loses bound water (held by physical forces of attraction within the cell walls, in contrast to the free water which is held in cell cavities) as the relative humidity (ratio of the amount of moisture in the air at a certain temperature to the amount it would be able to hold at that temperature) drops, regaining bound water as the relative humidity increases. For a given relative humidity level, a balance is eventually reached at which the wood is no longer gaining or losing moisture. When this balance of moisture exchange is established, the amount of bound water eventually contained in a piece of wood is called

the equilibrium moisture content (EMC) of the wood.

Green Wood Moisture Content

The amount of water in the living (or green) tree is quite variable. Table 2.3 [1] gives some average values of moisture content in trees for a number of species. In general, hardwoods have initial moisture contents in the 60% to 100% range. Notable exceptions are white ash, on the low side, and cotton wood, on the high side. In hardwoods, heartwood and sapwood have similar moisture contents though the ratio may vary. In softwood species, the general case seems to be that the heartwood has a fairly low moisture content, often scarcely above the fiber saturation point, while the sapwood is considerably higher. Among the lower density species such as balsa or even pine, the sapwood moisture content often exceeds 200% [1].

2.1.7 Selected Properties

Density and Specific Gravity

Density is defined as weight per unit volume. Specific gravity is the ratio of the density of a substance to the density of a standard substance (water, in the case of wood and other solids). Specific gravity is often called the density index. In measuring density and specific gravity, it is customary to use oven-dry weight and current volume. Density is expressed as weight per unit volume, customarily as pounds per cubic foot or grams per cubic centimeter. Water has a density of 62.4 lb/ft³ or 1 g/cm³. A wood weighing 37.44 lb/ft³ or 0.6 g/cm³ is thus six-tenths as heavy as water and has a specific gravity of 0.6 [1].

Elasticity and Strength

Selected mechanical properties of several woods are given in Table 2.4 [26]. In general, the Young's moduli lie near the centers of the following ranges:

longitudinal: 7,500 - 16,000 MPa (1,100,000 psi - 2,400,000 psi)
 radial: 500 - 1,000 MPa (75,000 psi - 150,000 psi)
 tangential: 400 - 700 MPa (60,000 psi - 100,000 psi).

The high values for longitudinal stressing are expected, since that is the alignment of the wood cells. The other two orientations are low because the cell cavity permits easy strain.

The longitudinal strength in tension, $\sigma_t(l)$, is commonly 20 times the radial strength in tension, $\sigma_t(r)$. Test specimens for mechanical properties must be specifically cut for each orientation. Unlike that in ductile metals, the strength in compression of wood does not closely match the strength in tension. Longitudinal compression strengths, $\sigma_c(l)$, are lower than in tension, $\sigma_t(l)$, because the denser latewood buckles and permits shear to occur. Radial strengths in compression, $\sigma_c(r)$, are higher than in tension, $\sigma_t(r)$, because the tension occurs by splitting [26].

2.2 Materials For Woodcutting Tools

Steels

The oldest, yet still widely used materials for making wood machining tools, are steels which include carbon steel, tool steel and high speed steel. Steels for making bandsaws typically have 0.7 wt% carbon and 2 wt% nickel. Tool steels and high speed steels for making knives often contain chromium, tungsten and vanadium (carbide forming elements).

Carbide Tipping

The most successful method commercially employed in reducing sawtooth dulling has been cemented carbide tipping. Cemented carbide refers, in most cases, to a tungsten carbide cobalt composite unless otherwise specified. Tipping of wood cutting tools with cemented tungsten carbides has been used for almost 60 years [27]. The composite consists of the hard tungsten carbide embedded in a cobalt binder, with the Co content commonly ranging from 3 to 25 wt%. Cemented carbides are manufactured by a powder metallurgy process (sintering) consisting of many steps. By varying two variables, the carbide grain size (commonly 2 to 8 μm in diameter), and in particular the cobalt content, the mechanical properties can be changed to such an extent that a large number of grades of cemented carbides can be produced to meet a wide range of applications.

Kalish [28] indicated that as the cobalt content was increased, the hardness was decreased, abrasion resistance was decreased but transverse rupture strength rose (up to 15 wt% Co). Cemented carbides with fine grains had higher hardness and abrasion resistance than those with coarse grains. However, Sugihara and his coworkers [29] showed that the saw with coarse grained tips (5.0 μm verse 1.5 μm of fine grained) had lower hardness (HV 1501 versus HV 2008 of fine grained) but longer life (69,000 m cutting length versus 16,000 m of fine grained) than that with fine grained during a laboratory test by cutting particleboard.

Cemented carbide tips are brazed on the prepared blank saw blade, normally in the sawmill. Kirbach has described tipping processes in great detail in an unpublished report [27].

Cobalt and Chromium Alloy (Stellite™) Tipping

Another widely used tipping material is the cobalt-base alloys, well known as the Stellite™ alloys. Cobalt-base alloys have enjoyed extensive use in wear-related

engineering for well over 50 years because of their inherent high-strength, corrosion resistance, and ability to retain hardness at elevated temperatures. Microstructurally, the cobalt-base alloys consist of hard particles (Cr_7C_3) dispersed in cobalt-rich ($\text{Co} > 50 \text{ wt}\%$) solid solution matrix alloys (generally Co-Cr-W/Mo) [30].

The initial Stellite alloys, so called because of their permanent star-like luster, were simply binary cobalt-chromium alloys which were subsequently modified and improved by the addition of tungsten, molybdenum, or both. There are over 20 Stellite alloys commercially available today. Contemporary Stellite alloys are divided into two major types: 1) Co-Cr-W-C and 2) Co-Cr-W/Mo-Ni/Fe-C with Si and B modifications thereof for special hardfacing applications [30].

The carbon contents of the Stellite alloys vary from 0.1 to 3.2 wt%. More than half of the Stellite alloys have carbon contents greater than 1 wt%. However, at least half of those alloys which have carbon contents less than 1 wt% have combined carbon plus boron contents well in excess of 1 wt%. As a rule, Stellite alloys with carbon (plus boron) contents less than approximately 1.3 wt% can, depending on tungsten level, be produced in either the cast or the wrought forms. However, Stellite alloys with carbon (plus boron) contents greater than approximately 1.3 wt% can be produced only in cast form [30].

A Stellite alloy typically exhibits a hypoeutectic microstructure with interdendritic arrays of carbides in both as-cast and GTAW (gas-tungsten-arc-weld) conditions. However, the same alloy may also be produced in a wrought form. Carbides coalesce during the hot-working process. This results in a uniform distribution of relatively coarse M_7C_3 carbides in a fine-grained matrix [30].

The hardness of most of the Stellite alloys are derived from dispersions of hard carbides in a somewhat softer, solid solution alloy matrix, with bulk hardness values in the range of 30 to 60 HRC. Exact hardness depends on composition, solidification kinetics, and, in the case of hardfacing deposits, the extent of base metal dilution [30].

It was shown by Kirbach and Bonac that a Stellite alloy commercially known as Stellite 12, was superior in wear resistance to cemented tungsten carbide containing 6 and

18 percent cobalt as binder when western red cedar, western hemlock, and white spruce were cut in the unseasoned state [31]. However, Bayoumi and Bailey [32] demonstrated that cemented carbide materials had a greater wear resistance than Stellites, and Stellites, in turn, had a greater wear resistance than high speed steels during both dry and wet fiberboard cutting. The carbides tested had cobalt ranging from 6 to 10 percent (wt%) while Stellites contained cobalt from 32 to 45 percent (wt%) and chromium from 23 to 31 percent (wt%).

Hard Metal and Ceramic Coatings

Methods have been developed to coat metal cutting tools with tungsten, tungsten carbide, cemented tungsten carbide, titanium carbide and titanium nitride by physical vapor deposition (PVD), chemical vapor deposition (CVD), plasma spraying and electro-spark deposition. These coatings have also been applied to wood cutting saw teeth but not with the same success as has been achieved with metal machining tools. A major drawback is the highly labor-intensive application process [33].

Hard Chromium Plating

Hard-chromium plating has proved to be an efficient method for improving the wear resistance of standard steel saw blades. Electroplated chromium coatings (about 10 μm in thickness) have been successfully applied on saw chain cutters.

Fondronnier [34] showed a sharper edge and less power consumption of thermal-chemical deposited chromium coating (15 to 25 μm in thickness) on a 2 percent carbon steel than G2 tungsten carbide (French steel) during cutting of makore, a French wood with African origin. The wood was believed to be highly abrasive due to its high silica content. The tool was sharpened at the clearance face after coating so that a self-sharpening process was maintained.

Kato and his coworkers [35] showed that a knife with chromium plating on the back surface (clearance face) had ideal self-sharpening characteristics. The chromium layer prevented wear of the back while the face (rake face) was only polished by the wear processes occurring when the wood chips contacted the face. Air-dried wood specimens of *Magnolia obovata* Thunb. were cut repeatedly, orthogonally perpendicular to the grain during the test.

Kirbach indicated in an internal report [27] that chromium coating normally increased the running time, depending on such factors as wood species, roughness of the ground surface and jaggedness of the cutting edge, cleanliness of the tooth before plating, tooth section to which the plating has been applied, and plating conditions. The prolonged sharpness was believed to be due to three factors: the high hardness of the chromium layer, 66 to 68 HRC; the high resistance of chromium to corrosion by chemically reactive extractives in wood; and the low frictional forces developed between the chromium layer and the wood. The low friction also reduced heating in the rim zone of the saw, with the result that stability of the saw was improved.

The use of chromium-plated saws is rather limited primarily because of the relatively high costs of chromium plating and the fact that the saws, in general, have to be sent to sawshops or saw manufacturers for replating. The future of chromium plating is quite vague, primarily due to environmental concerns.

Boronizing

Boronizing has been developed to improve the wear and corrosion resistance of steel components. In wood cutting, boronizing has been tested thus far on steel cutter knives cutting fiberboard. The wear resistance in cutting this highly abrasive material increased by a factor of 10, but did not reach the resistance of carbide-tipped cutters. Boronizing involves the treatment of steel with boron-containing compounds at temperatures of 800 to 1000°C and over a time period of 2 to 8 hours. The boron reacts with the steel producing a 0.013 to 0.13 mm (0.0005 to 0.005 in) thick, very hard and

wear resistant layer of iron borides (FeB , Fe_2B). The borides are needle shaped and penetrate deep into the underlying parent material, thus providing a strong bond between the surface layer and the parent material. The hardness of a boronized surface layer is in the range of HRC 73 to 85 [27].

Stewart [36] demonstrated that tool forces and edge recession were less for borided tungsten carbide than untreated tungsten carbide during cutting of medium density fiberboard. Most of the benefits were retained after resharpener the borided tools on the clearance face, thus producing a self-sharpening effect. The beneficial properties of borides were believed to include extreme hardness, low surface coefficient of friction and corrosion resistance in certain chemical environments.

The Borofuse Process, developed by Materials Development Corp., involves a series of thermal diffusion treatments that lead to the formation of borided compounds at the metal surface and substrate. The Union Camp particleboard plant in Franklin, VA., regularly uses borided tungsten carbide tips on its tools for shaping the round profile on one edge of its East Coast particleboard. On average, regular tungsten carbide tools can cut approximately 14,000 square feet of material on a $\frac{3}{4}$ inch basis before being resharpener. With the new tips, an average of 39,000 square feet of material on the same basis can be cut [37].

Polycrystalline diamond (PCD)

Since GE introduced the COMPAX tool blanks in 1973, diamond tools have been successively applied in the machining of nonferrous and highly abrasive materials. While PCD tools were considered for woodworking operations as early as 1975, it was 1978 before they were successfully applied commercially by a European cabinetmaker [38]. Saws carrying diamond coated tips can be operated for several months provided that no mechanical damage occurs during the cutting period [33].

Diamond coated tips are manufactured by sintering together carefully selected fine diamond particles at very high temperature and ultra-high pressure. The polycrystalline

diamond layer can be bonded to the cemented tungsten carbide parent material during the sintering process. The tips are brazed in a recess of the saw tooth.

PCD tips are more brittle than cemented tungsten carbide and are more sensitive to shock. Diamond-tipped saws are very expensive and require careful cost justification. The cost of one PCD saw tooth may range from \$50 to \$80, whereas a comparable cemented tungsten carbide tipped saw tooth would cost approximately \$1.25. In general, however, PCD cutting tools last 100 to 300 times longer than cemented tungsten carbide tools for each sharpening [39].

2.3 Edge Degradation

Tool edge blunting or degradation has long been acknowledged as a serious problem in the wood cutting industry [27,29,31-36,38-148]. However, compared with the extensive research work conducted on the wear of metal cutting tools, the research effort on wear of wood cutting tools is minimal. As a result, edge degradation mechanisms of wood cutting tools are still poorly understood. Among the limited body of literature, several tool deterioration mechanisms have been proposed or demonstrated including, corrosion [32,43,50-51,66,72,81,84-90,92-94,98-101,107-111,134,142], abrasion [51,89,123,142,144], high temperature phenomena or thermal effects [45,56,89,132-134,147], and edge fracture [149].

Corrosion (Chemical/Electrochemical Wear)

Corrosion assisted degradation phenomena are often subdivided in the literature into two categories: chemical and electrochemical wear. Here the term 'wear' can be simply interpreted as a process of material loss, and it may not be the same as the 'wear' due to mechanical interaction.

In a 1964 publication, Hillis and McKenzie [66] described possible chemical attack on steel tools by organic acids, primarily the acetic acid, and polyphenolic

extractives in wood. Hillis and McKenzie performed a slow (3 inch/min) linear cutting test using various steels to cut water saturated radiata pine sapwood. Blue staining at the polished sharp edge was observed after only 9 inches of cutting. The staining was found to be a deposit which could not be removed by water, alcohol or other organic solvents, but was removed by dilute alkali. The grain structure of the metal was visible after removal of the products of chemical attack, using interference and interference-contrast microscopy techniques. No description was given about the techniques and the interference photographs presented in the paper.

Krilov and Gref [98] assessed the acidity of fifteen Australian hardwoods of major economical importance and found that almost all species were substantially acidic, with pH values ranging from 3.12 to 4.88 and thirteen of pH values less than 4. In addition, they measured the weight losses of four major commercial sawblade steels in Australia after being submerged in water saturated sawdust from *Lophostemon condertus*. New fresh sawdust produced an average corrosion rate of about 5.3 g/m²/hr while the old sawdusts had 4.9 g/m²/hr, suggesting that the fresh sawdust is more corrosive than old sawdust.

In their paper [98], Krilov and Gref describe the formation and roles of organic acids and polyphenolic compounds. Acetic acid is believed to be present in most timbers and is believed to be formed by hydrolysis of acetyl (CH₃CO) groups of hemicelluloses. Other types of organic acids include fatty acid esters. Under aqueous conditions these esters could hydrolyze to produce the free acids. Dissociations of the low molecular weight organic acids produce hydrogen ions which could impose attack on iron, i.e., the iron atoms would give up their valence electrons to hydrogen ions which would then become hydrogen gas molecules (H₂). However, it is believed that these acids are fairly inactive and consequently have little corrosive effect in practice. Polyphenolic compounds are considered to be the other source of hydrogen ions. These compounds contain one or more hydroxyl groups attached to an aromatic ring, which can supply hydrogen ions. Some polyphenols also contain a functional carboxylic acid group. Typical examples of polyphenolics in wood are gallic, digallic and ellagic acids, which

are often found in appreciable quantities in a wide range of eucalypts. Such compounds react with Folin-Denis reagent to produce a typical dark-blue color. In Krilov and Gref's study, Folin-Denis reagent was used to quantify polyphenolic material in aqueous extracts obtained from above species, in terms of tannic acid equivalents. The timber species in their study showed a considerable variation in polyphenol content. They contained between 1.23 wt% (*Lophostemon confertus*) and 17.0 wt% (*Eucalyptus microcorys*) polyphenolic material with respect to dry weight. The role of polyphenolics in corrosion, however, was believed to go beyond acidity. This is because polyphenols which have two or more adjacent hydroxyl groups have the ability to form the specific compounds named "chelates" with some metal ions. These are ring structures of high stability. During the reaction when chelates are forming, the ferric ions are removed from the acid-metal equilibrium, which is displaced towards the production of more ferric ions. Corrosion is thereby increased. It is, however, necessary that the iron is initially oxidized to ferric ion and dissolved before it can combine with the appropriate polyphenol. A theoretical reaction scheme was proposed for the corrosion of the iron in sawblade steels, and a set of equations was given in the paper. The equations given indicate that the initial step in the corrosion of sawblade steels should be acid attack upon the iron, which would result in the formation of a certain quantity of ferrous ions. In the presence of air, these ions would be further oxidized to the ferric state, in which they would combine with different polyphenols to produce the chelates [92].

Cemented carbide tools were found to be susceptible to chemical attack by wood extractives by several researchers. For example, Kirbach and Chow [84] placed new cemented carbide saw tips, used cemented carbide cutters and pure cobalt into a slurry of water and each of 3 types of western red cedar extractives for 48 hours at 20°C and 60°C. Three types of extractives included a mixture of α -, β - and γ -thujaplicin; β -thujaplicinol; and plicatic acid. Weight losses ranging from 400×10^{-6} to 7109×10^{-6} g were detected. An increase of testing temperature led to a rise in weight loss. In the case of cemented carbides, more cobalt was lost than tungsten. A comparative test, in which the metallic materials were submerged in distilled water for 48 hours, gave only

a negligible amount of weight loss (from 32×10^{-6} to 186×10^{-6} gm). Scanning electron micrographs demonstrated that the cobalt binder appeared preferentially removed by the extractives from the tool surfaces, leaving unsupported tungsten-carbide grains. It was believed that cedar extractives readily attacked the cobalt matrix and to a lesser extent the tungsten carbide grains, by forming metal chelates. However, no discussion about how the chelates could be formed was given.

In another experiment by Bailey and his coworkers [43], nose rounding and sharp angular carbide exposure were found on cemented carbide circular saws and knives after cutting oaks containing a high moisture content. It was proposed that the wear mechanism might involve the preferential removal of the binder (cobalt) through chemical reaction with extractives present in the oak (tannin), followed by mechanical loss of tungsten carbide grains when the strength of the remaining bond between them and the binder was insufficient to resist the action of the shear forces generated by motion of the chip and the freshly machined workpiece surface over the faces of the tool.

Evidence of a chemical effect also includes higher weight loss due to higher moisture content [84] and greater weight loss due to higher cobalt binder concentration [81]. Perhaps the idea about an electrochemical effect originated from Kivimaa's paper [85] in 1952 which is often the earliest paper cited in later publications on the subject. McKenzie and McCombe [109] applied a negative potential of 60 volts with respect to the nosebar in a veneer lathe test when using low carbon tungsten molybdenum alloy steel to cut alpine ash. Both wood and knife were insulated from the rest of the machine. Edge recession was found to be reduced by about 40%. In a slow lathe cutting test with 1.3 to 5.3 m/sec liner cutting speed, Klamecki and Tsai [90] showed that flank wear of high speed steels varied from low to high as the potential applied changed from -480V to +480V. Both wet and dry incense cedar and ponderosa pine were used in the test.

Mohan and Klamecki [110] characterized the corrosion susceptibility of cemented carbide tools by measuring the electrical potential developed between the component materials when exposed to electrolyte solutions typical of those found in wood. The tungsten carbide particles were of 1.5, 6.5, 10 and 25 μm mean diameters. The

electrolyte solutions were prepared by soaking wood chips in distilled water (0.110 kg of chips per liter) at 65°C for 24 hours. White fir with a pH of 5.0, California black oak with a pH of 3.7 and incense cedar with a pH of 3.1 were used. An average of 75 mV potential difference was found between tungsten carbides with grain sizes of 1.5 μm and 6.5 μm . The electrical potential differences were found in the range of hundreds of millivolts between tungsten carbides (1.5 μm grain size) and cobalt in solutions of varying pH. As a result, it was proposed that electrochemical factors would affect the overall cutting tool wear when wet wood was cut.

Abrasion

The classic abrasive wear mechanism is the progressive removal of material from a surface through interaction with another body which deforms, cuts, or fragments a groove in the surface. One characteristic of worn surfaces having undergone an abrasive process is the presence of grooving.

Abrasion is commonly mentioned as an edge degradation mechanism of woodcutting tools [89]. Inorganic elements including K, Ca, Mg, Na, Mn, Fe, Zn and Cu were all found distributed in some Japanese wood species [24], and inorganic deposits were observed as crystals in tropical woods [10,12-13,16,20,22,24-25]. Tool wear was found to increase with the rise of sand and adhesive resin concentrations when man-made wood composite, such as particleboard and hardboard, were machined [89]. However, direct evidence for abrasives and abrasive mechanism is lacking when considering the cutting of most North American natural wood species.

In a 1987 field study by Scholl and Clayton [123], abrasion was found to be the dominant deterioration process for saw chain cutters used for felling trees and cutting them to length. The conclusion was based on optical and scanning electron microscopy observations on both un-coated and Cr-plated tool steel cutter. Volcanic ash, approximately 65 to 70 wt% silica and 18 to 20 wt% alumina in the test site, Mt. St. Helens areas in Washington, contained primarily within the bark of the trees, was

considered to be the most likely cause of the abrasive damage observed. Subsequent laboratory tests by Wang [144] using PVD TiN-coated saw chain cutters cutting Douglas fir with Al_2O_3 present, showed similar abrasive grooves while tests without Al_2O_3 did not.

High Temperature Phenomena (Thermal Effects)

Stewart [132] used high speed steel to cut medium density fiberboard and claimed to find plastic deformation at the cutting edge due to possible high temperature softening. The conclusion was made based on scanning electron micrographs and energy dispersive X-ray analysis on the cutting edge surface. The result showed that 0.22 wt%Ca and 0.29 wt%K were found at the cutting edge. They were believed to exceed the normal total ash content of 0.2 to 0.3 wt% found in most wood, and it was claimed to be due to elemental diffusion from wood to tool at very high temperature. However, no calcium and potassium concentration in the steel before the cutting test nor the distribution of these elements within the steel were given.

Other investigators have attempted to measure cutting edge peak temperatures by means of thermocouples and micro-optical and infrared pyrometry. Temperatures near the cutting edges from 300 °C [45] to 800 °C [89] have been reported.

Fracture

Although fracture is commonly suggested as an edge degradation mechanism [149], there are relatively few references concerning edge fracture as a degradation mechanism. Fracture is considered a potential mechanism when the impact loading of the cutting edge is coupled with a hard and brittle tool material. Cutting edge fracture has been observed but is usually attributed to foreign materials such as rocks or nails in the wood.

Summary

In summary, more evidence was available on the corrosion aspects, less on abrasion, and little on other degradation mechanisms. However, most experiments aimed at investigating corrosion (chemical and electrochemical attack) were performed in either static or near static testing conditions, e.g. soaking a piece of steel in a water-sawdust solution. In reality, the mechanical, chemical and electrical interactions between the tool and wood occur at relatively high speeds. Research aimed at extrapolating the static corrosion phenomena to the dynamic state existing in sawing is limited. In abrasion, the abrasive is almost necessarily as hard or harder than the bulk material. If abrasion is an operative mechanism in wood cutting under sawmill conditions, then a question has to be raised as to what abrasive is present. Extraneous materials identified in North American commercial wood species are found not sufficient to cause abrasive grooving of cutting edges.

Results from previous studies suggest that wear or deterioration of cutting tool edges may be summarized as due to the following three aspects:

- (1) the tool itself which is subdivided into factors of chemistry, microstructure, hardness, fracture toughness, cutting edge geometry and grinding quality including surface roughness;
- (2) the wood species which is subdivided into factors of wood physical (such as density) and mechanical properties, moisture content, chemistry and elemental distribution;
- (3) tool-wood working environment which is subdivided into factors such as cutting orientation (versus grain direction), cutting velocity and depth of cut, with or without cooling during cutting, and sawblade vibration.

However, these factors might affect only the extent or degree of edge deterioration, which may be considered as a "surface" phenomenon. The fundamentals of what really causes edge wear remains unanswered.

The degree of wear may be evaluated by monitoring edge geometry changes (such as edge recession and edge radius change etc), tool cutting forces (at edges), saw power consumption, noise level or finished product quality (wood surface finish). Which method is most appropriate is still a question to be answered.

Measuring edge recession is perhaps the most common and easiest method of observing cutting edge wear. Typically measurement is made by projecting the cutting edge with some sort of light source to a background (making cast), photographing the edge profile and then measuring the recession from the edge's original position. Figure 2.11 illustrates a blunt edge profile and edge recessions W_c (clearance face recession) and W_r (rake face recession). However, the effectiveness of this method is still questionable since measurements can only be done at certain points (such as corners) along the edge while edge profiles often vary. Additionally, this method assumes that the cutting edge is at its original position (shown as point O in Figure 2.11), which is not true in reality. In this thesis, a new method, edge width increase, was proposed and proved to be effective for evaluating the degree or progression of wear.

Table 2.1 Forest growing stock in various countries and regions [4]

Species Group	Region	Growing Stock (billion m ³)
All	World	323
		(per cent)
Conifers	World	35.0
	Japan	0.3
	Europe	3.0
	N. America	8.4
	former USSR	20.7
	Other	2.6
Broadleaved	World	65.0
	Temperate	11.8
	Japan	0.3
	Europe	1.7
	N. America	2.9
	former USSR	3.7
	Other	3.1
	Tropical	53.3
	Asia, Far East	8.4
	Africa	18.6
	Latin America	26.3

Source:
FAO Forestry paper 4/1, Rome 1977. World Pulp & Paper: Demand, Supply & Trade., Vol.1

Table 2.2 Forest classification and distribution in the United States [3]

Western softwoods		Southern hardwoods	
Alaska cedar	Ponderosa pine	Ash	Magnolia
Incense cedar	Sugar pine	Basswood	soft maple
Port Orford cedar	Western white pine	American beech	Red oak
Douglas fir	Western redcedar	Butternut	White oak
White fir	Redwood	Cottonwood	Sassafras
Western hemlock	Engelmann spruce	Elm	Sweetgum
Lodgepole pine	Sitka spruce	Hackberry	American sycamore
Northern softwoods		Pecan hickory	Tupelo
Northern white cedar	Eastern white pine	True hickory	Black walnut
Balsam fir	Eastern redcedar	Honeylocust	Black willow
Eastern hemlock	Eastern spruce	Black locust	Yellow poplar
Jack pine	Tamarack	Northern and Appalachian hardwoods	
Red pine		Ash	Hackberry
Southern softwoods		Aspen	True hickory
Atlantic white cedar	Southern pine	Basswood	Honeylocust
Baldcypress	Eastern redcedar	Buckeye	Black locust
		Butternut	Hard maple
		American beech	Soft maple
		Birch	Red oak
		Black cherry	White oak
		American chestnut	American sycamore
		Cottonwood	Black walnut
		Elm	Yellow poplar
		Western hardwoods	
		Red alder	Pacific madrone
		Oregon ash	Bigleaf maple
		Aspen	Paper birch
		Black cottonwood	Tanoak
		Golden chinquapin	California black oak
		Oregon white oak	

Table 2.3 Average green moisture content of common wood species [1]

Softwoods	Heartwood	Sapwood	Hardwoods	Heartwood	Sapwood
	%	%		%	%
Cedar, Alaska	32	166	Apple	81	74
Cedar, eastern red	33	-	Ash, white	46	44
Cedar, incense	40	213	Aspen	96	113
Cedar, Port Orford	50	98	Basswood, American	81	133
Cedar, western red	58	249	Beech, American	55	72
Douglas fir, coast type	37	115	Birch, yellow	74	72
Fir, grand	91	136	Cherry, black	58	-
Fir, white	98	160	Cottonwood, black	162	146
Hemlock, eastern	97	119	Hackberry	61	65
Hemlock, western	85	170	Hickory, pecan, bitternut	80	54
Pine, loblolly	33	110	Magnolia	80	104
Pine, lodgepole	41	120	Maple, sugar	65	72
Pine, longleaf	31	106	Oak, California black	76	75
Pine, ponderosa	40	148	Oak, northern red	80	69
Pine, red	32	134	Oak, southern red	83	75
Pine, shortleaf	32	122	Oak, white	64	78
Pine, sugar	98	219	Sweetgum	79	137
Pine, western white	62	148	Sycamore, American	114	130
Redwood, old-growth	86	210	Tupelo, black	87	115
Spruce, eastern	34	128	Walnut, black	90	73
Spruce, engelmann	51	173	Yellow-poplar	83	106
Spruce, sitka	41	142			

Table 2.4 Selected properties of common woods (12% moisture) [26]					
Property	white oak	paper birch	douglas fir	white pine	redwood (old rough growth)
Density, g/cm ³	0.68	0.55	0.5	0.38	0.4
Hardness along radial, N*	6000	4000	2900	1900	2100
Young's modulus along longitudinal, MPa (10 ⁶ psi)	12,300 (1.78)	11,300 (1.60)	12,500 (1.81)	10,100 (1.46)	9200 (1.33)
Strength					
Tension along radial, MPa (psi)	5.4 (780)		2.4 (350)		1.7 (250)
Compression along longitudinal, MPa (psi)	51 (7400)	39 (5700)	51 (7400)	35 (5100)	42 (6100)
Compression along radial, MPa (psi)	7.4 (1100)	4.1 (590)	5.2 (750)	3.2 (460)	4.8 (700)
Modulus of rupture, MPa (psi)	105 (15,200)	85 (12300)	87 (12,600)	67 (9,700)	69 (10,000)
* Force required to embed 0.444 in (11.3 mm) ball to one half of its diameter.					

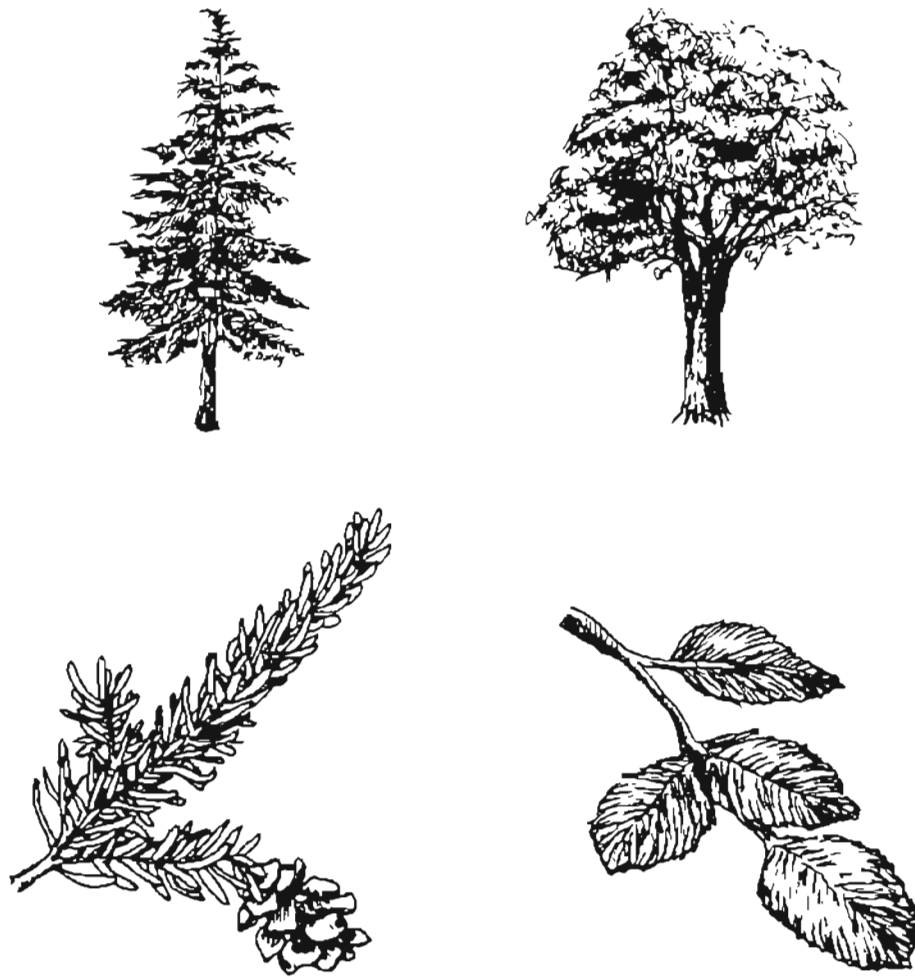


Figure 2.1 Representation of typical softwood (left) and hardwood trees (right).

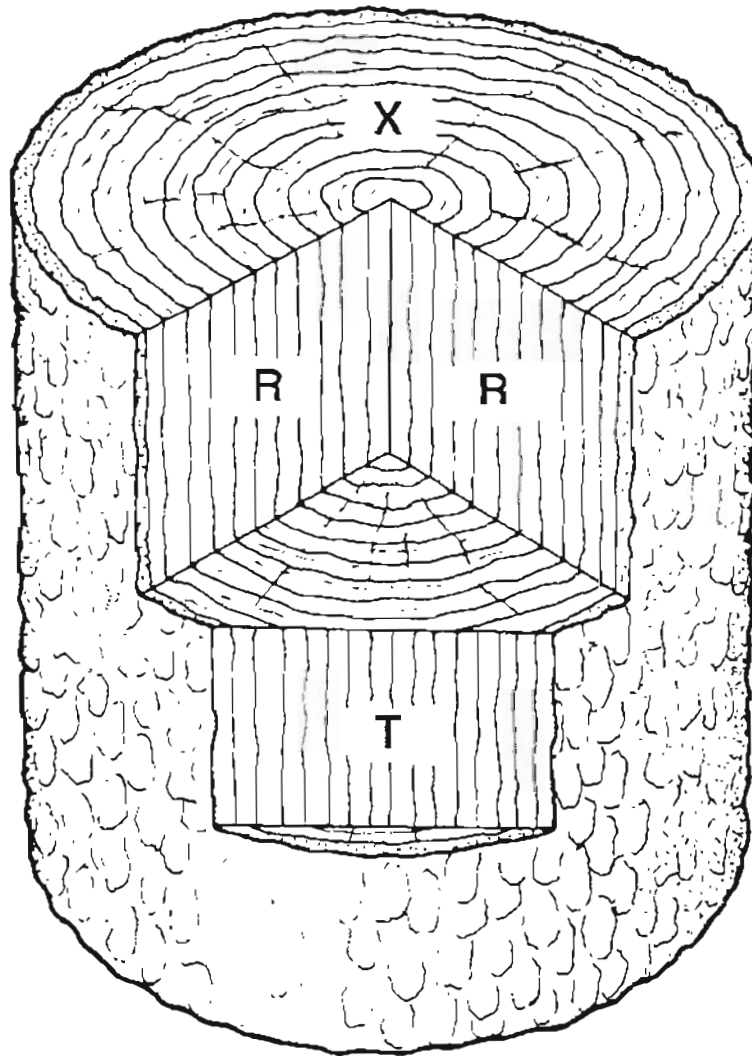


Figure 2.2 Three wood planes: the transverse or cross-sectional (X), the radial (R) and tangential (T).

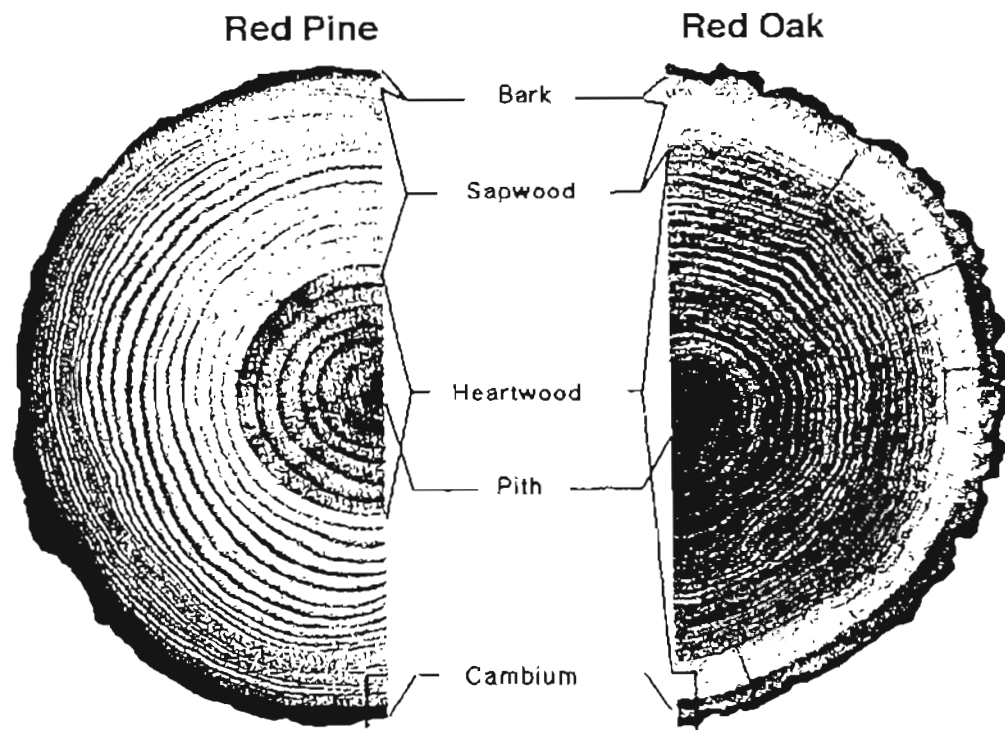


Figure 2.3 Wood cross-sections showing growth rings, gross and fine structures of a typical softwood (red pine) and a typical hardwood (red oak).

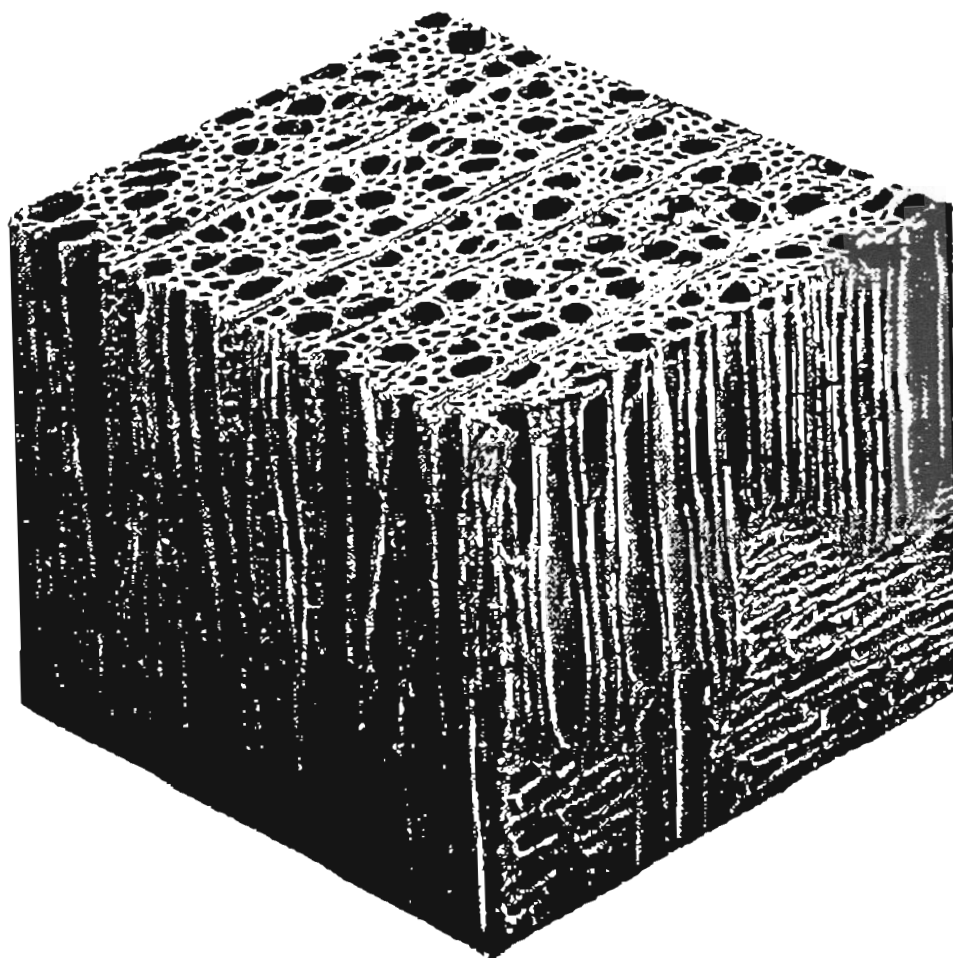


Figure 2.4 Wood made of countless cells orientated in three directions [5].

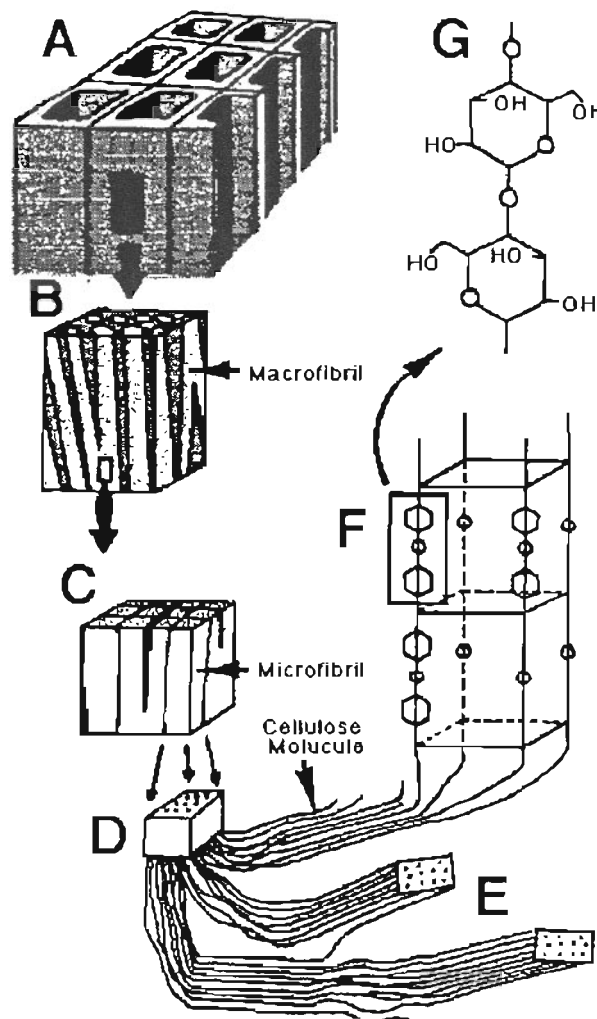


Figure 2.5 Diagrammatic representation of cellulose in the wood fiber wall [2].

A. Transverse/longitudinal view of several wood fibers.

B. Portion of a fiber layer, shown here to consist of macrofibrils aggregated microfibrils (white)-with interceding noncellulosic materials (black).

C. Portion of a macrofibril, shown here to consist of aggregates of microfibrils which are in turn composed of aggregates of cellulose molecules.

D. Cross-section of a single microfibril

E. Organization of cellulose molecules into a series of unit cells, showing the basic repeating unit of cellulose—the cellobiose unit.

F. A cellobiose unit—two adjacent glucose residues connected by an oxygen atom.

G. Same as F except in two dimensional view.

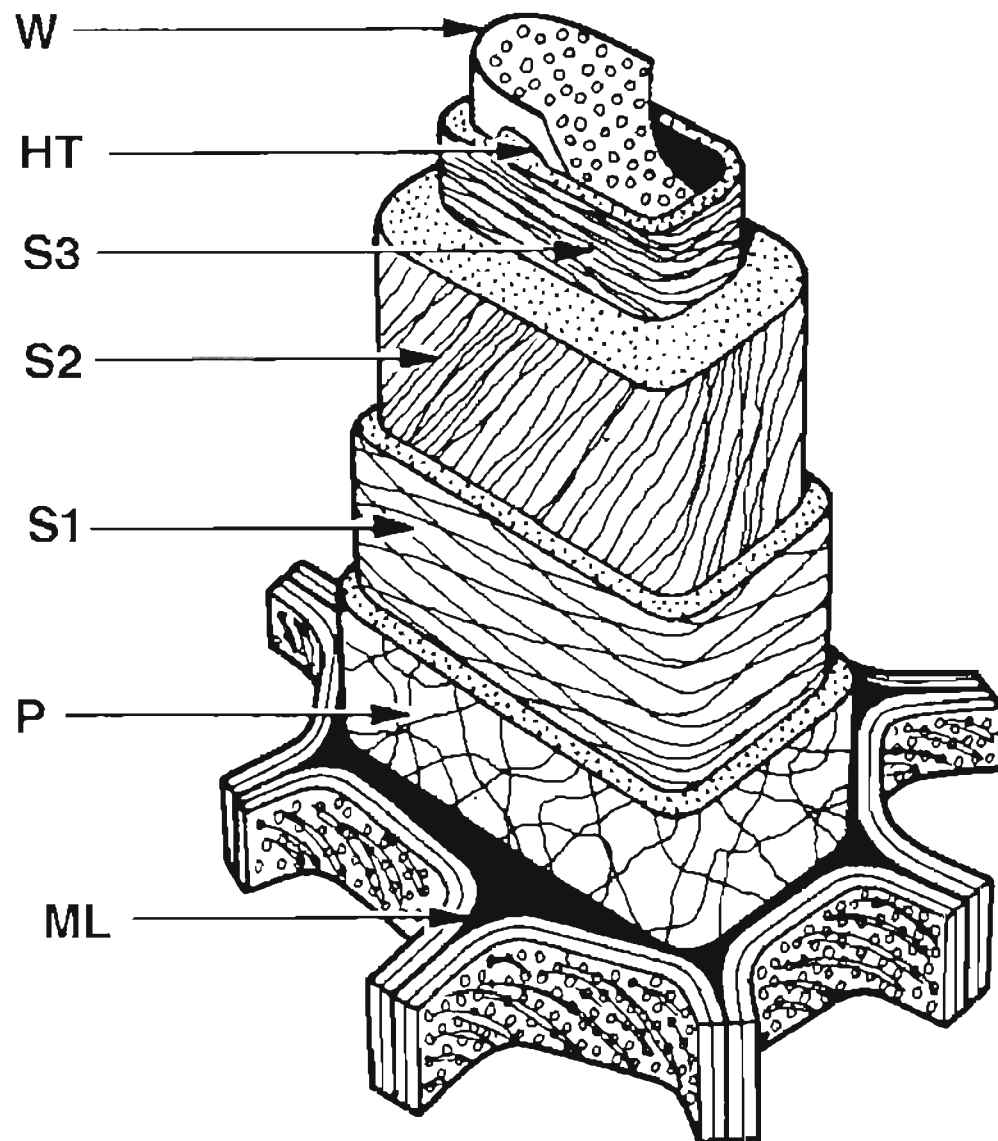
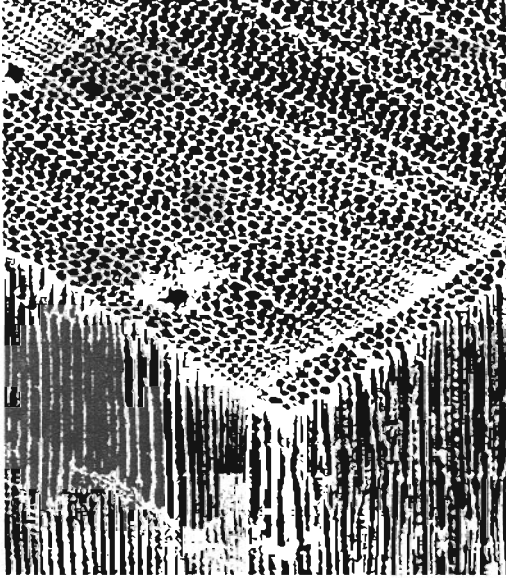
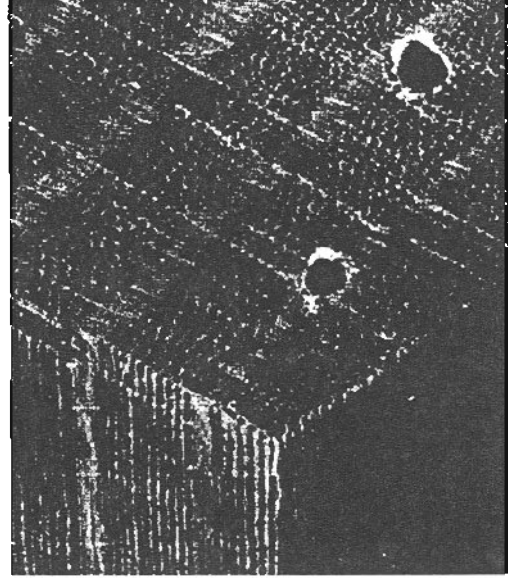


Figure 2.6 Schematic of the structure of the plant woody cell wall and the orientation of the cellulose microfibrils within the various layers. ML, middle lamella; P, primary wall; S1, outer layer of the secondary wall; S2, middle layer of the secondary wall; S3, innermost layer of the secondary wall; HT, helical thickening; W, warty layer [5].

Eastern White Pine

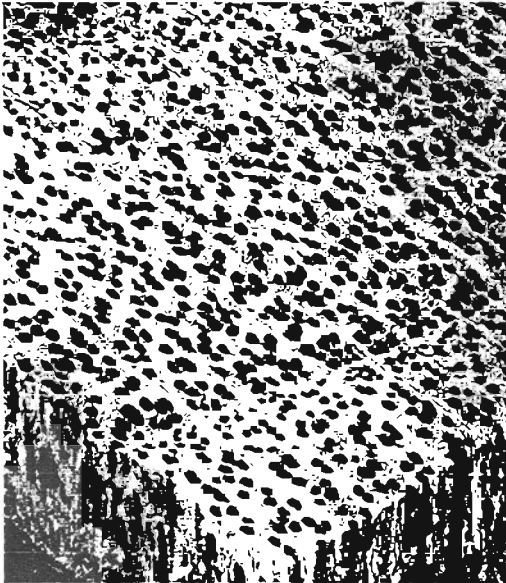


Southern Yellow Pine

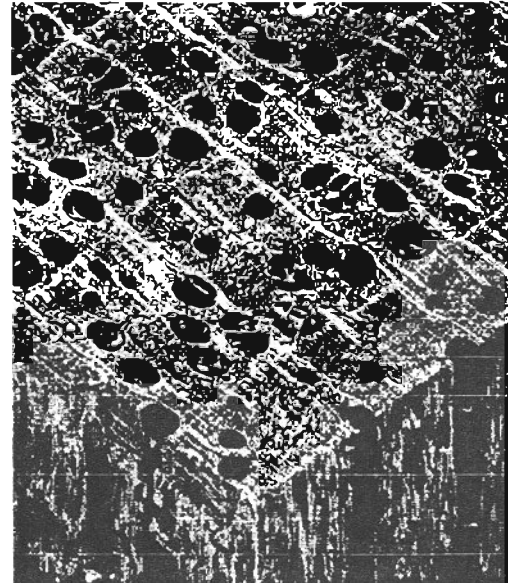


(a)

Black Cherry



Black Walnut



(b)

Figure 2.7 Characteristic cell structure and typical differences between (a) softwoods and (b) hardwoods [1].

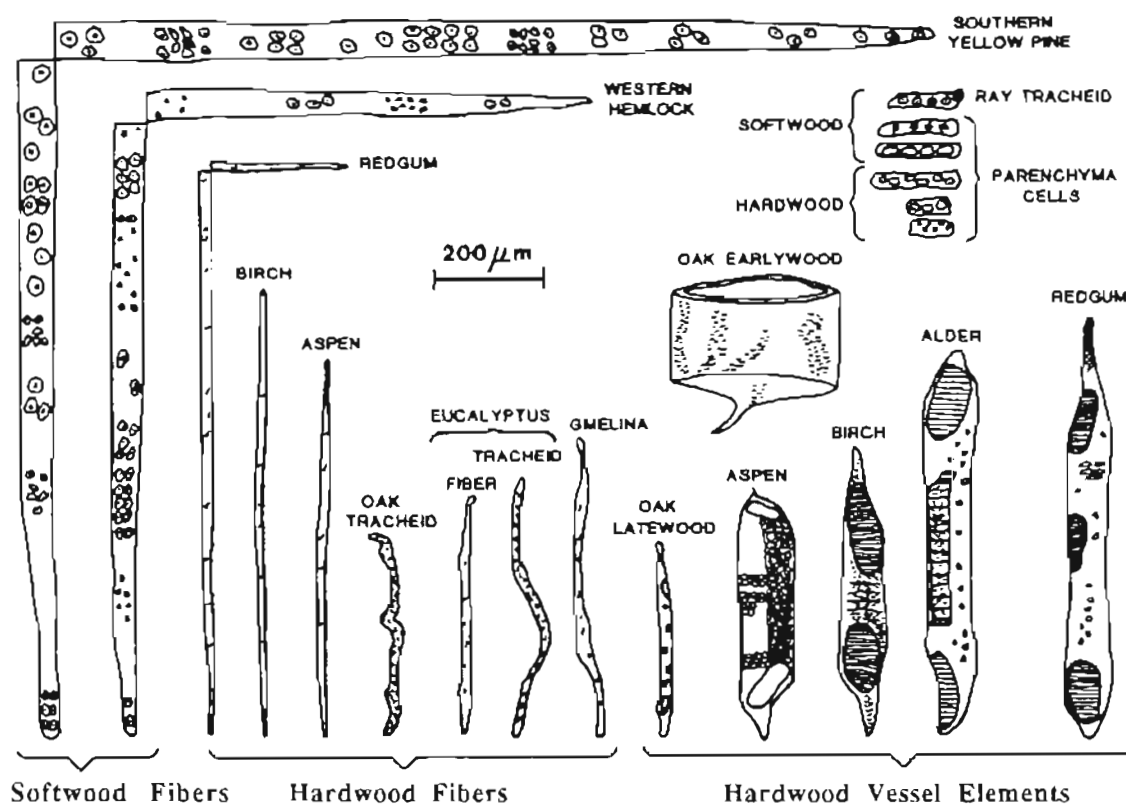


Figure 2.8 Major cell types in softwoods and hardwoods. All diagrams are at the same magnification to show the relative size of these elements [2].

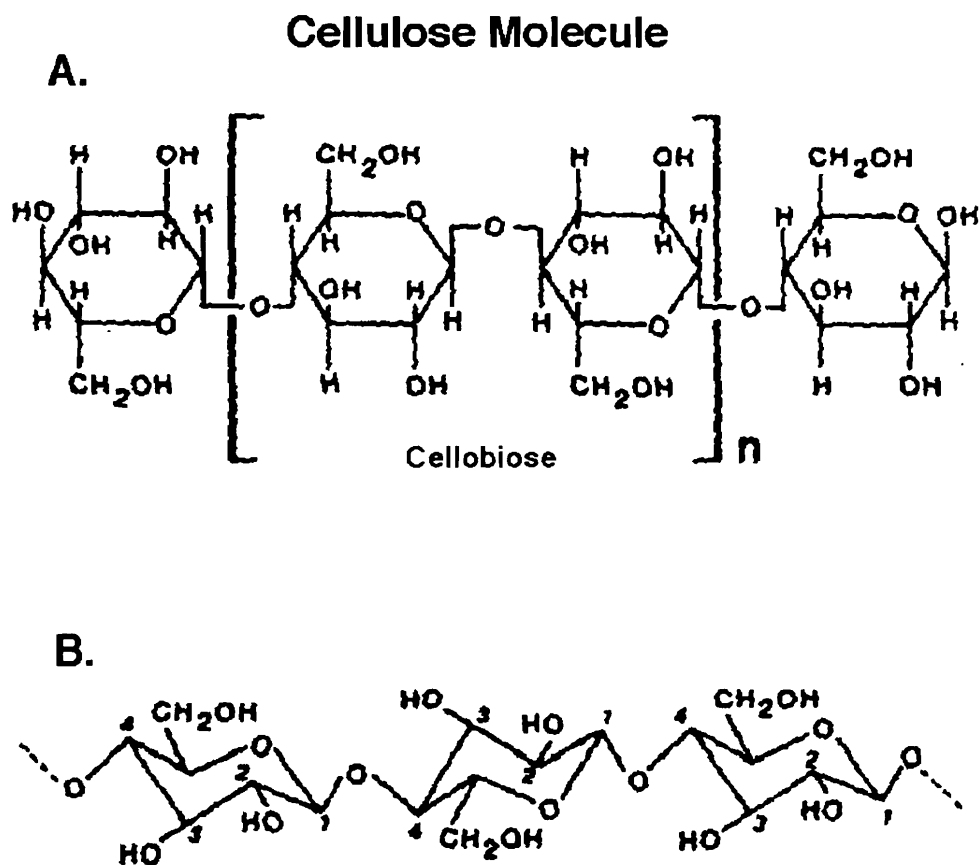


Figure 2.9 Structure of a cellulose molecule showing it to be a linear, unbranched, homopolysaccharide of glucose units [2].

A. Simplified diagram. The molecule degree of polymerization or DP is $2n-2$, and in wood is about 10,000.

B. Arrangement that a cellulose chain normally adopts in space. This form is called a chair conformation.

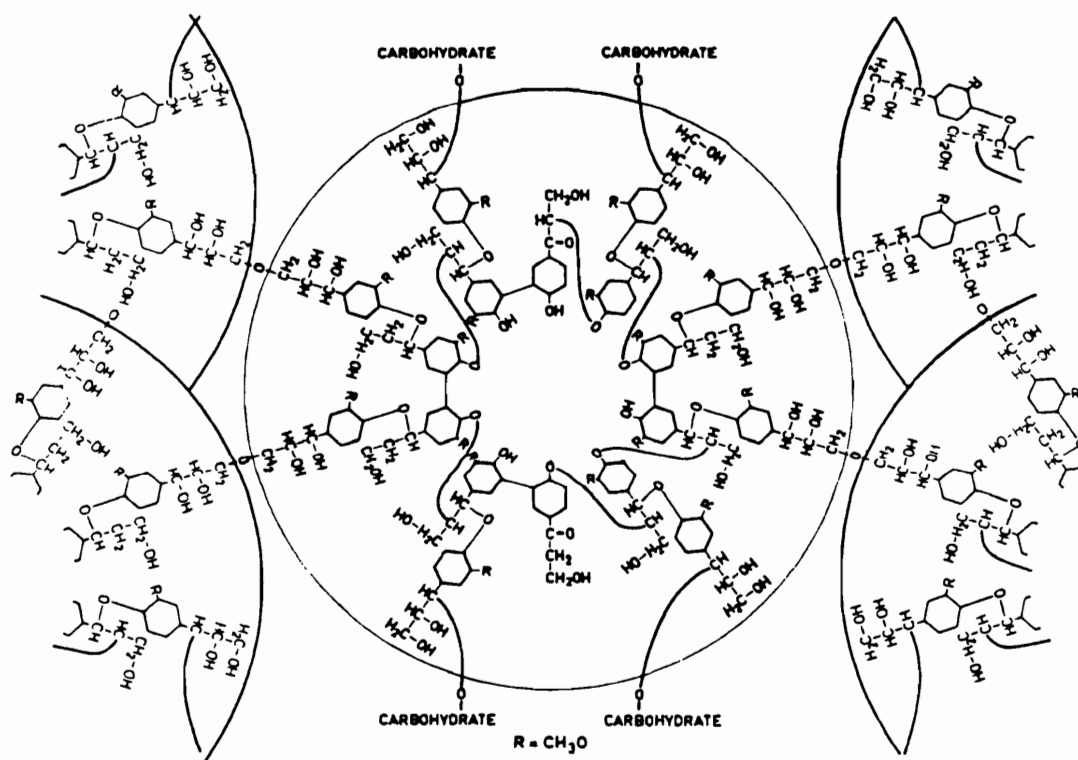


Figure 2.10 Formulation for the repeating unit of spruce lignin (actual structure is three dimensional) [4].

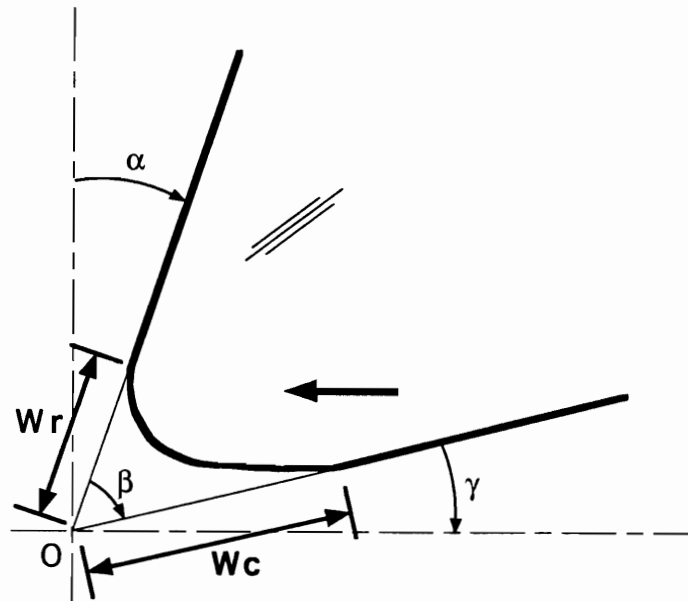


Figure 2.11 A blunt edge profile and its recessions along the rake face (W_r) and the clearance face (W_c). Point O is assumed the extreme end point of a sharp edge.

CHAPTER 3. EXPERIMENTAL

3.1 Field Study

3.1.1 The Cutting Tools

A variety of woodcutting tools, including head saw bands, quad resaw bands, circular saws, chipper knives, canters and planer knives, were obtained from three lumber companies, Boise Cascade, Van Port Manufacturing and Simpson located in Oregon and Washington (Table 3.1). Most of the tools received, 19 out of 22, were band saws and circular saws, which are the most heavily used tools in the lumber industry. These tools were used to cut red fir, hemlock and pine, three widely distributed and widely used wood species in the Pacific Northwest.

Cutting edge materials were made of steel, tool steel, high speed steel (HSS), cemented carbide (WC-Co alloy) tips (brazed), and Stellite (Co-Cr-W-C alloy) tips (welded). Among the one dozen band saws, two of them had Stellite tips, the rest were made of steel with swaged teeth. All six circular saws had hard alloy teeth or tips, two with cemented carbide and four with Stellite. The number of teeth in the circular saws ranged from 26 to 48. Among the Stellite teeth, two were fastened to the sawbody by two different tipping processes. In one process in which a Vollmer machine was used, a Stellite wire was melted with a gas tungsten arc welding system and welded to the saw, followed by a sharpening (or grinding) process. Another process, used by a Wright machine, resistance welds Stellite balls to the saw, followed by a sharpening process. Chipper and canter knives were both made of tool steels. These tools had greater sharpness angles and were much larger in edge length than teeth from band and circular saws. Planer knives made of high speed steel, were thinner, about 0.15 inch in

thickness, than chipper and canter knives of about 0.5 inch in thickness.

The tools were obtained in either the as-worn or resharpended condition. No information on sharpening or grinding was provided. For steel tipped head saw and resaw bands, four hours of operation was the typical duration of one shift and the time between sharpenings. Most tools, however, with hard tips such as cemented carbide or Stellite last considerably longer.

All as-received tools underwent a common analysis procedure. After being cut to smaller sizes using a plasma cutting torch, individual teeth from saws and lengths of cutting edges from knives and chippers were further sectioned by an abrasive cutoff saw. Cutting was performed along dashed lines as shown in Figure 3.1. Teeth or lengths of edges were used for chemistry analysis, visual examination of the cutting edges, metallography and microhardness testing.

3.1.2 Chemical Composition Analysis

Chemical compositions of band saws, chipper knives and canter knives were analyzed using the Inductively Coupled Plasma (ICP) emission spectrograph at a local company. Carbide and Stellite tips were analyzed by an energy dispersive X-ray (EDX) analyzer in a scanning electron microscope (SEM). The ICP method can give information on bulk chemistry while EDX analysis provides only surface chemistry.

3.1.3 Surface Topography Examination

The surfaces of cutting edges were examined in scanning electron microscopes, a JEOL JSM-35 and a ZEISS DSM 960, at magnifications ranging from 100 to 10,000X. The cutting edges were examined by looking directly down at the rake face, or the clearance face, or the cutting edge (top view or bi-sector view), as shown in Figure 3.2. Three teeth from each saw, or lengths from each knife, were examined, and each tooth or length was inspected along the edge from corner to corner. Surface appearance

(topography) was examined, and typical topographical characteristics were photographed. At least nine photographs, three each from the rake face view, clearance face view, the top view, at magnifications of 100X, 1,000X and 5,000X, were taken from each cutting tool.

3.1.4 Cross-section, Microstructure Examination & Microhardness Testing

Samples of the edges of selected tools were prepared for metallographic work which included cross-sectional profile, microstructural examination and microhardness testing. Steel, HSS and Stellite samples were mounted in conventional phenolic mounting powders in such a way that a cross-sectional view was obtained. They were then wet ground using water lubricated SiC abrasive papers at 120, 240, 400, and 600 grit papers in an automatic grinding machine. Polishing was performed by hand, on low-nap synthetic polishing cloths, using diamond pastes at 6 μm , 1 μm and 0.05 μm , and an oil-based lubricant. Cemented carbide tips were very hard to grind and polish by this procedure, and often their edges rounded during polishing. A variety of trials were performed and an optimum procedure was obtained. Carbides were cold mounted using epoxy resin (Struers EPOFIX) with Al_2O_3 powder added as hard fillers in a vacuum mounting chamber. To prevent edge round-off, grinding and polishing were performed following recommendations from the ASTM standard practice for metallographic sample preparation of cemented carbides. Samples were coarse ground flat, using an automatic grinding machine, with a resin-bonded diamond wheel (100 mesh) operated at 29 psi and 300 rpm. They were then coarse polished on a 15 μm diamond lap, followed by fine polishing with 6 μm and 1 μm diamond pastes on hard cloth (silk) with an automatic polishing machine operated at 58 psi and 150 rpm. Each step, either grinding or polishing, was strictly limited to 1 minute.

As-polished samples were used for obtaining a cross-sectional profile of the cutting edge and microhardness testing. For microstructure examination, steel samples were further etched in 2% nital with etching time ranging from a few seconds to minutes.

For samples with carbide and Stellite edges, Murakami's reagent, prepared by mixing 5 g $\text{K}_3\text{Fe}(\text{CN})_6$ (potassium ferricyanide), 5 g NaOH and 50 ml H_2O , was used to reveal carbide grains of cemented carbide tips (etching 120 seconds) and cast structure of Stellite tips (etching 60 seconds). Microstructural analysis was performed with a Nikon Epiphot Inverted Metallurgical Microscope and a SEM.

One tooth from each of four steel band saws, including one as-sharpened and one dull head saw, one as-sharpened and one dull resaw, were used for Knoop microhardness testing. The tests were performed at three locations, near the extreme cutting edge (as close as 30 μm), 5 mm and 10 mm away from the extreme edge with indentation loads of 25 and 500 g. Three to five indentation tests were performed in a close area with the distance between any two indentations more than three times of the indentation width. The average value was taken as one datum point for that location. The microhardness values at a total of three locations, about 5 mm apart, were plotted against the distance away from the extreme cutting edge. A LECO M-400 microhardness tester was used.

3.2 Wood Cutting Test

3.2.1 A General Description

A used circular saw, or table saw (as shown in Figure 3.3a), was used for the wood cutting tests. The sawbody, 16 inches in diameter with 7 sockets, was driven by a 5 hp motor running at a constant speed of 3480 rpm.

For each experiment, seven pairs of bits and shanks were inserted into the sockets in the blade and taken out by a special wrench. A close-up of the sawblade, the bit and the shank setup is shown in Figure 3.3b. The configuration was designed such that bits and shanks were locked onto the sawblade with no allowable relative movement.

The workpieces, i.e., wood cants, dragged by a power feeder with 4 rubber rollers above the table, were cut by about 1.5 inches in depth and 0.28 inch in width (kerf) during each pass. This created a half through kerf for a four by six (4×6 inches)

or four by eight, and near full through kerf for a two by six piece.

Interrupted tests were performed for monitoring the edge degradation process. Each bit set (7 bits) was used to cut wood at one condition for a given cutting distance. The bit weight losses and edge width change were determined after each test interval to evaluate wear. Each bit edge surface was also examined after every test interval. After all the examination and measurements were completed, the bit set was re-inserted into the sawblade for the next increment of cutting. After the final cutting increment, a bit portion containing the cutting edge was sectioned for a cross-section examination.

3.2.2 Cutting Edge Materials, Wood and Wood Moisture Content

As-sharpened bits with four types of cutting edge materials, steel, high speed steel (HSS), cemented carbide (tungsten carbide cobalt alloy) tipped and Stellite (cobalt chromium carbon alloy) tipped, were tested (Figure 3.4). They were all obtained from commercial vendors. Information on grinding, such as grinding materials, grit size of grinding material particles and depth of grinding, etc., was not provided. The four types of materials will be referred as steel, HSS, carbide and Stellite for simplicity.

Three types of wood were used: Douglas fir (botanical name: *Pseudotsuga menziesii*), because of its high volume of use and low density, western red cedar (botanical name: *Thuja plicata*) for its corrosivity and low density, and Oregon white oak (botanical name: *Q. garryana*) for its corrosivity and high density. All wood cants, in sizes of 2×6, 4×6, 4×8, and 2×8", were pre-sectioned to two feet in length prior to the cutting test.

Wood was cut under green (fir, cedar and oak), wet (fir and cedar), laboratory dried (fir, cedar and oak) and oven dried (fir only) conditions. Green wood refers to that which was freshly cut, often with a very high moisture content (MC). Laboratory dried (lab-dry in subsequent sections for simplicity) wood refers to those pieces stored in an air conditioned and humidity controlled laboratory for a period of time until an equilibrium moisture content (EMC) was achieved. This term is similar to the term, 'air

dried', which is often used by lumber workers. In the latter case, the wood is often exposed to outdoor conditions, and generally equilibrates at a higher moisture content, about 19%, than lab-dry wood with about 9% in fir and 8% in cedar. To simulate the field conditions when wood is freshly cut, often with quite high moisture contents (up to 150%), the wood cants (fir and cedar) were also soaked in tap water and deionized water for 2 to 3 weeks when the weight stabilized (weight monitored by regular weighing), this condition is referred as 'wet wood'.

The wood moisture contents were determined by oven-drying, a method widely used in industry and research laboratories. A sample of 1 to 1.5 inches in length along the grain direction was cut from a 4×8 or 2×6 inch wood piece and then placed in an oven set at 214 to 221 °F (101 to 105 °C) until a constant weight was obtained (typically takes 24 hours). The sample weight before and after drying was measured and the moisture content was calculated using the following equation

$$\text{Moisture Content (MC)} = (W_i - W_{od})/W_{od} \times 100$$

where W_i was the sample initial weight and W_{od} was the sample weight after the oven-drying. All the bound water in wood is expected to be depleted and the wood moisture content is considered to approach zero upon oven-drying. The term oven-drying should not, therefore, be confused with kiln-drying which might mean an MC of below 10% to a cabinet maker and 19% or less in structural lumber.

3.2.3 Miscellaneous Testing Parameters

Cutting Tooth Bite

Four wood feed rates, 156 in/min, 312 in/min, 432 in/min and 864 in/min, could be selected by pre-setting the gear ratio on the power feeder mentioned earlier. When the sawblade rotates at a constant rate of 3480 rpm, these feed rates generate four cutting

tooth bites (Table 3.2) based on the following relationship:

$$F = t \times N \times \text{rpm}$$

where

F - wood feed rate (in/min)

t - tooth bite or chip thickness (in)

N - number of bits (constant at 7)

rpm - sawblade rotation speed (constant at 3480 rpm)

The cutting tooth bite is defined as the depth each tooth cut into the wood during one sawblade revolution. The four wood feed rates generate four cutting tooth bites, 0.0064 inches, 0.0128 inches, 0.017 inches and 0.035 inches correspondingly. During the preliminary test, a feed rate of 156 in/min, or tooth bite of 0.0064 inches, was used for both dry and wet wood cutting in order to get as much cutting distance (at the edge) as possible from a given volume of wood. It was later learned from the Industrial Advisory Group that in industry, a tooth bite of 0.020 to 0.035 inches is typically used for green or wet or any wood with high moisture content cutting, and a lower bite used for dry wood cutting to minimize thermal effects. A tooth bite of 0.035 inches, generated by the highest wood feed rate of 864 in/min, was used for green wood cutting in later tests. It is expected that the feed rate or the cutting tooth bite may strongly affect the degree of cutting edge wear. A higher feed rate (tooth bite), is expected to generate a greater impact or loading or cutting force on the cutting edges than a lower feed rate (tooth bite) will. Instead of using a lower tooth bite of less than 0.020 inches, a tooth bite of 0.035 inch was used for most dry wood cutting in the current experiment. In order to reduce the thermal effects, an air jet cooling was used, which proved to be effective. In addition to the preliminary test, limited cutting tests were performed using steel bits to cut lab-dry fir at the low tooth bite of 0.0064 inches. The results were compared with those of cutting green fir without air cooling and lab-dry fir with air cooling at the high tooth bite of 0.035 inches.

Bit Cooling During Dry Wood Cutting

To reduce any potential thermal effect during dry wood cutting at a high cutting tooth bite of 0.035 inch, an air cooling jet was installed to blast cool air directly onto the moving bits. In addition, a water spray system was also used to achieve a similar effect.

Cutting Distance at Cutting Edges

Interrupted tests were performed for monitoring the progression of the edge wear process. In other words, the tool life was divided into portions. Test intervals were based on the cumulative cutting distance (at the edge) and/or volume of wood cut. Cutting distance for each interval ranged from a low of 2,700 inches (corresponding to one cutting pass, the lowest possible value), to a high of 100,000 inches. The cutting distance was determined based on the analysis below.

The sawblade in the table saw used in this experiment rotates on a fixed axis while the wood travels horizontally across the table. As a result, each bit edge follows a trochoidal path [1]. To avoid complicated mathematical calculations for the trochoidal path, a simplified estimate was made. Figure 3.5 schematically illustrates the relative position and movement of a woodpiece and the sawblade. If the wood is stationary, the cutting edge would follow curve AB during one sawblade revolution. As the wood moves, the cutting edge travels along a different path, curve AC.

To determine the linear path length or cutting distance (D) at the bit edge, several parameters are considered:

ω , sawblade rotation speed (constant at 3480 rpm)

V, wood feed rate (range of 156 - 864 in/min)

L, wood travel distance per pass (constant at 24 in/pass)

T, depth of cut (range of 1.25 - 1.66 in)

R, radius at the bit edge (constant at 8 in)

In one sawblade revolution:

$$AB = R \times \theta = R \times \arccos((R-T)/R) \times (\pi/180)$$

$$BC = V/\omega$$

The maximum and minimum length of line BC and curve AB are

$$BC_{\max} = 0.25 \text{ in } (V_{\max} = 864 \text{ in/min})$$

$$AB_{\min} = 5.04 \text{ in } (T_{\min} = 1.25 \text{ in to maintain efficient cut})$$

and

$$AB_{\min} \gg BC_{\max}$$

To a good approximation,

$$AC \approx AB = R \times \arccos((R-T)/R) \times (\pi/180)$$

The wood piece travels L inches in each pass, the total number of sawblade revolutions during each wood pass is

$$N = \omega \times L/V$$

The total cutting path length or distance at each cutting edge during one wood pass would be

$$D = AC \times N$$

When $R = 8$ inches, $T = 1.5$ inches, $\omega = 3480$ rpm, $L = 24$ inches and $V = 156$ in/min, the cutting distance in one pass, $D \approx 2,700$ inches. When $V = 864$ in/min, $D \approx 481$ inches.

Volume of Wood Cut

The volume of cut was calculated based on sawkerf width, depth of cut, length of cut per pass and total number of passes. The saw kerf width was constant throughout the test at 0.28 inch, and length of cut was constant at 24 inch. If the depth of cut is 1.5 inches, the volume of cut in one cutting pass is 10.2 in^3 .

3.2.4 Bit Weight Loss & Edge Width Measurements

Each bit was weighed using an electronic balance with 10^{-5} g (or 10 microgram) sensitivity before and after each cutting test interval to determine its weight loss. The average weight loss from all of the 7 bits in one set after a cutting test was taken as one single data point. The weight loss data were plotted against the total cutting distance or volume of cut as a way to evaluate the progression of tool wear. Prior to any cutting test, each bit was inserted and removed from the saw body a minimum of 20 times to reduce the contribution of bit socket wear (wear at contact areas between the sawbody socket and the bit) to the total weight loss. In addition, a dry film lubricant, MoS_2 in a grease carrier, was applied to bit sockets before each test for the same purpose. Samples were thoroughly cleaned before they were weighed. They were first spray cleaned by a heptane-based cleaning agent to remove the lubricant on bit sockets, followed by ultrasonic cleaning in acetone for two minutes to remove any remaining grease. To remove sawdust deposits on the bit, all surfaces were cleaned in soapy water by a toothbrush. Final cleaning involved rinsing in ethanol and drying.

As an alternative to, and in conjunction with, weight loss measurements, each bit edge width or 'bi-sector width' (Figure 3.6), was measured in a SEM after each cutting

test, cleaning and weighing. Each bit was tilted inside the SEM so that a direct view of the cutting edge was obtained. All edge width measurements were performed at a 200X magnification. Since the edge width may not be consistent along its whole length for each bit, three to five points along the edge were measured and an average value was taken. Because each set has a total of 7 bits, the edge width value for a particular type of bit cutting a particular wood species was obtained by taking the average edge width of the 7 bits. One data point thus came from about 35 measured values. The average edge width increase, calculated by subtracting the width of a sharp bit (average 30 μm) from the measured average value, was plotted against the total cutting distance and volume of cut.

3.2.5 Cutting Edge Surface Topography

The cutting edge of each bit was examined in a SEM prior to any test and after each cutting test, cleaning and weighing. The edge was analyzed by looking down to the rake face, clearance face and at the bi-sector, so that a near three dimensional view was obtained, as shown in Figure 3.2. Surface topography along the edge of each bit was compared, and the characteristic and unique topography of a set were photographed. After each interrupted cutting test, at least one bit was photographed from both rake face and bi-sector views at magnifications, typically, of 100X, 1,000X and 5,000X. Clearance face views for most bits were not photographed because grinding marks and wear grooves were parallel and thus difficult to distinguish. This means at least 6 photographs were taken after one interrupted cutting test. In many cases, since surface appearance varied along the edge of one bit, and from bit to bit, 12 to 20 photographs were taken after one cutting test to establish the 'typical' characteristics.

3.2.6 Edge Cross-section/Microstructure Analysis & Microhardness Testing

Sections containing cutting edge materials were cut from each bit using a cutoff saw after the cutting test was finished. Sample metallographic preparation and microstructure analysis were performed following procedures described in section 3.1.4.

Microhardness of both as-received bits and selected used bits was measured using a Knoop microhardness testing machine (LECO M-400 Hardness Tester). The results were compared to detect any possible thermal effect during the cutting tests.

Loads of 10, 25, 100 and 500 g were attempted for the microhardness test, and loads of 25 and 500 g were used. A load of 10 g produces very small indentation scars that are difficult to measure. Loads of 100 and 500 g were found to crush the sample edge or cause edge deformation. The load at 25 g did not cause edge deformation as long as the indentation was more than 20 μm away from the edge. Using a 25 g load, indentations were made starting close to the edge, with 20 μm increments on a traverse perpendicular to the cutting edge up to 200 μm away from the edge. Each sample was ground and polished (using 1 μm diamond paste as the final polishing abrasive) prior to the microhardness test. This sequence of grinding, polishing and microhardness testing was performed five times, so that data scatter and microhardness variations along the edge could be obtained. The depth of each grinding and polishing was about 0.5 mm. All data points from one sample were plotted against the distance from the edge, and appeared as a band in one graph. With a load of 500 g, tests were performed at 300 μm , 5 mm and 100 mm away from the edge for comparison.

3.2.7 Saw Kerf and Wood Chip Surface Characteristics

Surfaces of the saw kerf bottom were visually inspected, and sections were examined in the SEM. Wood chips were also collected and compared. Attention was paid to the size distribution, surface topography and roughness of wood chips. For SEM observations, wood samples were stored in a low vacuum chamber for 24 hours prior to

the observation to remove moisture, followed by sputter deposition of a coating (a few hundred angstroms in thickness) of gold-palladium to enhance electron conduction in the SEM. Photographs were taken at various magnifications from 8X to 10,000X.

3.3 Abrasion Test

The standard dry sand rubber wheel test (ASTM standard G65, 1985 edition) was modified for an abrasion test. A schematic of the test apparatus is shown in Figure 3.7. Testing was performed at a wheel rotation speed of 200 rpm and a normal load of 130 N. The abrasive flow rate was controlled between 250 and 350 g/min. The diameter of the rubber wheel, about 9 inches, was measured periodically during the test.

An AISI 1065 carbon steel, in the annealed condition, was used as the testing material. The samples were 3 inches long, 1 inch wide and 1/4 inch thick. They were wet ground by hand using cold water and SiC abrasive papers with grits of 120, 240, 400 and 600. They were polished on a synthetic low-nap cloth using diamond paste, 6 μm , 1 μm and 0.25 μm , and an oil-based lubricant. Dry walnut shells from a commercial source were used as the abrasive. The walnut shells had a fairly uniform size distribution with average diameter of about 1 mm (Figure 3.8).

Sample surfaces were examined using both an optical microscope and a SEM. Up to 400X magnification was used with the optical microscope, and up to 10,000X magnifications in a SEM, and photographs were taken from 100X to 10,000X magnifications.

The surface roughnesses of the testing coupons before and after each abrasion test were measured using a surface roughness tester (Mitutoyo Surftest 401). A cutoff length of 0.25 μm and frequency of 5 were used. The R_a values, the arithmetic mean of the departures of the roughness profile from the mean line, were used as the indicator of surface roughness.

Table 3.1 List of commercial woodcutting tools obtained from field

Number	Type	Material	Wood	State	Source
B1	head saw	steel	red fir	4hrs/dull	Boise Cascade
B2	head saw	steel	red fir	4hrs/resharpened	Boise Cascade
B7	head saw	steel	hemlock	1.5hrs/dull	Van Port
B9	head saw	steel	fir	resharpened	Boise Cascade
B10	head saw	steel	fir	dull	Boise Cascade
B3	resaw	steel	red fir	4hrs/dull	Boise Cascade
B4	resaw	steel	red fir	4hrs/resharpened	Boise Cascade
B5	resaw	steel	hemlock	4hrs/dull	Van Port
B11	resaw	steel	pine	4hrs/resharpened	Boise Cascade
B12	resaw	steel	pine	4hrs/dull	Boise Cascade
B15	resaw	steel	fir	4hrs/dull	Simpson
B13	resaw	Stellite tip	fir	4hrs/resharpened	Simpson
B14	resaw	Stellite tip	fir	4hrs/dull	Simpson
CS3	circular saw	Stellite tip, Vollmer-tipped	hemlock	3 days/dull	Van Port
CS4	circular saw	Stellite tip, Wright-tipped	hemlock	1.5-2days/dull	Van Port
CS5	circular saw	Stellite tip	fir	resharpened	Simpson
CS6	circular saw	Stellite tip	fir	dull	Simpson
CS1	circular saw	cemented carbide tip	red fir	176hrs/resharpened	Boise Cascade
CS2	circular saw	cemented carbide tip	red fir	176hrs/dull	Boise Cascade
CH1	chipper knife	tool steel	red fir	16hrs/dull	Boise Cascade
CE1	canter	tool steel	red fir	16hrs/dull	Boise Cascade
P1	planer knife	high speed steel	red fir	72hrs/dull/resharp.	Boise Cascade

Table 3.2 Wood feed rate and cutting tooth bite				
F, feed rate (in/min)	156	312	432	864
t, tooth bite (inches)	0.0064	0.0128	0.0177	0.0350

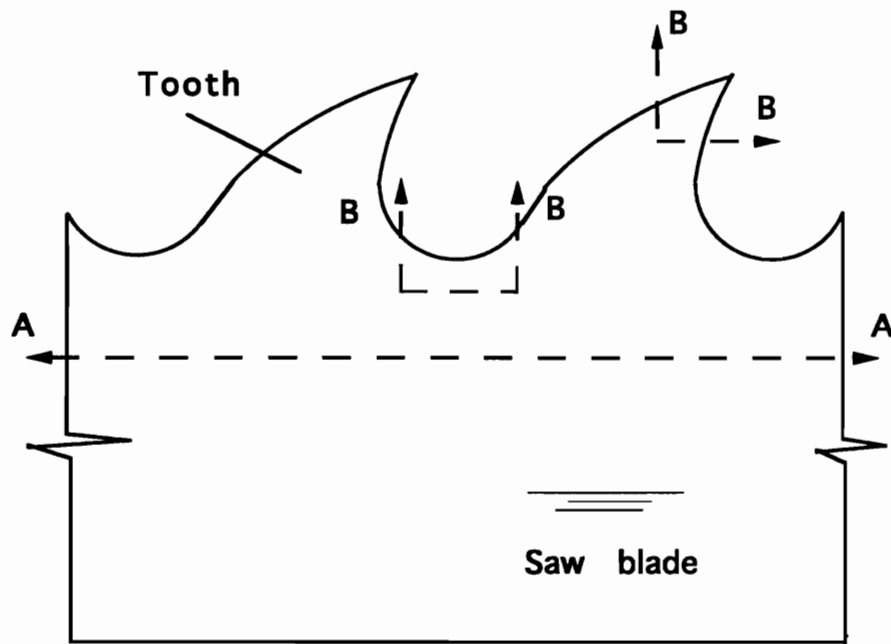


Figure 3.1 Schematic showing where the plasma torch cuts (dashed line A-A) and the abrasive saw cuts (B-B) were made.

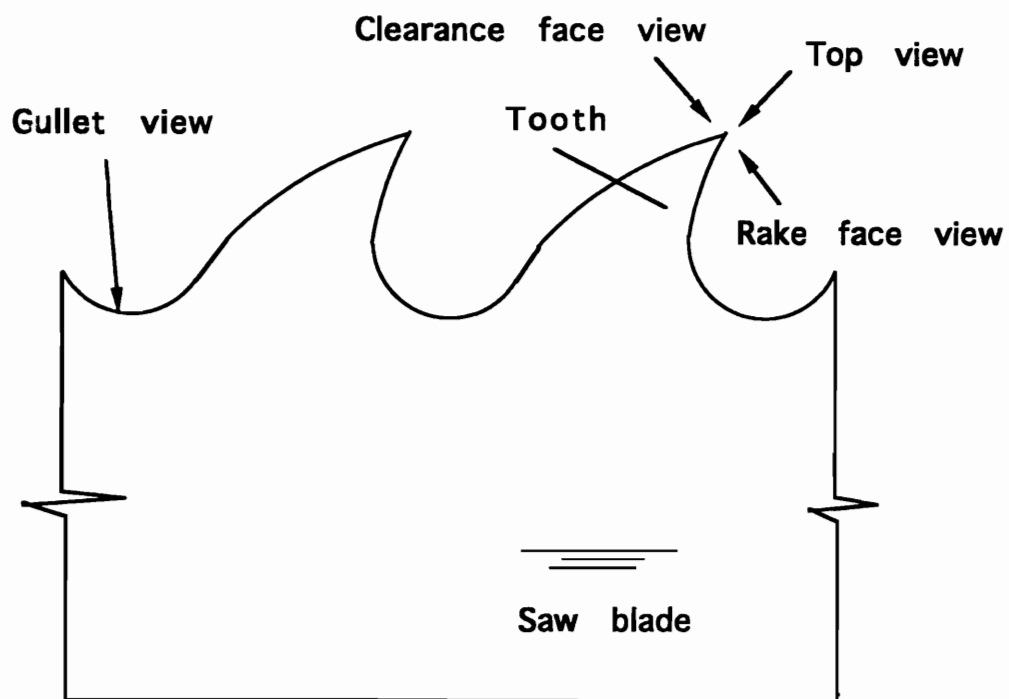
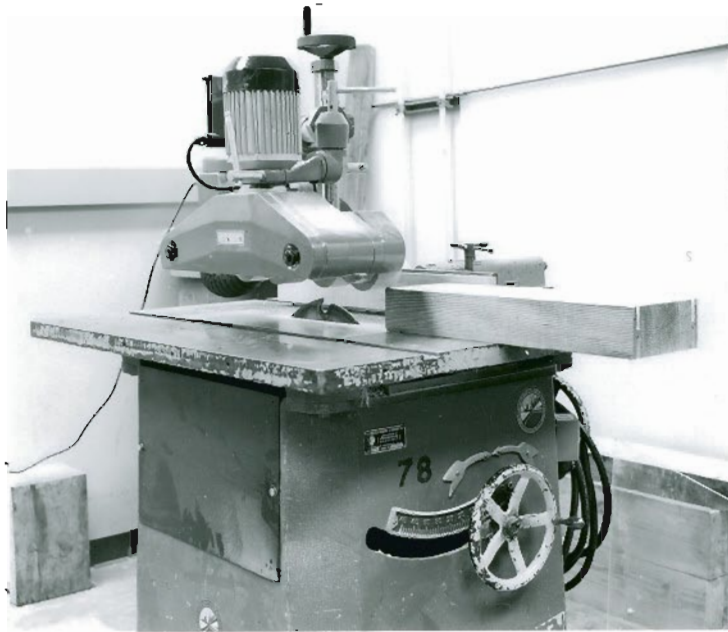


Figure 3.2 Schematic showing directions along which observations were made in a SEM.



(a)



(b)

Figure 3.3 Table saw (a) and configuration of the inserted tooth circular sawblade showing bit and shank (b).



Figure 3.4 Four types of tool materials for the cutting test, from top to bottom: cemented carbide tipped, Stellite tipped, high speed steel and steel.

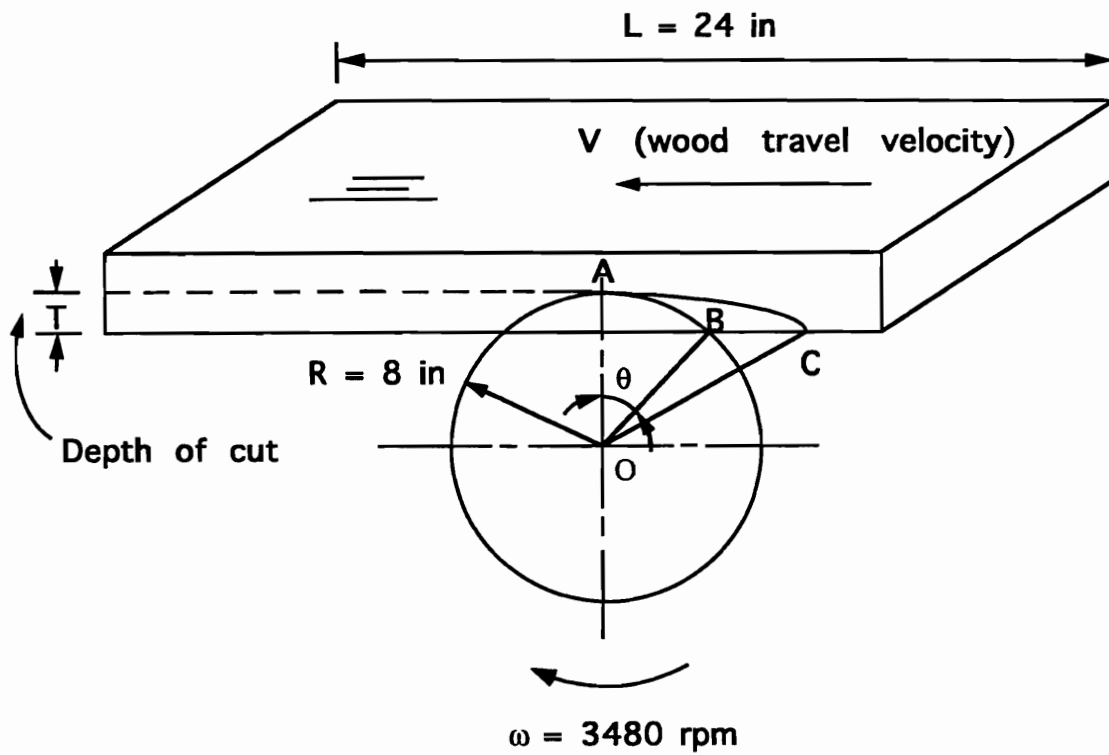


Figure 3.5 Schematic of wood/tool relative position and bit edge cutting path (curve AC) during one saw blade revolution.

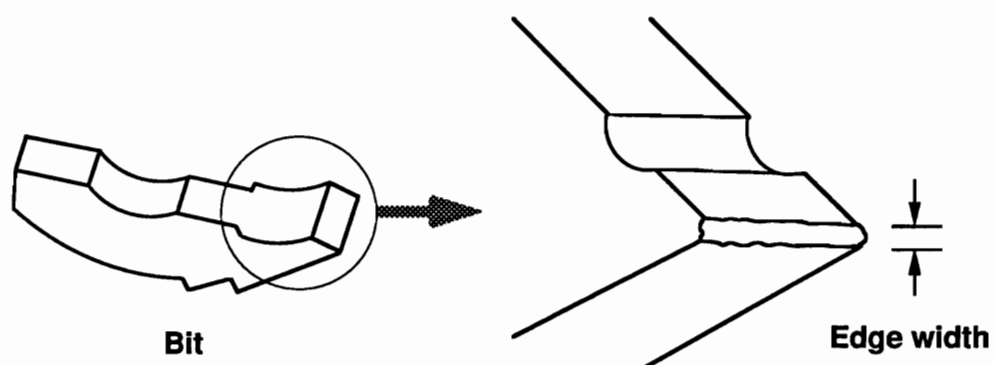


Figure 3.6 Schematic of a bit and its edge width.

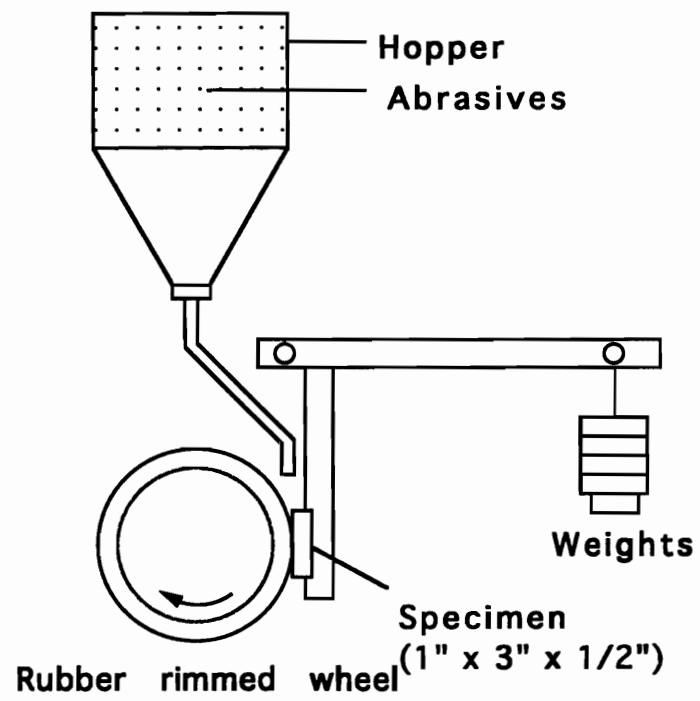


Figure 3.7 Dry Sand Rubber Wheel (DSRW) test apparatus.

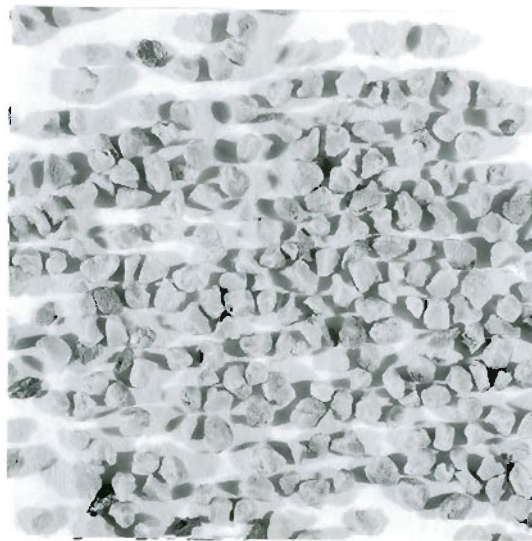


Figure 3.8 Walnut shells used for the DSRW abrasion test.

CHAPTER 4. RESULTS

4.1 Field Study

4.1.1 Cutting Edge Materials Composition

Chemistries of cutting edge materials (tips) from commercial woodcutting tools are listed in Table 4.1. Although from different sources, all band saws with swaged teeth had very similar compositions, about 0.7 wt% carbon, 2 wt% nickel and less than 0.5 wt% manganese. This range of composition closely matches that of Uddeholm UHB15N20, a commercial Swedish steel widely used to make band saws.

EDX analysis indicated that the two cemented carbides tipped circular saws (CS1-resharpened and CS2-as worn) had tungsten contents in the range of 83 to 86 wt% in the tips. However, the cobalt content on the worn surface (CS2-worn, 0.3 wt%Co) was less than that on the as-sharpened (CS1-sharpened, 4.4 wt%Co). The two Stellite tipped circular saws from Simpson (CS5 and CS6) had similar composition, 42-45 wt%Co, 30-31 wt%Cr, 10 wt%W and about 2 wt%Ni. However, the Stellite tips on two circular saws from Van Port, CS3 produced by the Vollmer-tipping process and CS4 by the Wright-tipping method had different compositions. The Vollmer-tipping method produced tips with a lower chromium (20 wt%) and cobalt (38 wt%) yet a greater iron (38 wt%) concentration than that by Wright-tipping (41 wt%Cr, 50 wt%Co and 2.1 wt%Fe), indicating a higher dilution of the base metal to the tip during the Vollmer-tipping process.

Chipper knives (CH1) and canters (CE1), made of tool steels, had similar composition, nominally 7 wt%Cr, 1 wt%Mo, 1 wt%Si, 0.5 wt%C and 0.5 wt%Mn. Planer knives (P1) were made of high speed steels with about 4 wt%W, 4 wt%Cr,

3 wt%Mo, 1.4 wt%V, 0.9 wt%C, 0.6 wt%Ni and 0.6 wt%Mn.

4.1.2 Cutting Edge Surface Topography

Differences in surface topography, or wear patterns, were found to be related more to the cutting edge material, rather than the tool type. Of the tools obtained, cutting edge materials were categorized into three groups, 1) steels, including carbon steel, tool steel and high speed steel; 2) cemented carbide; and 3) Stellite.

Steels

Cutting edges of as-sharpened steel tools typically showed grinding marks or grooves which were parallel to the cutting edge, as well as fractures at the extreme edges due to sharpening processes. Figure 4.1 compares the rake face edges of steel head saws in resharpened and worn (4 hour cutting red fir) conditions. After woodcutting, the number of visible grinding marks was reduced, and abrasive grooves perpendicular to the cutting edges were observed. Worn cutting edges appeared slightly different from a rake face view and a clearance face view. More abrasive grooves were observed on the rake face than on the clearance face (Figure 4.2).

The difference between an as-resharpened and a used cutting edge was pronounced when viewing directly at the edge (a top view), as shown in Figure 4.3. The edge and the grinding marks are parallel to each other and difficult to distinguish (except at the corner as shown in Figure 4.3b) after the resharpening process. However, a wider edge was formed after a 4-hour cutting operation (Figure 4.3c and d).

Similar to those surfaces of steel head saw edges cutting red fir, grooving due to the woodcutting process was also observed on the surfaces of steel resaw edges cutting hemlock for 4 hours, as shown in Figures 4.4 and 4.5. Grooves as wide as 2 μm were observed. Cutting pine also resulted in surface grooves, similar to those seen after cutting fir.

A higher density of grooves was observed on surfaces of a tool steel canter after cutting red fir for 16 hours (Figure 4.6) than those observed on steel saws cutting red fir for 4 hours. Chipper knives, which were also made of tool steel, showed very similar surface wear patterns after cutting red fir for 16 hours. Planer knives made of high speed steels showed fewer and smaller wear grooves than tools made of tool steels.

Carbide Tips

The rake face edges of cemented carbide tips from circular saws after sharpening displayed grinding marks parallel to the edge, as well as edge fracture, with exposed sharp and angular carbide particles (Figure 4.7). However, after cutting red fir for 176 hours, not only were all grinding marks removed from the edge surfaces (Figure 4.8), but the fractured edges and carbide particles were smoothed, rounded or flattened. The difference between a sharpened and a worn carbide tip is illustrated by the top views in Figure 4.9. The width of the worn edge is almost three times that of the sharpened one.

Stellite Tips

Cutting edges of as-sharpened Stellite tips (Figure 4.10) appeared rougher (having a rougher profile) than those of as-sharpened steel and carbide tools. Sharp carbide particles of various sizes were exposed after the sharpening process. Additionally, many randomly orientated microcracks were observed, and some areas along the edge were surrounded by continuous cracks (Figures 4.10b and c). After cutting red fir for 4 hours, however, the edge (or edge profile) was smoothed and the number of cracks reduced (Figure 4.11). Surface wear grooves, with a lower density than those seen on steel tools, were also observed.

Stellite produced by the two types of tipping processes, Vollmer-tipping (arc-weld) and Wright-tipping (resistance-weld), displayed different surface appearances. Stellite edges by Vollmer-tipping from a circular sawblade after cutting hemlock for

about 3 days are shown in Figure 4.12. Rough edges, with many sections of the cutting edge missing, as well as some wear grooves, were observed. In particular, dendrites from the welding process, and microcracks extending from those dendrites, were revealed from a top view of the cutting edge, as shown in Figures 4.12c and d. In comparison, the Wright-tipped Stellite had a much lower density of microcracks, fewer wear grooves, and no dendritic structure (Figure 4.13).

Gullet edges of most tools appeared smooth, with no cracks or fracture observed. The gullet edge of a circular saw (with Wright-tipped Stellite) cutting hemlock for about 2 days appeared unique. Crater wear seems to have occurred, as shown in Figure 4.14a at a magnification of about 100 times. A higher magnification examination revealed cracks along lines appearing to be the grain boundaries (Figure 4.14c).

4.1.3 Edge Cross-sections and Microhardness

The cross-sections of as-sharpened and worn (4 hours cutting red fir) steel head saw edges are shown in Figures 4.15a and b while the cross-sections of as-sharpened and worn (176 hours cutting red fir) carbide tips from circular saws are presented in Figures 4.15c and d for comparison. In these micrographs, rake faces are located on the left hand side and clearance faces on the right hand side. The edge of the as-sharpened steel head saw (Figure 4.15a) was slightly inclined towards the rake face side, indicating edge plastic deformation during the grinding process. The extreme cutting edge width of the worn steel saw is about twice that of an as-received steel saw. The width of the worn carbide tips is about three times that of an as-received one.

For both sharpened and worn steel band saws, the microhardness close to the extreme edge was greater than that at areas about 5 mm away from the edge, as shown in Figure 4.16, regardless of the load used (either 25 or 500 g). With a 25 g loading indentation, hardness values at the extreme edges of worn saws (B1 and B3) were higher than those at the sharpened ones (B2 and B4). However, mixed results were obtained with a 500 g load.

4.2 Wood Cutting Test

Table 4.2 presents details of all tested bit sets (BS), conditions and results: edge materials (EM), wood and their moisture content (MC), tooth bite (TB) used, presence of air cooling (AC), depth of cut (DC), cant size (CS), volume cut per pass (VCP), total cutting pass (TP), total volume of cut (TVC), total cutting distance (TCD), accumulated total weight loss (ATW) and accumulated total edge width increase (ATEWI). Both intermediate and final results are presented in the table, and details are explained in the following sections.

4.2.1 Testing Woods-Moisture Content and Microstructure

Table 4.3 lists the measured wood moisture contents using the oven-dry method. The moisture content after oven-drying is assumed to be zero. After lab drying, the moisture content or the equilibrium moisture content for the three wood species, were slightly different. Cedar had the lowest moisture content of about 8%, fir 10% and oak with the highest value, 15%. The moisture content difference among green woods was considerably larger. The cedar and oak had about 70% moisture content, while the fir varied from 50 to 110%. Green fir having more heartwood, was in the lower end of this range (50%), and green fir with more sapwood was in the upper end of the range (110%).

The cross-section microstructures of fir and cedar samples are shown in Figure 4.17, showing the open end of longitudinal fibers. Portions containing both the earlywood and the latewood (transition zones in terms of fiber geometry and wall thickness) of fir and cedar are shown in Figures 4.17a and b. Fir has a very smooth transition from earlywood to latewood while cedar has a drastic change from earlywood to latewood. For both fir and cedar, the earlywood is featured with fibers of larger diameters and thinner walls in comparison with those of latewood. On average, cedar earlywood is slightly larger in fiber diameter than fir earlywood. However, cedar

latewood shows less open space than fir latewood and the cedar fibers appear to be squeezed together. Figure 4.17c illustrates the fiber wall thicknesses in the fir latewood, about 7 μm , five times greater than that in the cedar latewood. The wall thicknesses of both fir earlywood and cedar earlywood are very close, about 2 μm .

4.2.2 Testing Bits-Chemistry, Microstructure and Microhardness

Results from semi-quantitative chemistry analysis were obtained using the EDX analyzer attached to the SEM. The steel bit was found to have about 1 percent of nickel (in weight). The high speed steel (HSS) consisted of about 6 wt%W, 4 wt%Cr, 1 wt%V, and 0.5 wt%Mn. The primary alloying element in cemented carbide, the tungsten, was about 86 percent, balanced by the cobalt. In the Stellite, there was about 63 percent of cobalt, 30 percent of chromium, 2 percent of iron and 4 percent of tungsten. No carbon concentration data were obtained from any tool.

The microstructure of a steel bit is shown in Figure 4.18. It illustrates the grain size, but can not be used to determine the phases present.

The microstructure of a high speed steel bit is shown in Figure 4.19, consisting of rounded carbide particles, with sizes ranging from less than 1 μm to over 10 μm , embedded in the steel matrix. Figure 4.19c is a backscattering electron image (BEI) of the HSS which again illustrates the size and distributions of the carbide particles. The white areas, due to the presence of elements with higher atomic numbers, are carbide particles.

The secondary and backscattering electron images of tungsten carbide cobalt are shown in Figure 4.20. Instead of being rounded, as in the high speed steel, the carbides were all angular, and of various sizes. The white areas in the BEI photos (Figure 4.20c) illustrate the overwhelming majority of tungsten carbide present.

A thin layer of Stellite, about 600 μm , was revealed on the rake face of Stellite tips after etching by Murakami's etchant (Figure 4.21a). The Stellite exhibits a classic hypoeutectic microstructure with interdendritic arrays of carbides. The as-cast condition

is observed in Figure 4.21b at the upper left portion, and as-gas tungsten arc welded (GTAW) at the lower right portion. This type of morphology, with partial carbide continuity, is different from those of high speed steel and cemented carbides. The carbide particles from the latter two were exclusively separated in the matrix.

Table 4.4 lists the Knoop microhardnesses of all four types of tested bits measured on cross-sections. The steel bit had an average Knoop hardness of 433, about HRC 43. The Stellite had a similar hardness of 438, or HRC 43. The HSS was much harder, with an average of 652 or HRC 56, and cemented carbide had the highest hardness, 1042 (>HRC 65). The base metal for carbide tips had a very low Knoop hardness of 256 or HRC 21, while the base metal for the Stellite tip had an equivalent hardness to the Stellite tip, about 449 or HRC 44.

The backscattering electron images presented above were used for determining carbide area fractions with an image analyzer (LECO 2001 Image Analysis System). The results are shown in Figure 4.22a together with the microhardness for comparison (Figure 4.22b). Except for Stellite, the higher the carbide area fraction, the greater the microhardness. The cemented carbide, having the highest carbide area (and volume) fraction, also had the highest microhardness. The HSS had a lower carbide area fraction yet a higher microhardness than that of Stellite. The Stellite had about 31 wt% carbides while the steel bit had none, yet the two had equivalent microhardness values.

4.2.3 Weight Loss & Edge Width Increase

Data Scatter

Discrepancies in weight loss and edge width increase among the 7 bits in a set were found during the preliminary testing at a low cutting tooth bite of 0.0064 inch. It was further realized that this data scatter was related to the bit height, which reflected the actual cutting radii variation of individual bits. To evaluate this, a dial indicator was used to measure the highest point of each bit reaches (bit height) during a sawblade

rotation. As shown in Figure 4.23, the dial indicator was stabilized on the saw table by a magnet. The discrepancy between any two bits in a set was found to be consistent.

As an example, bit height, weight loss and edge width increase data from individual bits of several bit sets are shown in Tables 4.5 to 4.7. The value of each bit height has no meaning unless compared with the height of other bits in the same column. In the T1 set (Table 4.5), bit T1-6 had the lowest bit height of 0.061 inch and the lowest edge width increase of 10 μm , but not the lowest weight loss. T1-3 and T1-7 were the two with the highest bit height (0.101), and T1-7 had the highest bit edge width increase (72 μm). Excluding T1-6, the largest bit height difference among the other 6 bits was 0.014 inch. This is greater than the cutting tooth bite (the depth each bit cut into the wood during one saw blade revolution) of 0.0064 inch used in the preliminary cutting test. This means that while those bits with greatest heights were cutting aggressively, others were barely cutting at all.

In the bit set T14 (Table 4.6), the bit T14-4 had the greatest bit height, weight loss, and edge width increase while the bit T14-6 had the lowest values of bit height and edge width increase (zero), but not the lowest weight loss.

The magnitude of data scatter among different steel bit sets varied, either larger or smaller than the given examples. In comparison, the heights of carbide tipped bits were relatively uniform (Table 4.7). Except for one bit, T20-6 in the set T20, the height difference between any two of the rest was less than 0.004 inch, the lowest among all four types of tested tool materials. The bit No. 6 consistently had the lowest height in all tested sets.

Steel Bits Cutting Fir/Cedar at 0.0064" Tooth Bite

In the preliminary tests, steel bits were used to cut lab-dry fir, tap water soaked (wet) fir, lab-dry cedar and tap water soaked (wet) cedar at a low cutting tooth bite of 0.0064 inch. The accumulated weight loss versus accumulated cutting distance is shown in Figure 4.24. Wet wood caused a greater weight loss and weight loss rate to the steel

bits than lab-dry wood and the difference was significant. The ranking from high to low in terms of total weight loss and weight loss rate is listed as follows: wet cedar, wet fir, lab-dry cedar and lab-dry fir. Weight loss rates were higher at the initial short cutting distance of about 5,000 inches for all four types of wood.

The accumulated weight loss of all tested bits after 800,000 inches distance is illustrated in Figure 4.25a. For comparison, the total edge width increase is shown in Figure 4.25b, with a different ranking from that of weight loss. The lab-dry cedar caused the lowest edge width increase, followed by wet cedar and wet fir, and lab-dry fir resulted in the greatest edge width increase. Fir resulted in a greater edge width increase than cedar under both green and lab-dry conditions.

Steel Bits Cutting Fir in Various Conditions at 0.035" Cutting Tooth Bite

The total weight losses of steel bits cutting fir at 0.035 inch cutting tooth bite for 100,000 inches of cutting distance is shown in Figure 4.26a. The fir was cut in various conditions: fresh green, tap water soaked for 3 weeks, deionized water soaked for 3 weeks, lab-dry with air cooling during cutting, lab-dry without air cooling during cutting, lab-dry with a high density of knots and without air cooling during cutting, and lab-dry with deionized water spray during cutting. The tap water soaked, lab-dry with air cooling, and lab-dry with no air cooling were among the lowest causing bit weight loss, while lab-dry with knots and without air cooling, and lab-dry with deionized water spray caused the greatest bit weight loss. The difference between the highest (lab-dry with deionized water spray) and the lowest (lab-dry with air cooling) was about 60 percent.

Similar to the results from cutting at the low tooth bite, results from the edge width increase measurements (Figure 4.26b) displayed a different ranking to that of weight loss at the high tooth bite. In general, dry fir caused greater edge width increase than wet fir. The lab-dry with knots and no air cooling resulted in the greatest edge width increase, as much as three times the lowest, the deionized water soaked fir. The tap water soaked was slightly higher than fresh green which was in turn greater than the

deionized water soaked. The difference among lab-dry with and without air cooling, and lab-dry with deionized water spray was within 10 percent.

Figure 4.27a shows the total weight loss versus total cutting distance of steel bits cutting green fir with no air cooling and lab-dry fir with air cooling, both at the high cutting tooth bite of 0.035 inch. The green fir caused more weight loss than the lab-dry fir, and the difference was significant. The weight loss rate caused by green fir also appeared to be higher than that by lab-dry fir. Contrary to the weight loss result, the corresponding edge width increase against total cutting distance shows that lab-dry fir led to a much greater edge width increase than green fir (Figure 4.27b). The edge width increase rate in cutting lab-dry fir appeared to be slightly greater than that of cutting green fir.

After cutting at a high tooth bite of 0.035 inch for a short cutting distance of 5,000 inches, oven-dry fir caused an edge width increase to steel bits nearly twice that by lab-dry fir (Figure 4.28).

Comparison Between Low (0.0064") and High (0.035") Cutting Tooth Bite

The difference in edge changes at the low (0.0064 inch) and the high (0.035 inch) tooth bites using steel bits cutting lab-dry fir is shown in Figure 4.29. Cutting green fir at the high tooth bite is also shown in the graph for comparison. The edge width increase rate versus total cutting distance was much greater at the high tooth bite (for both lab-dry and green fir) than at the low tooth bite. In contrast to the edge width increase versus the cutting distance plot, the edge width increase rate was much smaller (for all three cutting conditions) when the edge width increase was plotted against the total volume of cut (Figure 4.29b). The edge width increase rate was greater cutting lab-dry fir at the high tooth bite than both cutting lab-dry fir at the low tooth bite and green fir at the high cutting tooth bite. However, the rates for the latter two, lab-dry at the low cutting tooth bite and green at the high cutting tooth bite, were close.

Steel/HSS/Carbide/Stellite Cutting Fir/Cedar/Oak at the High Cutting Tooth Bite

The weight loss and edge width increase using all four types of tool materials to cut fir, cedar and oak in lab-dry and green conditions is shown in Figure 4.30. All bits were tested at the same condition of 0.035 inch tooth bite and 100,000 inches of cutting distance. Except for the high speed steel, green wood caused more weight loss than lab-dry wood. Taking steel bits as an example, steel bits cutting green fir resulted in almost twice as much weight loss as lab-dry fir did, and cutting green cedar and oak led to much more weight loss than cutting wood under lab-dry conditions. The weight loss difference to the cemented tungsten carbide bits between green and lab-dry cedar was also very prominent. The weight loss difference cutting green and lab-dry wood using Stellite bits was relatively small. High speed steel bits were used to cut fir only, and lab-dry fir caused more weight loss than green fir to the bits.

The results from the edge width increase measurement again shows a different pattern from that of the weight loss. The edge width increase of Stellite cutting all types of wood was insignificant compared with that of other materials and thus Stellite outperformed all other materials. Except for the green cedar, which caused the greatest edge width increase among all three types of wood, carbide bits performed better than steel and high speed steel bits. For steel bits, cutting lab-dry wood caused higher edge width increase than cutting green wood. High speed steel did slightly better than steel, but still had a greater edge width increase cutting lab-dry fir than cutting green fir.

4.2.4 Cross-sectional Profile of Selected Steel Bits

By grinding a bit in its cross-section, the 'actual' edge profiles may be observed. Edge profiles were found to be inconsistent along the cutting edge; which was already noted during the edge width measurement in the SEM. However, the average tip width measured on the cross-section matched the edge width arithmetic average obtained from SEM observations. Figure 4.31 shows the cross-sections of an as-received steel bit, and

steel bits after cutting green and lab-dry fir for 300,000 inches. At the extreme edge of an as-received (sharp) bit, the edge material was pushed slightly from the clearance face towards rake face due to the grinding process (Figure 4.31a). After cutting lab-dry fir, however, the edge was pushed slightly in the opposite direction (Figure 4.31c). The bit edge after cutting green fir was sharper than that after cutting lab-dry fir.

4.2.5 Cutting Edge Surface Topography

As-received (new) Steel Bits

As-received steel bits were examined prior to any testing, and the cutting edges were often characterized by grinding marks parallel to the cutting edge and grinding burrs on rake faces, and grinding marks perpendicular to the cutting edge at clearance faces. Figure 4.32 displays both the rake face and the clearance face edges of as-received steel bits. Those grinding marks on the edge surfaces indicated that grinding or sharpening was done along the direction parallel to the cutting edge on the rake face (Figure 4.32a and b), and was performed in the direction of nearly perpendicular to the cutting edge on the clearance face (Figure 4.32c and d). The relatively rough edge with burrs and plastic deformation on the rake face and the 'clean' edge on the clearance face indicate that the commercial bits used were ground first on the rake face and then on the clearance face. This led to the bit materials rolling over from the clearance face to the rake face. Since grinding marks were perpendicular to the cutting edge and in the same direction as most wear grooves on the clearance faces, later examination work was focused on the rake faces. By appropriate tilting of a bit in the SEM, both the rake and the clearance faces can be viewed at the same time, referred to as a 'top view' in this thesis. Unless otherwise noted, the rake face will always be on the left side of the micrograph and the clearance face on the right.

Steel Bits Cutting Lab-dry and Wet Fir at 0.0064" Tooth Bite

During the initial period of cutting, grinding burrs were often removed from the edge, frequently leading to further edge fractures. For example, after one cutting pass, about 2,700 inches cutting distance at the cutting edge, most grinding burrs and lengths of edges were removed and fracture surfaces were exposed (Figures 4.33a and b). Grinding burrs were completely removed at extended cutting distances, and at the same time, fracture surfaces were smoothed (Figure 4.33c and d). Based on the edge surface appearance, or the magnitude of wear, the steel bits of one set (total 7 bits) cutting lab-dry fir at 0.0064 inch tooth bite were divided into two groups. The first group of 5 bits had relatively mild edge degradation compared with the greater wear in the second group (2 bits, T1-3 and T1-7 in Table 4.5). Figure 4.34 displays the typical rake faces in the mild wear group. They were smoothed and rounded with traces of wear grooves perpendicular to the extreme edge after 230,000 inches cutting distance. In the high wear group, a far greater number of wear grooves were observed (Figure 4.35). The grooves seen in the high wear group were also wider, with widths ranging from less than 1 μm to over 5 μm , and deeper than those observed in the mild wear group. Figure 4.36 illustrates cutting edges from a top view and compares the typical cutting edges of those in the mild wear group (Figure 4.36b) with those in the high wear group (Figure 4.36c). Both were rounded, yet the latter had greater edge width and more wear grooves. As shown in Figure 36c, parts from the cutting edge were missing, appearing to have caused subsequent wear grooves on the rake face due to the dragging of small pieces across the tool surface.

Similar to cutting lab-dry fir, burr removal and edge fracture were also observed, though in a lesser degree, during the initial cutting interval when wet fir was cut. In addition, a small number of round spots (Figure 4.37a) and areas of stains (Figure 4.37b) were observed on the cutting edges in the SEM. After a long cutting distance of 760,000 inches, the cutting edge was characterized visually by two distinct areas; bright, as if polished, at the extreme edge, darker (apparently stained) areas 1 to 2 mm away from

the extreme edge. For most bits, the extreme edge appeared much smoother (Figure 4.37c) than those after cutting lab-dry fir at the same cutting distance. For 1 out of 7 bits in the set, the edge appeared similar to those shown on the high wear group of bits cutting lab-dry fir where a rough edge and a great number of wear grooves were observed.

Steel Bits Cutting Lab-dry and Wet Cedar at 0.0064" Tooth Bite

Cutting lab-dry cedar resulted in surface appearances much closer to those observed on steel bits after cutting wet fir. A small number of round pits were again observed on the cutting edge during the initial cutting interval when cutting lab-dry cedar. For most bits, after long cutting distances, the edges visually appeared bright and shiny and were observed to be very smooth in the SEM (Figure 4.38a). Stained areas a few millimeters away from the extreme edge were also observed.

A greater amount of staining was observed on the cutting edges after cutting wet cedar than were seen after cutting lab-dry cedar. Most edges became extremely smooth after only 230,000 inches of cutting (Figure 4.38b). Overall, fewer wear grooves were observed on cutting edges of steel bits cutting cedar, either dry or wet, than cutting fir.

Steel Bits Cutting Green, Lab-dry and Wet Fir at 0.035" Tooth Bite

The edges, at a high cutting tooth bite of 0.035 inch, during the initial periods of cutting appeared to be similar to those after cutting at the low tooth bite of 0.0064 inch, with grinding burr removal and edge fracture. The cutting edges after cutting green fir for 100,000 inches became very smooth and some areas of stains were observed. As cutting distance increases from 100,000 to 300,000 inches, the surfaces were further smoothed and grinding grooves near cutting edges that were visible after 100,000 inches distance were completely removed after 300,000 inches distance (Figure 4.39a and b). At a high magnification of 10,000X, traces of shallow wear grooves were visible.

Without high magnification, the edges after cutting green fir were identified as bright and shiny, similar to those after cutting cedar (either green or lab-dry) at the low tooth bite. However, slightly away from the edge (1 to 2 mm), the surfaces (both rake and clearance) appear to be much darker (dark grey/black) than those of as-sharpened, corresponding to stains observed under a SEM.

In contrast, the edges appeared much rougher after cutting lab-dry fir with air jet cooling than those after cutting green fir at the same distance. Many wear grooves were visible in the SEM. Unlike cutting green fir, the cutting edge surfaces did not become smooth but showed even more wear grooves as the cutting distance extended from 100,000 to 300,000 inches (Figure 4.39c and d). Another visible difference between cutting green and dry fir was that the former resulted in the removal of all grinding grooves near the edge while the latter did not after a cutting distance of 300,000 inches.

Cutting lab-dry fir without air jet cooling resulted in a higher density of wear grooves than cutting with the presence of air cooling. In particular, under the most aggressive cutting condition, cutting lab-dry fir with a high density of knots and in the absence of air cooling, a great number of deep and wide wear grooves were observed (Figure 4.40).

The extreme cutting edge of a steel bit after cutting wet fir for 100,000 inches was smooth and only a small number of wear grooves were observed. The features appeared to be between those resulting from cutting lab-dry and green fir.

Cutting lab-dry fir without air jet cooling but with deionized water spray resulted in a cutting edge appearance very similar to that of cutting lab-dry fir with no air cooling instead of similar to that of cutting wet fir.

Black strips, a surface color change, were visible by eye on the edges after cutting lab-dry fir, especially after cutting without air jet cooling. The width of the strips varied up to 1.5 mm. However, the effect was not observed on all bits, even within the same set.

Steel Bits Cutting Green, Lab-dry and Wet Cedar at 0.035" Tooth Bite

After cutting green cedar for 100,000 inches, stains were visible both by eye and under a SEM. The extreme edges were very smooth due to the fact that many grinding marks were removed. The edge surface featured many white areas in high contrast with the black matrix under a SEM (Figure 4.41). More white areas were observed after cutting green cedar than cutting green fir. Visually bright and shiny edges, less than 1 mm wide, could be distinguished very easily.

The edge surface after cutting lab-dry cedar at the high tooth bite was much like that of cutting the lab-dry cedar at the same cutting distance with a low tooth bite. The cutting resulted in the least surface wear evidence (grooves or stained areas) among the three types of wood in various conditions at the high tooth bite. After cutting lab-dry cedar at the high tooth bite the bits did not display significantly visible (by eye) differences compared with those of as-received bits, though their edges appeared smoother than the as-received ones in a SEM.

The edge of a steel bit after cutting wet cedar for 100,000 inches distance appeared quite similar to those cutting wet cedar at the low tooth bite (0.0064 inch) and those cutting green cedar at the high tooth bite (0.035 inch), visually shiny (eye view) and smooth (SEM) with few grooves at the extreme edges, and stained areas 1 to 2 mm away from the extreme edges.

Steel Bits Cutting Green and Lab-dry Oak at 0.035" Tooth Bite

Steel bits after cutting green oak appeared similar to those after cutting green cedar, smoothed and with white areas, while steel bits after cutting lab-dry oak looked more like those after cutting lab-dry fir, with wear grooves.

High Speed Steel (HSS) Bits Cutting Green and Lab-dry Fir at 0.035" Tooth Bite

HSS bits have been used to cut only fir in lab-dry and green conditions at 0.035 inch tooth bite for 100,000 inches of cutting distance. Little grooving was observed on bits cutting green fir and the surfaces were relatively smooth (Figure 4.42). Magnification of up to 5,000X revealed that individual carbides in the matrix were smoothed during the cutting process (Figure 4.42c). In contrast, rough surfaces with areas of fracture and wear grooves were observed on HSS cutting edges after cutting lab-dry fir with the presence of air jet cooling (Figure 4.43). It also appeared that both the carbide particles and the matrix were equally worn. Black strips, as observed on steel bits, were also seen on HSS bit edges cutting lab-dry fir.

Cemented Carbide Tips Cutting Fir, Cedar and Oak under Green and Lab-dry Condition at 0.035" Tooth Bite

Cemented carbide bits were tested by cutting fir, cedar and oak in lab-dry and green conditions. All bits were tested at 0.035 inch cutting tooth bite and used to cut wood for 100,000 inches. Air jet cooling was used during lab-dry wood cutting but not during the green wood cutting.

At a magnification of 100X in the SEM, the edge appeared to be smoothed after cutting lab-dry fir and green fir, yet there was little change in terms of edge width. Individual carbide particles with round corners were clearly revealed at the cutting edge after cutting green fir at a magnification of 5,000X (Figure 4.44b). After cutting lab-dry fir, nevertheless, carbide particles were observed to be either flattened or smoothed (Figure 4.44c).

Cutting lab-dry cedar resulted in the least surface wear evidence to the cemented carbide bits among all three species tested. However, cutting green cedar led to the most severe damage to the carbide bits among all three types of wood. In comparison with as-received (new) bits (Figure 4.45), sharp or angular carbide particles were clearly

exposed, indicating preferential cobalt binder removal (Figure 4.46). The width of the affected worn zone was extended to about 200 μm away from the extreme edges, evidenced by the complete removal of grinding marks.

Cutting lab-dry oak produced similar surface features as cutting lab-dry fir. After cutting the green oak, the bits were worn in approximately the same degree as for cutting green cedar. After cutting the green oak, the carbide particles had slightly rounded corners, and were not as sharp as cutting the green cedar.

Stellite Tips Cutting Fir, Cedar and Oak under Green and Lab-dry Conditions at 0.035" Cutting Tooth Bite

The as-received Stellite bit appeared to be the roughest edge in terms of edge width and surface smoothness (Figure 4.47). There were more fractures or broken areas along the edge prior to any cutting than any other types of bits tested. The edge widths varied greatly from bit to bit and from point to point along the edge of one bit.

Unlike cemented carbide bits, wear grooves were observed on the Stellite surfaces after cutting lab-dry fir, though not as many as those seen on steel bits. Cutting green fir, lab-dry and green cedar resulted in very little change to the surface appearance. In the case of cutting oak (both green and lab-dry), carbide particles were observed projecting above the matrix (Figure 4.48). In certain areas, carbide particles were removed leaving pits on the surface (Figure 4.48d).

4.2.6 Microstructural and Microhardness Change of Steel Bits After Cutting Test

With most conditions, no significant microstructural changes were observed. However, under the most aggressive cutting condition, lab-dry fir with a high density of knots and without air cooling, the steel bit microstructure changed. Figure 4.49a shows a cross-section profile of a steel bit after cutting for 100,000 inches. The metal at the extreme edge has been pushed sideways (compared with the as-received condition in

Figure 4.31a). Higher magnification examination on etched cross-sections revealed that the grains were realigned and nearly parallel (Figures 4.49b and c) compared to the randomly orientated grains of as-received bits (Figure 4.18), indicating severe plastic deformation. No similar plastic deformation was observed on steel bits under any other test conditions.

A microhardness traverse of an as-received steel bit is shown in Figure 4.50a. Significant changes in microhardness were not observed between the extreme edge and 200 μm away from it. The microhardness profiles exhibited little change after cutting fir and cedar at the low cutting tooth bite of 0.0064 inch, cutting green and lab-dry fir with air cooling at the high tooth bite of 0.035 inch. However, a significant hardness drop after cutting lab-dry fir without air cooling was observed, particularly when cutting lab-dry fir with knots (Figure 4.50b). The hardness decreased from an average HK 370, 80 μm away from the cutting edge, to an average of HK 320 near the extreme edge, a drop of about HK 50.

To determine the corresponding working temperature at the edge during cutting which might have caused the hardness drop, as-received bits were tempered at different temperatures and a hardness versus tempering temperature plot was obtained (Figure 4.51). This shows a Rockwell hardness of 47 before tempering. However, Figure 4.50 indicates that as-received metal has a Knoop hardness of about 370 with a 25 g load. This is equivalent to only HRC 37 according to the conversion table between HRC and Knoop at a 500 g load. A discrepancy of hardness values between Rockwell testing and Knoop microhardness testing therefore exists. The microhardness drop of about HK 50 certainly showed a substrate softening, yet an estimate of the corresponding edge temperature during the cutting was not possible because of this discrepancy.

4.2.7 Wood Chip and Sawkerf Surface Characteristics

There were distinct differences among chips and sawdust from green, lab-dry and oven-dry fir. The drier the fir, the smaller the chip sizes (Figure 4.52). The length of

most green fir chips fell into the range of 1 to 2 inches. In comparison lab-dry fir chips were much shorter and narrower, and the oven-dried fir chips even smaller. A large portion from oven-dry fir was powder-like rather than discrete chips. Wet fir chips were also longer than the lab-dry but shorter than the green fir chips.

The difference in terms of chip surface appearance between a green and lab-dry fir was also distinct, illustrated by SEM micrographs shown in Figures 4.53 and 4.54. The green fir chip appeared to be broken and cut predominantly through individual fibers or by intrafiber break down, as shown in Figure 4.53. The dry fir chips were shorter with more fractured fibers at the chip ends (Figure 4.54b). High magnification examination revealed that the dry fir fracture surface was predominantly in the interfiber zone (Figures 4.54c). This indicates that wood fibers were broken in groups separated at the interfiber zone.

The sawkerf surfaces (kerf bottom) were also distinctly different when wood was cut green versus dry. The bottom of the kerf appeared to be smooth with a finer texture in green fir (Figure 4.55a) in contrast to the lab-dry fir (Figure 4.56a) at the same cutting distance using steel bits. Under a SEM, the surface roughness difference was found to be associated with the way the wood fibers break down. Green fir surfaces appeared to be more uniform overall (Figure 4.55), in terms of surface topography, displaying cut and sheared fibers. In contrast, on the sawkerf end face of lab-dry fir, groups of fibers which were pulled away from the bulk, were bent and broken down (Figure 4.56b). Most areas on the surface of lab-dry fir appeared to be the interfiber zone (Figure 4.56c) although some areas of intra-fiber fracture were also observed.

The wood surface roughness difference between cutting green and lab-dry fir also existed for the HSS and carbide tipped bits, but was not as significant as those seen on wood chips cut by the steel bit. Little difference was observed on wood surfaces cut by Stellite at green and lab-dry conditions. Additionally, saw kerf surface roughnesses were found to increase with cutting distance when the wood was cut lab-dry, yet varied little when the green wood was cut using steel bits.

4.3 Abrasion Test

Figure 4.57 demonstrates the difference between surface topographies of as-polished and after 500 revolutions of testing using walnut shells. A large number of wear grooves, parallel to the flow direction of abrasives, were observed on the surface after 500 revolutions. The number of wear grooves appeared to remain the same yet the depth of grooves appeared to be greater after 5,500 revolutions of testing (Figure 4.58). Many grooves had widths of about $1\text{ }\mu\text{m}$.

The surface roughness profiles prior to testing, after 500 revolutions, 3,500 revolutions and 5,500 revolutions of testing are shown in Figure 4.59. Before any testing, the arithmetical mean value (R_a) is only $0.008\text{ }\mu\text{m}$. This value was more than doubled after 500 revolutions, to $0.018\text{ }\mu\text{m}$, and increased up to $0.113\text{ }\mu\text{m}$ after 5,500 revolutions. Figure 4.59d shows that the depth of grooves was as high as $0.14\text{ }\mu\text{m}$ after 5,500 revolutions.

Table 4.1 Chemistry of commercial woodcutting tools (wt%)

Tools	Analysis Source*	C	Ni	Mn	Cr	Cu	W	Co	Mo	V	Si	Fe
B1	ESCO	0.705	1.949	0.401	0.134	0.149					0.285	bal
B4	ESCO	0.761	2.014	0.435	0.175						0.282	bal
B5	ESCO	0.583	2.061	0.420	0.142	0.202					0.287	bal
B7	ESCO	0.634	2.066	0.408	0.138						0.269	bal
B10	ESCO	0.664	1.894	0.384	0.109	0.099					0.027	bal
B11	ESCO	0.734	2.114	0.455	0.137	0.178					0.320	bal
UHB 15N20	FPL	0.750	2.000	0.400							0.300	bal
CS1	EDX		1.2				83.0	4.4				
CS2	EDX		1.1				86.0	0.3				
CS3	EDX				20.0		2.6	38.0				38.0
CS4	EDX		1.6		41.0		5.5	50.0				2.1
CS5	EDX		2.0		31.0		10.0	42.0				2.2
CS6	EDX		2.0		30.0		10.0	45.0				2.0
Co-Cr-W-C No.6	Ref.1	1.1			28		4	bal				
CH1	ESCO	0.501	0.209	0.557	6.915	0.122	0.135		1.173	0.490	1.133	bal
CE1	ESCO	0.424	0.206	0.547	6.907	0.091			1.129	0.459	1.070	bal
P1	ESCO	0.887	0.650	0.607	4.257	0.271	4.041	0.325	2.941	1.412	0.491	bal

*ESCO-analyzed by ESCO Corporation using Inductively Coupled Plasma (ICP) method.

FPL-provided by Forest Products Lab (FPL).

EDX-analyzed at OGI by Energy Dispersive X-ray (EDX) analyzer in a SEM (semi-quantitative with ZAF correction).

Ref.1-K.C.Antony, Journal of Metals, Feb 1993, p. 52.

Table 4.2. All tested bits, conditions, weight loss and edge width increase.

BS*	EM	Wood	WC	MC	TB	AC	DC	CS	VCP	TP	TVC	TCD	ATWL	ATEWI
T1	steel	fir	lab-dry	10	6.4	no	1.5	4X8	11.3	286	3218	762476	135	35
T4	steel	fir	tapwater.soaked	10	6.4	no	1.5	4X8	11.3	286	3218	762476	280	27
T6	steel	cedar	lab-dry	7	6.4	no	1.2	2X6	9.4	314	2939	761450	217	15
T7	steel	cedar	tapwater.soaked	80	6.4	no	1.2	2X6	9.4	314	2939	761450	416	18
T9	steel	fir	tapwater.soaked	50	35	no	1.5	4X6	11.3	199	2239	95719	135	38
T10	steel	fir	lab-dry	10	35	yn	1.5	4X6	11.5	10	115	4863	82	18
T11	steel	fir	lab-dry	10	35	no	1.5	4X6	11.3	199	2239	95719	126	42
T12	steel	cedar	tapwater.soaked	80	35	no	1.3	2X6	9.4	228	2138	100000	155	11
T13	steel	fir	tapwater.soaked	50	35	no	1.8	4X6	13.1	192	2520	100000	131	25
T14	steel	fir	lab-dry	10	35	yes	1.6	4X6	11.7	203	2379	100000	118	38
T14	steel	fir	lab-dry	10	35	yes	1.7	4X8	12.4	400	4968	200000	147	54
T14	steel	fir	lab-dry	10	35	yes	1.6	4X8	11.7	603	7069	300000	189	71
T15	steel	fir	oven-dry	0	35	yes	1.6	4X8	11.7	10	117	4916	N/A	30
T17	steel	fir	green	50-100	35	no	1.4	2X6	10.3	217	2238	100000	157	22
T17	steel	fir	green	50-100	35	no	1.4	2X6	10.3	434	4476	200000	231	31
T17	steel	fir	green	50-100	35	no	1.4	2X6	10.3	651	6713	300000	360	42
T30	steel	fir	lab-dry.withknots	10	35	no	1.6	4X8	11.7	203	2380	100000	180	54
T31	steel	fir	deion.water.soaked	50	35	no	1.6	4X8	11.7	203	2380	100000	159	15
T32	steel	fir	ldry.deion.w.spray	10	35	no	1.6	4X8	11.7	203	2380	100000	197	39
T33	steel	fir	lab-dry	10	6.4	no	1.6	4X8	11.7	190	2227	517275	N/A	18
T33	steel	fir	lab-dry	10	6.4	no	1.6	4X8	11.7	380	4453	1034550	N/A	26
T34	steel	fir	lab-dry	10	6.4	no	1.6	4X8	11.7	190	2227	517275	N/A	29
T34	steel	fir	lab-dry	10	6.4	no	1.6	4X8	11.7	380	4453	1034550	N/A	36
T34	steel	fir	lab-dry	10	6.4	no	1.6	4X8	11.7	570	6680	1551825	N/A	39
T35	steel	cedar	lab-dry	7	35	yes	1.3	2X6	9.4	228	2138	100000	62	16
T36	steel	cedar	green	69	35	no	2.0	2X6	15.0	178	2670	100000	260	23
T37	steel	oak	green	67	35	no	1.9	2X8	14.1	185	2602	100000	224	28
T38	steel	oak	lab-dry	15	35	yes	1.8	2X8	13.1	192	2520	100000	101	39
T16	HSS	fir	oven-dry	0	35	yes	1.6	4X8	11.7	10	117	4916	N/A	12
T18	HSS	fir	green	50-100	35	no	1.4	2X6	10.3	217	2238	100000	201	11
T21	HSS	fir	lab-dry	10	35	yes	1.6	4X8	11.7	203	2380	100000	307	26
T19	carbide	fir	green	50-100	35	no	1.4	2X6	10.3	217	2238	100000	237	2
T20	carbide	fir	lab-dry	10	35	yes	1.6	4X8	11.7	203	2380	100000	190	5
T40	carbide	cedar	lab-dry	7	35	yes	1.3	2X6	9.4	228	2138	100000	152	1
T41	carbide	cedar	green	69	35	no	1.9	2X8	14.1	185	2602	100000	373	62
T42	carbide	oak	green	67	35	no	2.0	2X8	15.0	179	2685	100000	222	16
T43	carbide	oak	lab-dry	15	35	yes	1.8	2X8	13.1	192	2520	100000	184	2
T50	Stellite	fir	lab-dry	10	35	no	1.6	4X8	11.7	203	2380	100000	161	3
T51	Stellite	cedar	lab-dry	7	35	no	1.3	2X6	9.4	228	2138	100000	161	4
T52	Stellite	cedar	green	69	35	no	1.7	2X8	12.7	196	2481	100000	171	2
T53	Stellite	oak	green	67	35	no	2.0	2X8	15.0	179	2685	100000	206	3
T54	Stellite	oak	lab-dry	15	35	yes	1.9	2X8	14.1	185	2602	100000	155	1

Note:

BS: bit set	AC: air cooling	TVC: total vol. of cut, in ³
EM: edge materials	DC: depth of cut, inch	TCD: total cutting distance, inch
WC: wood condition	CS: wood cant size	ATWL: average total weight loss, 0.01 mg
MC: wood moisture content	VCP: vol. of cut/pass, in ³	ATEWI: average total edge width increase, μ m
TB: cutting tooth bite	TP: total cutting passes	

Table 4.3 Moisture contents of tested woods under various conditions (in percent)

Wood	oven-dried	lab-dried	water-soaked	green
fir	0	10	50	50-110
cedar	0	8	80	69
oak	0	15	N/A	67

Table 4.4 Microhardness of tested bits (Knoop Indentor 500 g load)						
Test Number	Steel	HSS	Carbide Tip	Carbide Tipped, Base Metal	Stellite Tip	Stellite Tipped, Base Metal
1	460	665	1084	255	458	454
2	434	614	1013	251	428	446
3	424	685	1028	261	429	447
4	422	676				
5	423	619				
Average HK	433	652	1042	256	438	449
Approximate HRC	43	56	> 65	21	43	44

Table 4.5 The bit height, weight loss and edge width increase of steel bit set T1 cutting lab-dry fir at 0.0064 inch tooth bite with air cooling for 800,000 inches cutting distance

Bit Number	Bit Height (10^{-3} in)	Weight Loss (10^{-5} gm)	Edge Width Increase (μm)
T1-1	92	129	N/A
T1-2	94	146	30
T1-3	101	182	45
T1-4	87	149	19
T1-5	94	84	33
T1-6	61	87	10
T1-7	101	171	72
Average		135	35

Table 4.6 The bit height, weight loss and edge width increase of steel bit set T14 cutting lab-dry fir at 0.035 inch tooth bite with air cooling for 100,000 inches cutting distance

Bit Number	Bit Height (10^{-3} in)	Weight Loss (10^{-5} gm)	Edge Width Increase (μm)
T14-1	79	128	42
T14-2	74	81	28
T14-3	74	122	54
T14-4	89	202	61
T14-5	76	90	47
T14-6	45	107	0
T14-7	75	97	35
Average		118	38

Table 4.7 The bit height, weight loss and edge width increase of cemented carbide tipped bit set T20 cutting lab-dry fir at 0.035 inch tooth bite with air cooling for 100,000 inches cutting distance

Bit Number	Bit Height (10^{-3} in)	Weight Loss (10^{-5} gm)	Edge Width Increase (μm)
T20-1	69	121	0
T20-2	67	225	0
T20-3	69	271	10
T20-4	67	198	11
T20-5	65	106	3
T20-6	25	111	6
T20-7	68	301	4
Average		190	4.9

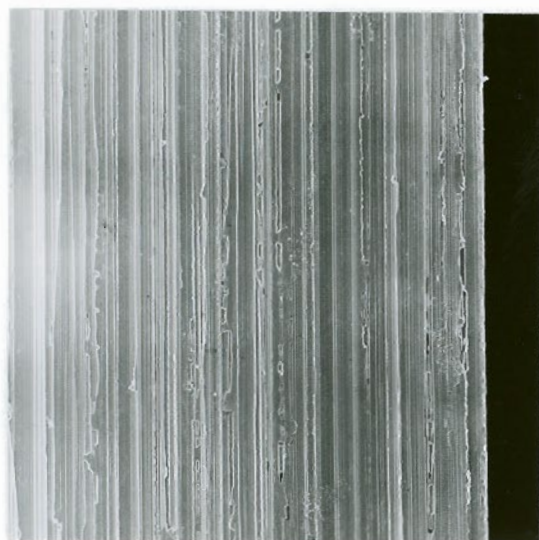
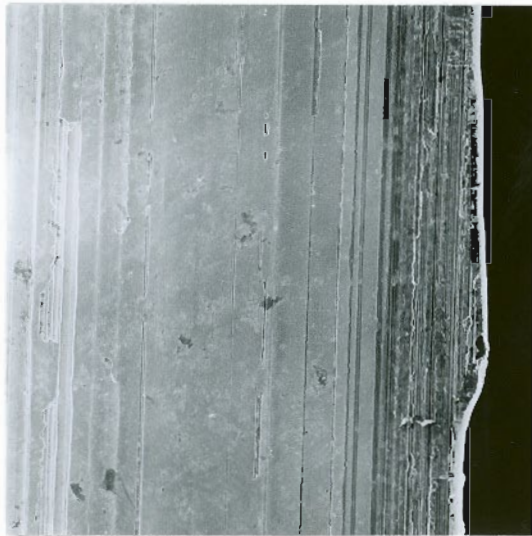
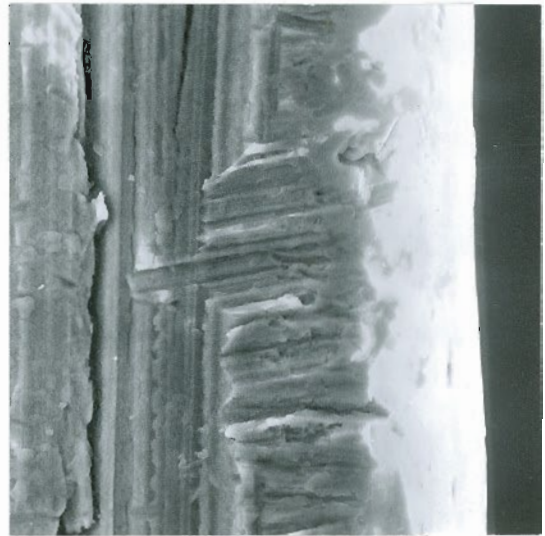
(a) 100 μm (b) 10 μm (c) 100 μm (d) 10 μm

Figure 4.1 Rake face edges of steel head saws: (a and b) as-resharpened; (c and d) after cutting red fir for 4 hours.



(a) $100\ \mu\text{m}$



(b) $10\ \mu\text{m}$



(c) $10\ \mu\text{m}$

Figure 4.2 Clearance face edges of steel head saws: (a and b) as-resharpened; (c) after cutting red fir for 4 hours.

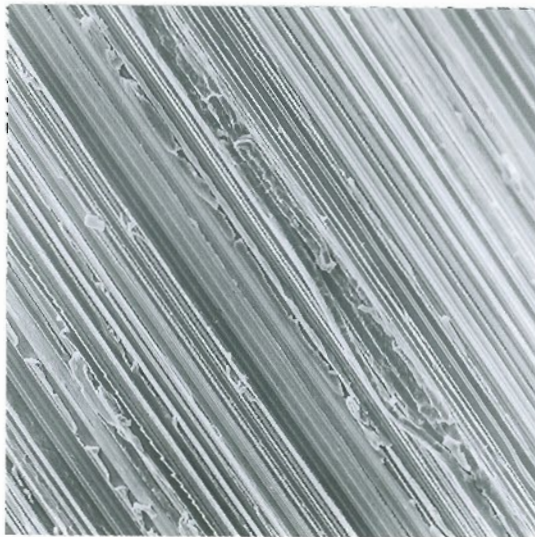
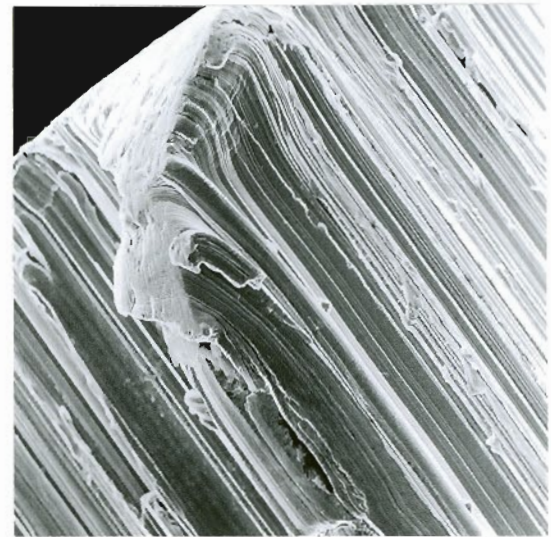
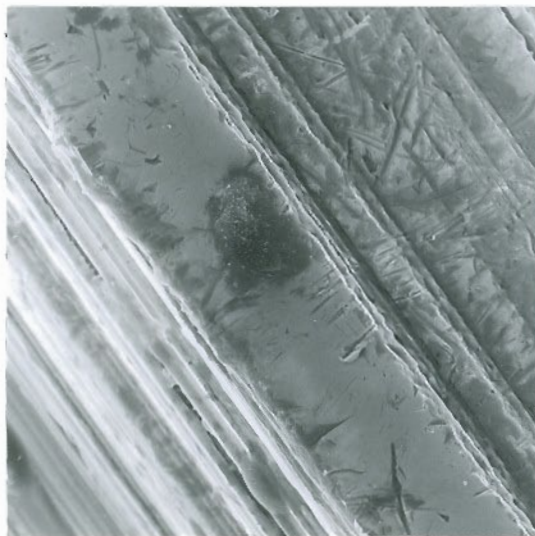
(a) $33\ \mu\text{m}$ (b) $33\ \mu\text{m}$ (c) $33\ \mu\text{m}$ (d) $33\ \mu\text{m}$

Figure 4.3 Top views of steel resaw edges and edge corners: (a and b) as-resharpened; (c and d) after cutting red fir for 4 hours.

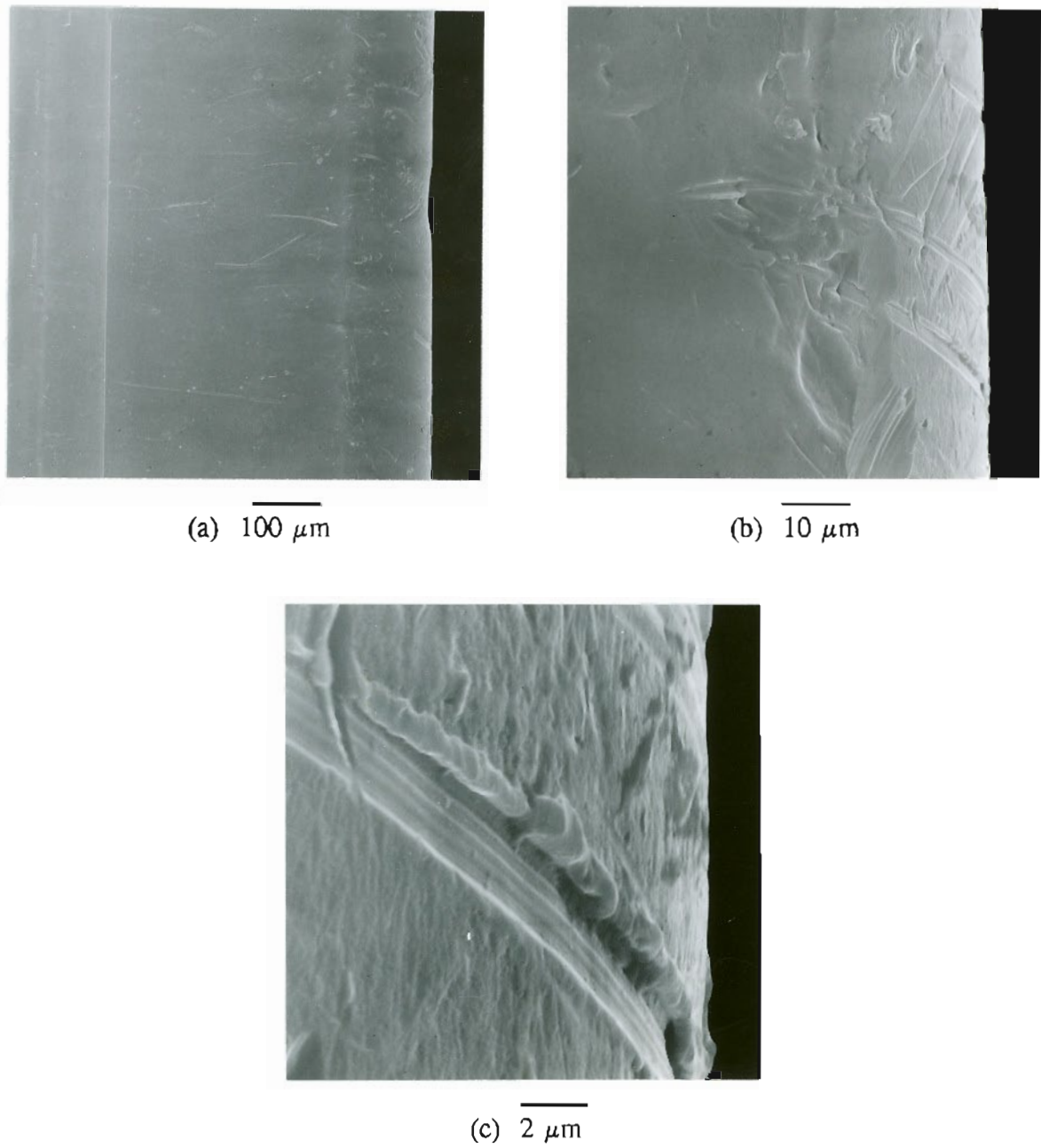
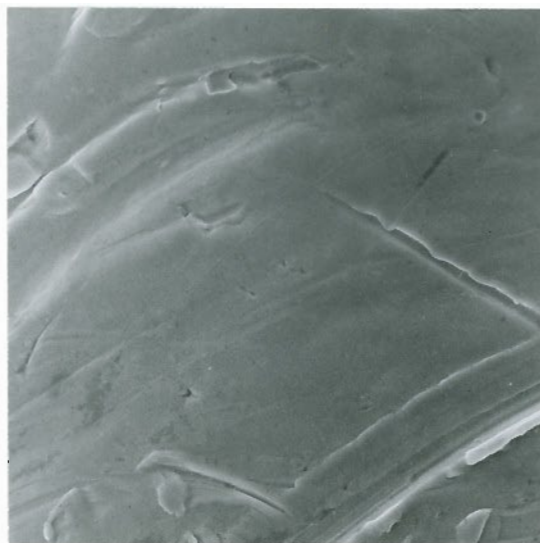


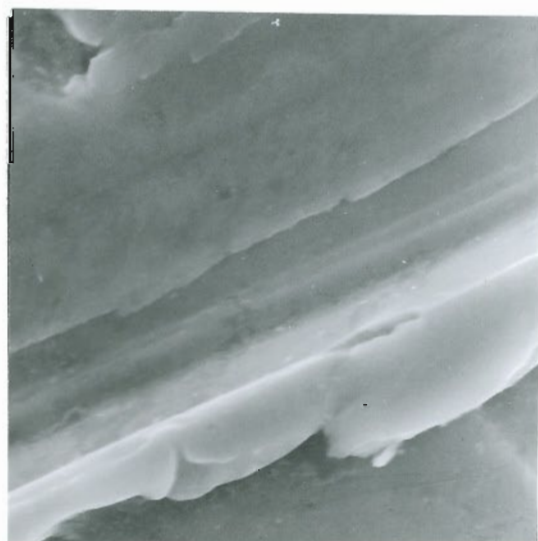
Figure 4.4 The rake face edge of a steel resaw after cutting hemlock for 4 hours showing extensive grooves.



(a) 100 μm



(b) 10 μm

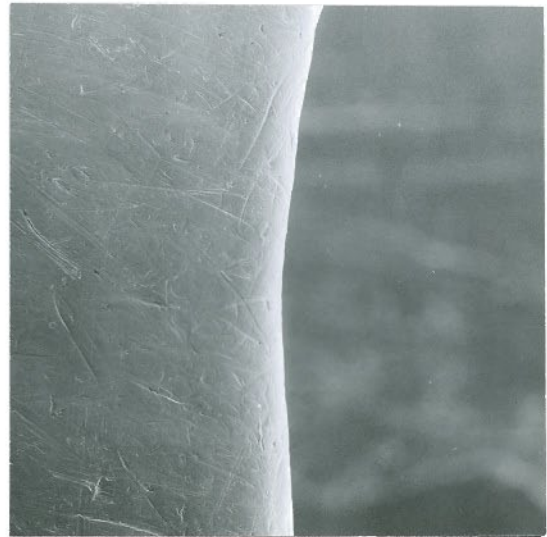


(c) 2 μm

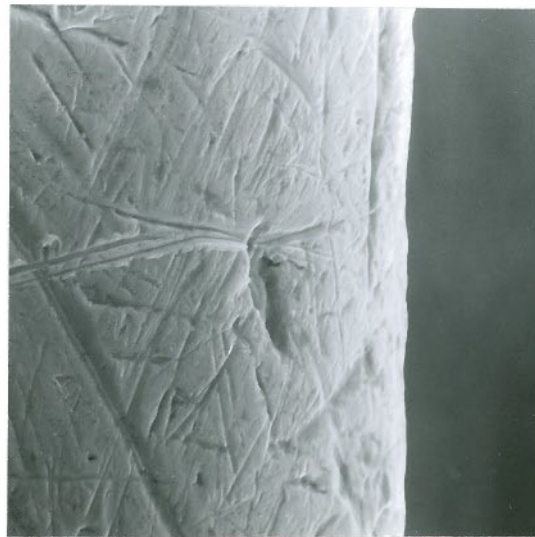
Figure 4.5 Top views on the edge of a steel resaw after cutting hemlock for 4 hours showing grooves.



(a) 500 μm



(b) 100 μm

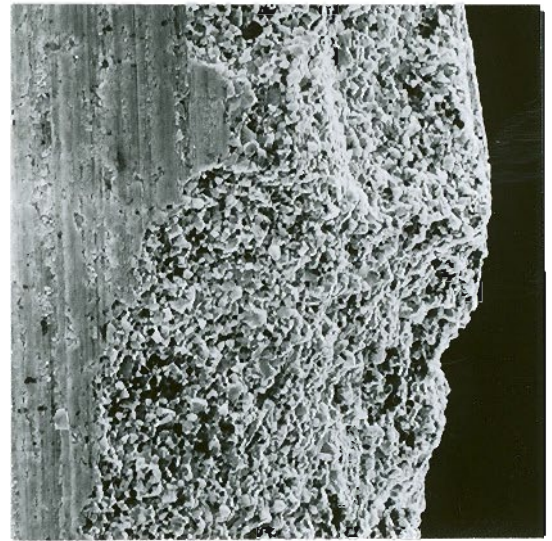


(c) 10 μm

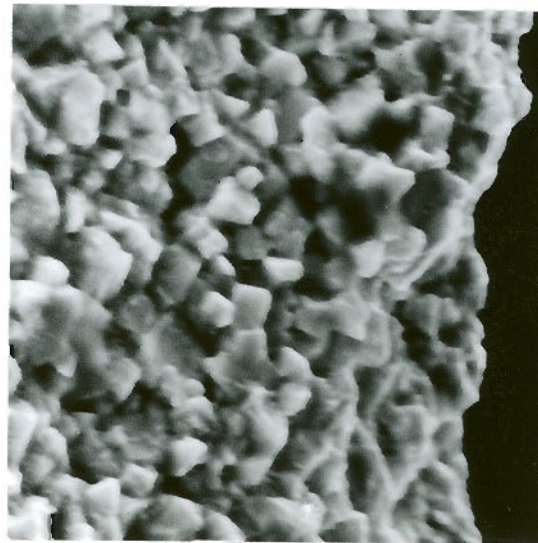
Figure 4.6 The rake face edge of a tool steel canter after cutting red fir for 16 hours showing extensive grooves.



(a) $100\ \mu\text{m}$



(b) $10\ \mu\text{m}$



(c) $2\ \mu\text{m}$

Figure 4.7 The rake face edge of an as-sharpened cemented carbide showing grinding grooves parallel to the edge, fracture at the edge and angular carbide particles.

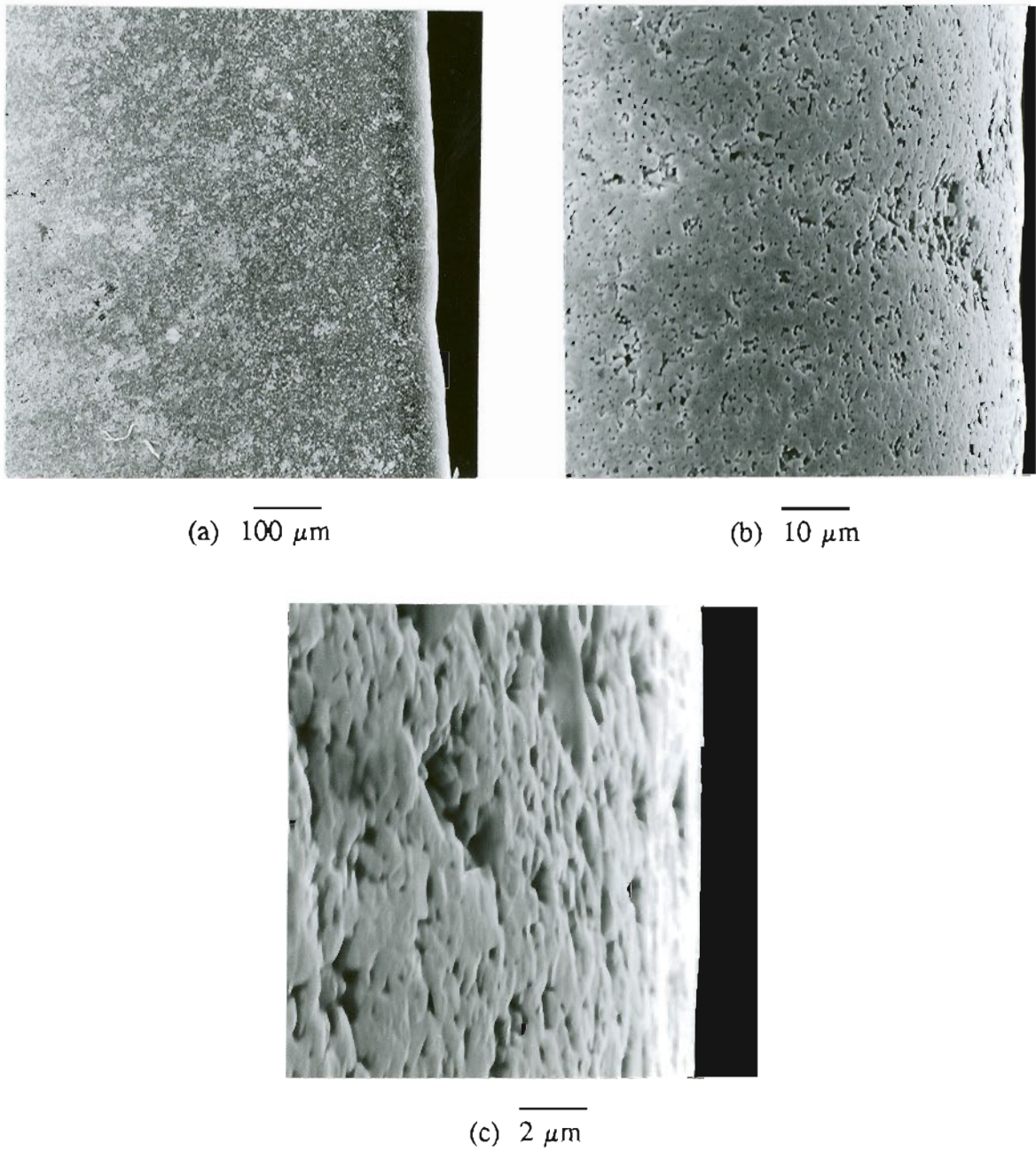
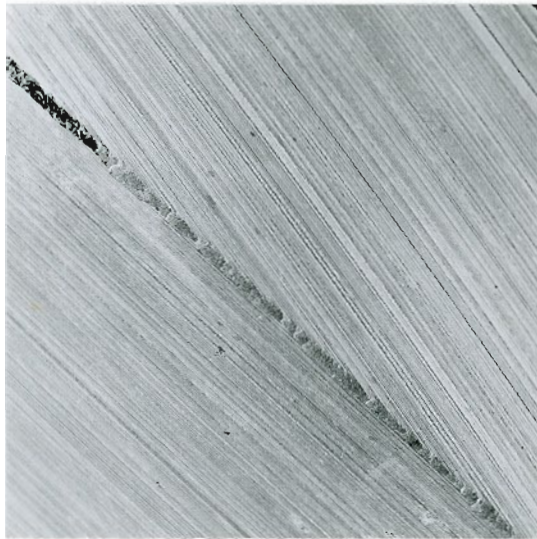
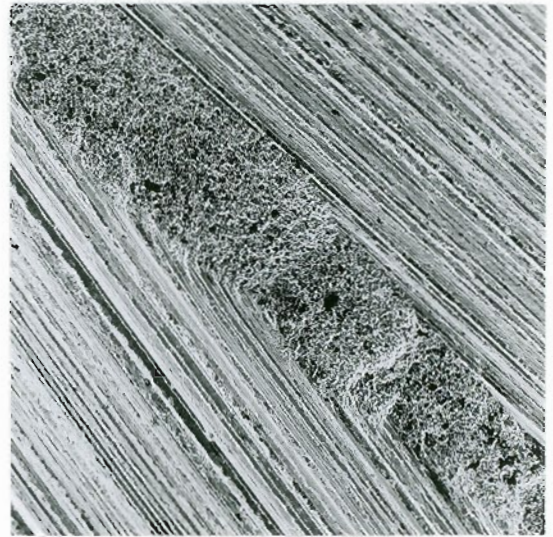


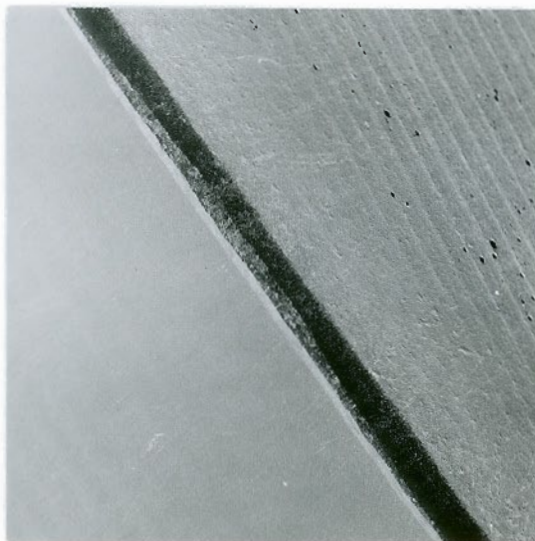
Figure 4.8 The rake face edge of a cemented carbide tip after cutting red fir for 176 hours showing absence of grinding marks, smoothed carbide particles and areas of carbide/matrix removal (pits).



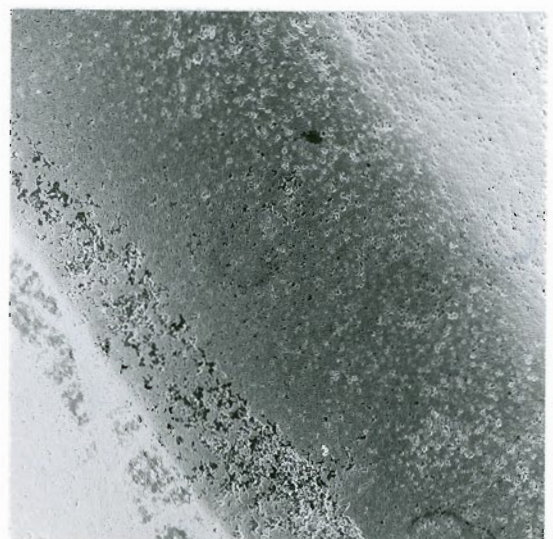
(a) $333\ \mu\text{m}$



(b) $33\ \mu\text{m}$



(c) $333\ \mu\text{m}$



(d) $33\ \mu\text{m}$

Figure 4.9 Top views of cemented carbide edges of as-sharpened (a and b) and after cutting red fir for 176 hours (c and d).

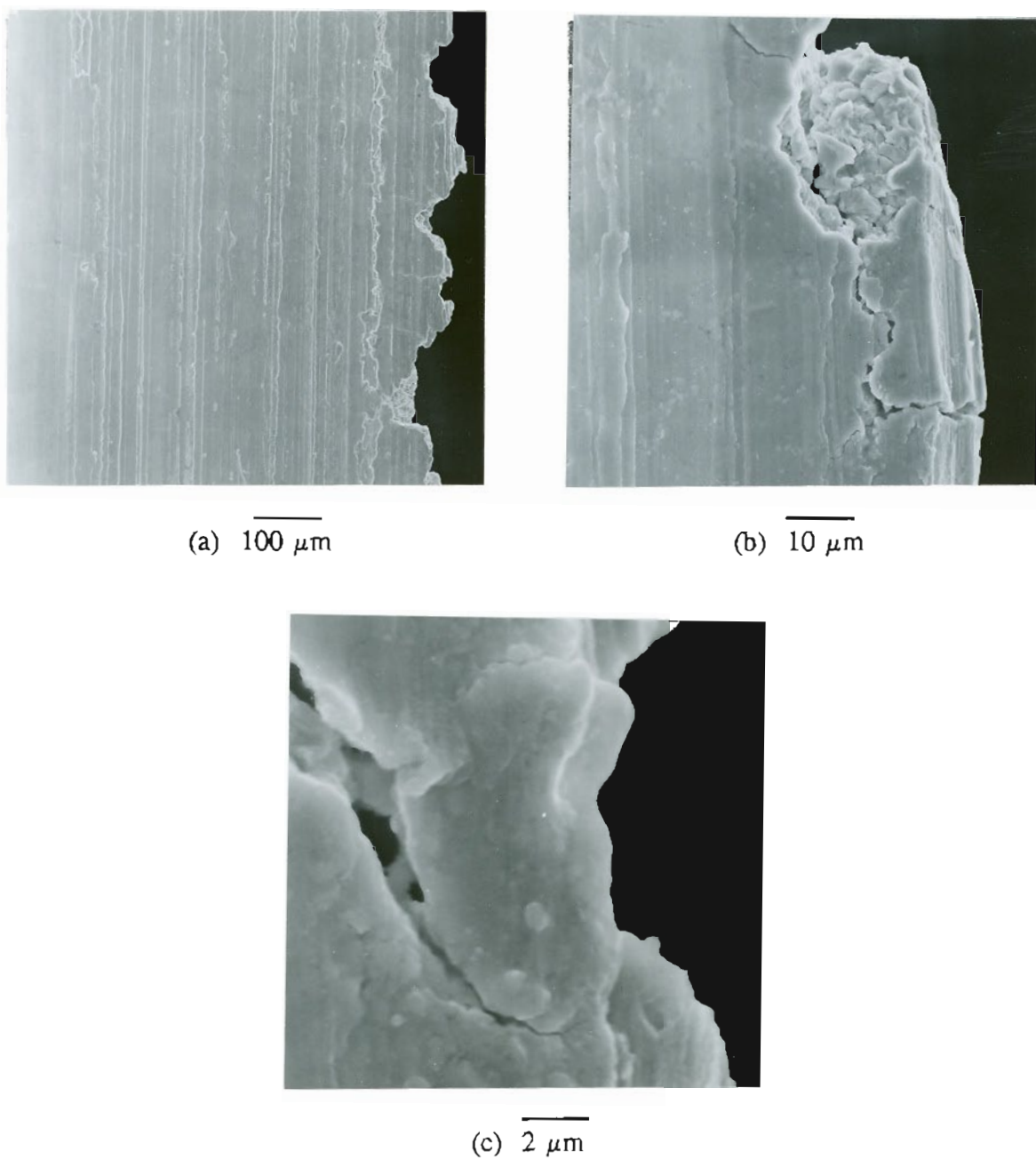
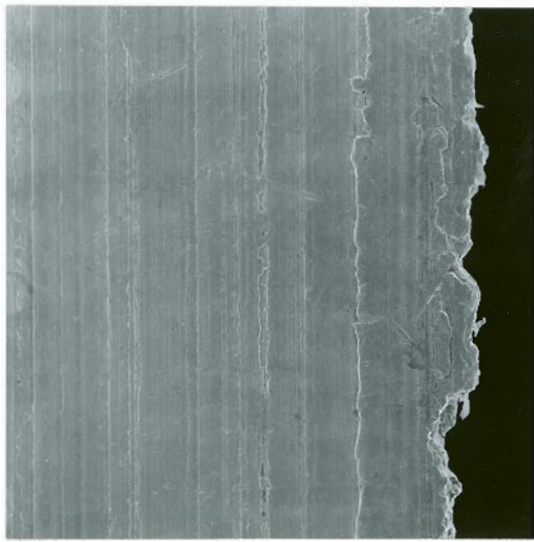


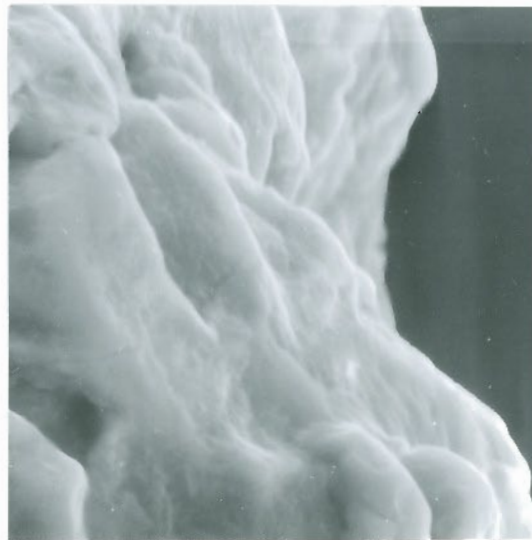
Figure 4.10 The rake face edge of a Stellite tip after cutting red fir for 4 hours and then being resharpened showing rough edge and fracture.



(a) $100\ \mu\text{m}$



(b) $10\ \mu\text{m}$



(c) $2\ \mu\text{m}$

Figure 4.11 The rake face edge of a Stellite tip after cutting red fir for 4 hours showing smoothed edge compared with the resharpened one.

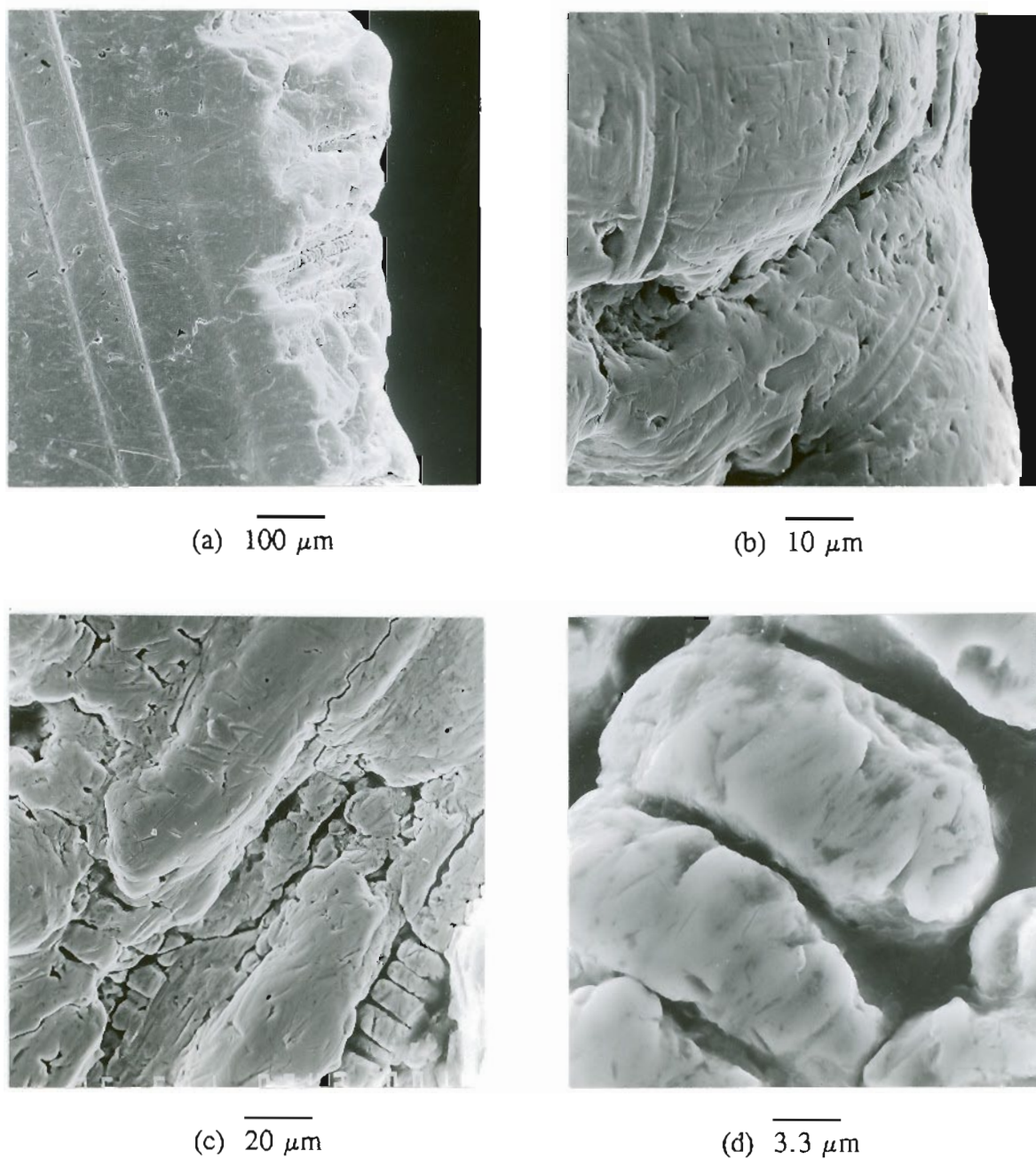
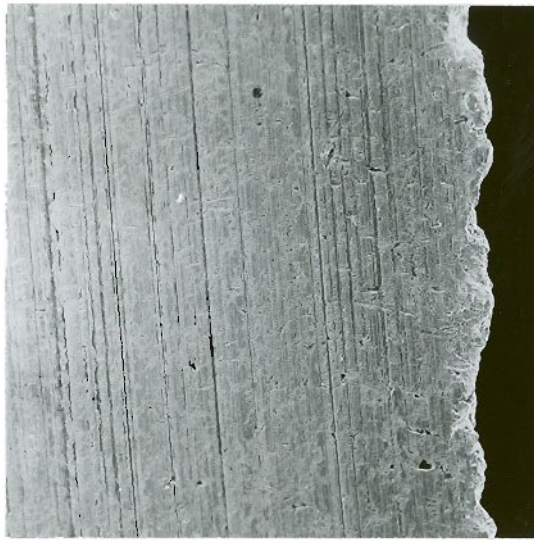
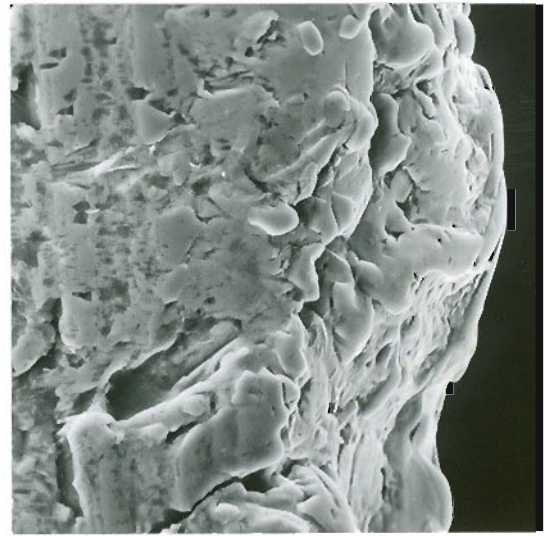


Figure 4.12 The rake face edge (a and b) and the edge from a top view (c and d) of a Vollmer-tipped Stellite tip after cutting hemlock for about 3 days showing traces of wear grooves, dendrites and associated cracks (c and d).



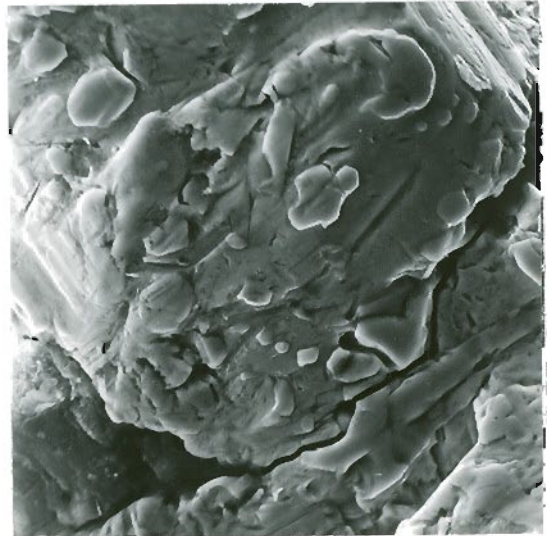
(a) 100 μm



(b) 10 μm



(c) 100 μm

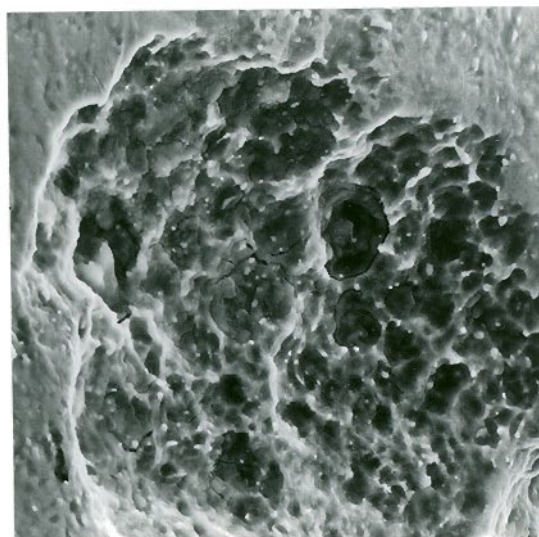


(d) 10 μm

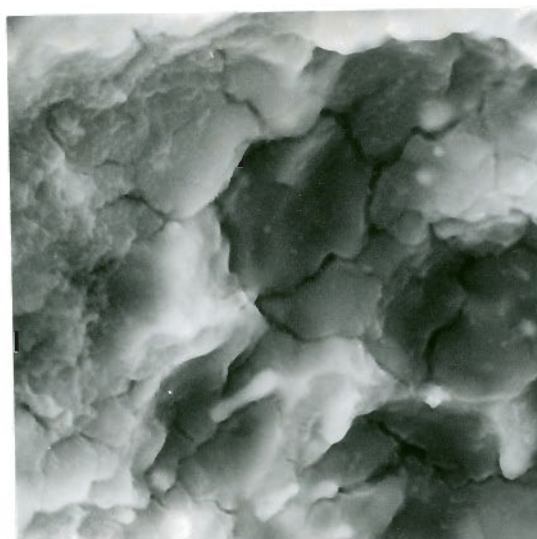
Figure 4.13 The rake face edge (a and b) and the edge from a top view (c and d) of a Wright-tipped Stellite tip after cutting hemlock for about 2 days.



(a) 100 μm



(b) 10 μm



(c) 2 μm

Figure 4.14 The gullet edge of a circular saw (with Wright-tipped Stellite as cutting edges) after cutting hemlock for about 2 days showing craters.

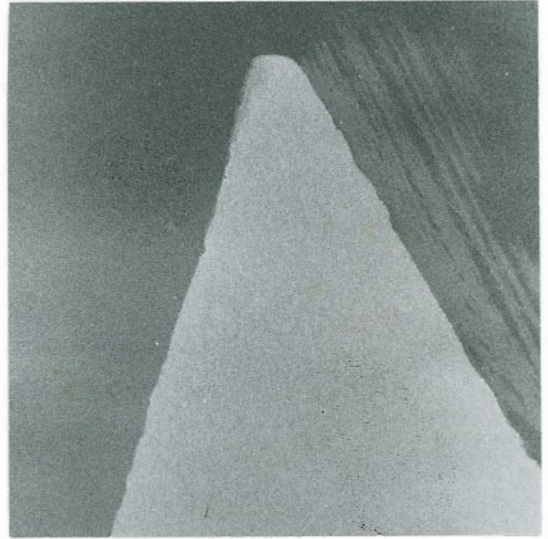
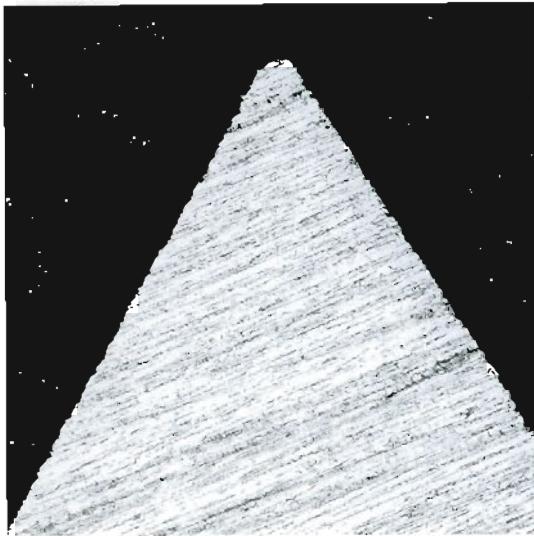
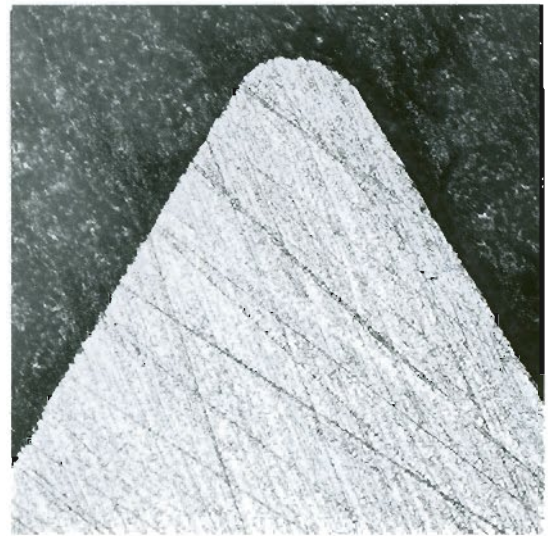
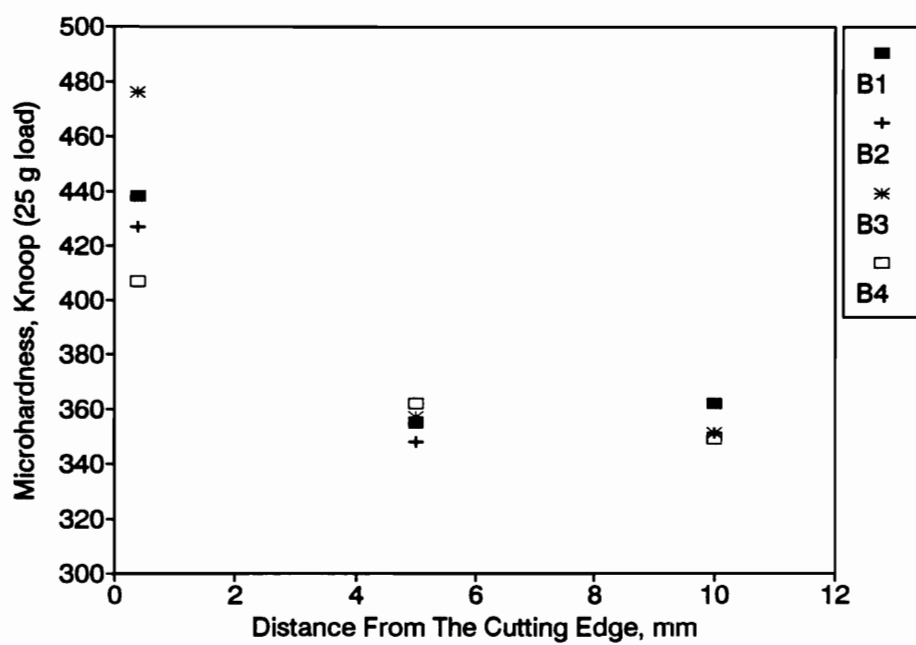
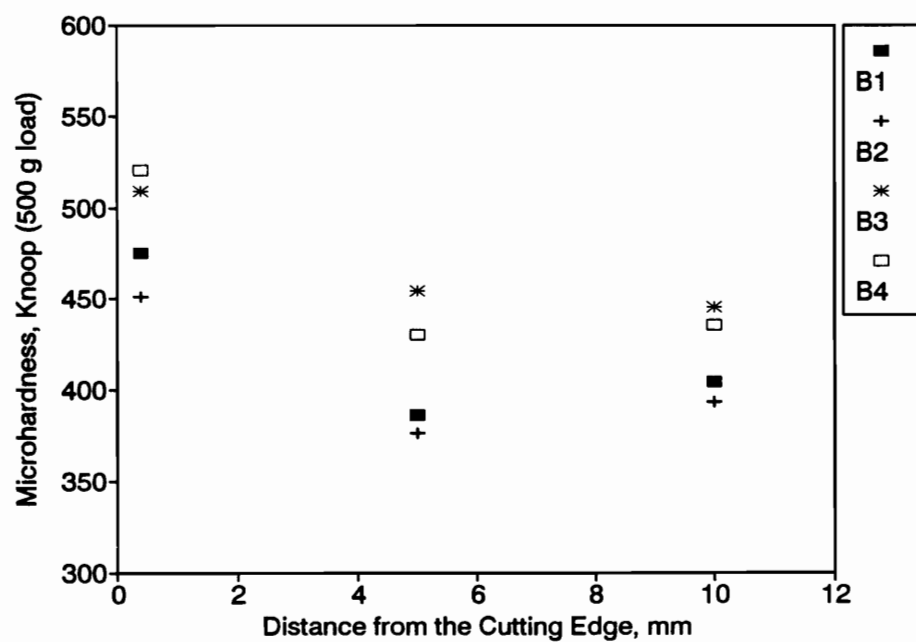
(a) 100 μm (b) 100 μm (c) 100 μm (d) 100 μm

Figure 4.15 Edge cross-sections of (a) an as-sharpened steel head saw, (b) a steel head saw after cutting red fir for 4 hours, (c) an as-sharpened cemented carbide and (d) a cemented carbide after cutting red fir for 176 hours.



(a)



(b)

Figure 4.16 Microhardness vs distance from cutting edges: (a) 25 g load; (b) 500 g load. B1 and B3-worn edges, B2 and B4-resharpened edges.

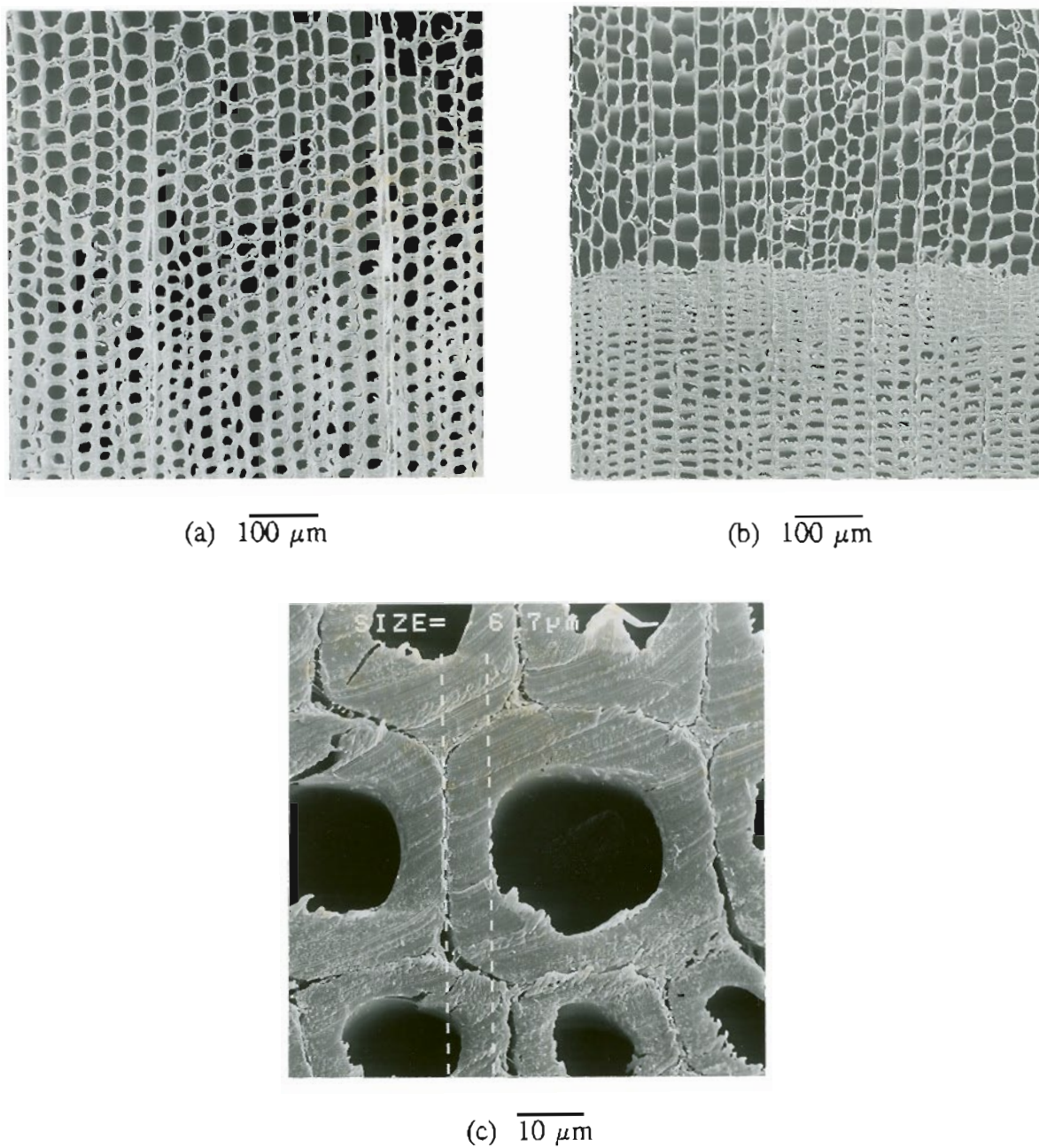
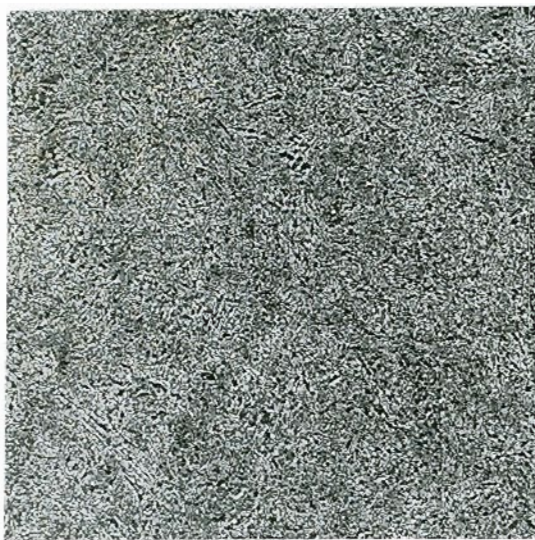
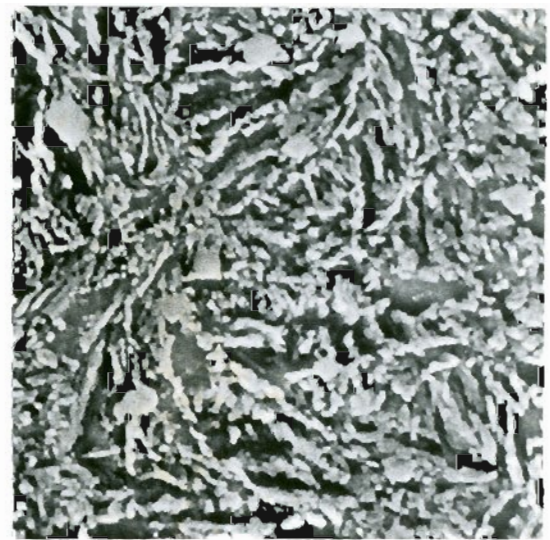


Figure 4.17 Cross-sections of fir (a and c) and cedar (b) showing wood fiber diameter, size distribution and fiber wall thickness (c).



(a) $\overline{10\ \mu\text{m}}$



(b) $\overline{1\ \mu\text{m}}$

Figure 4.18 Microstructure of steel bits (2% nital etch for 2 minutes).

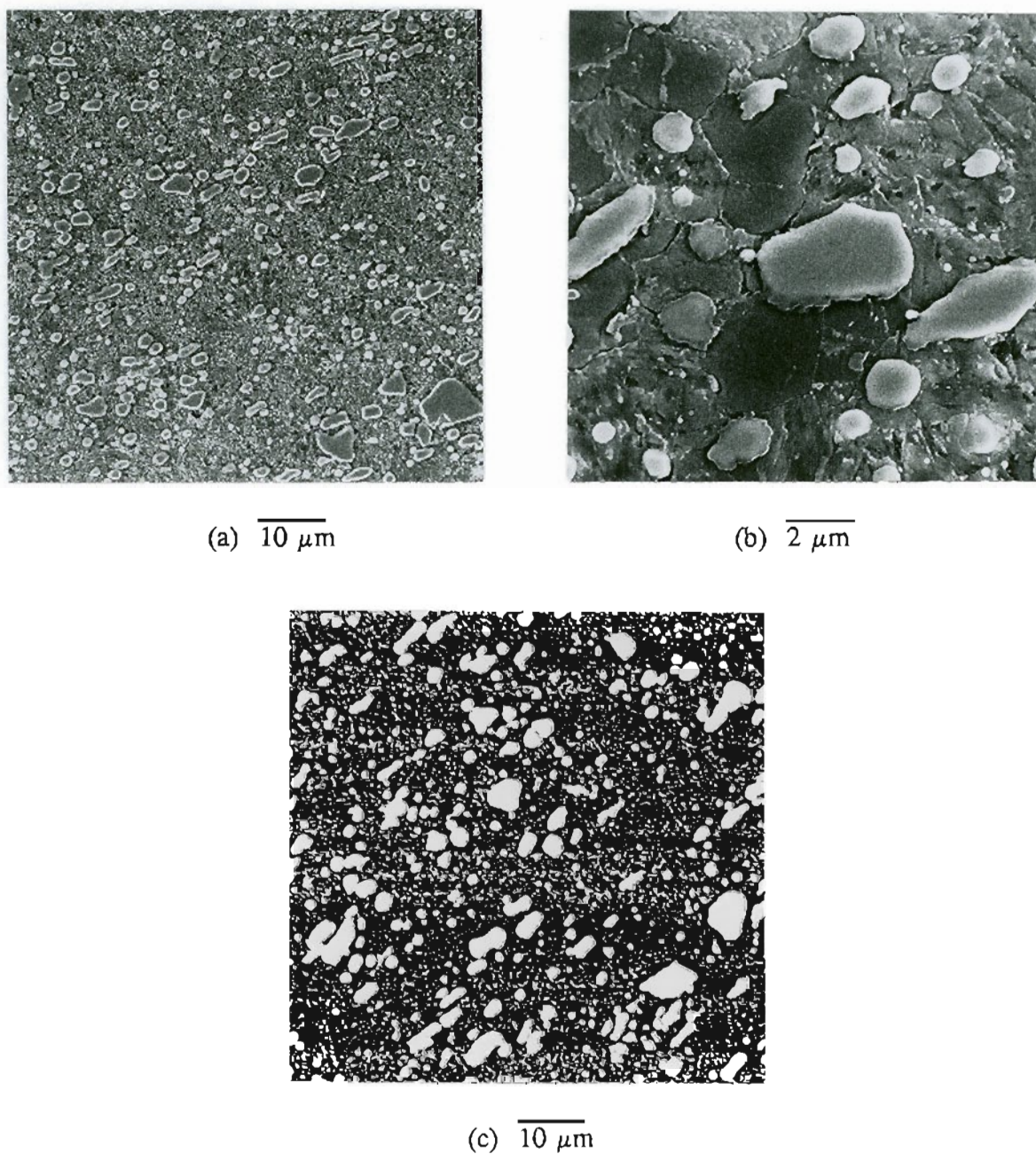


Figure 4.19 Microstructure of high speed steel bits: (a) and (b) SEM secondary electron images (2% nital etched), and (c) SEM backscattering electron image (as-polished and no etching) showing round carbide particles, their sizes and distributions.

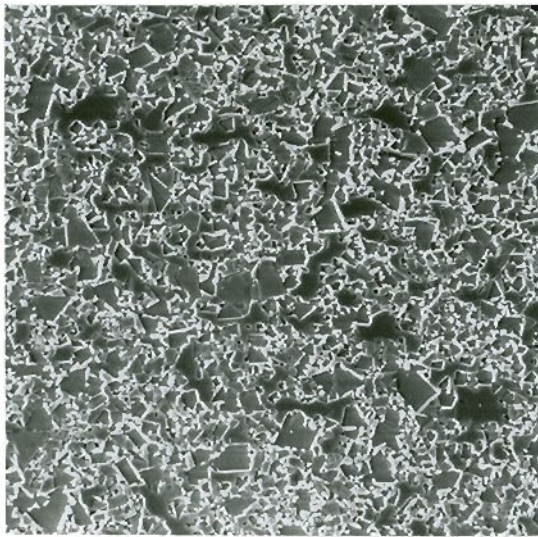
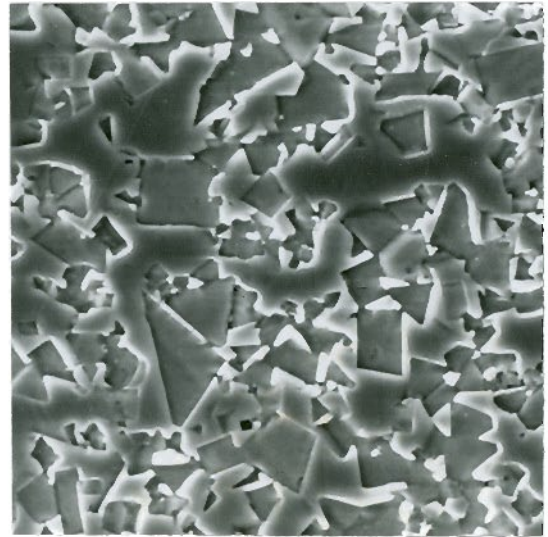
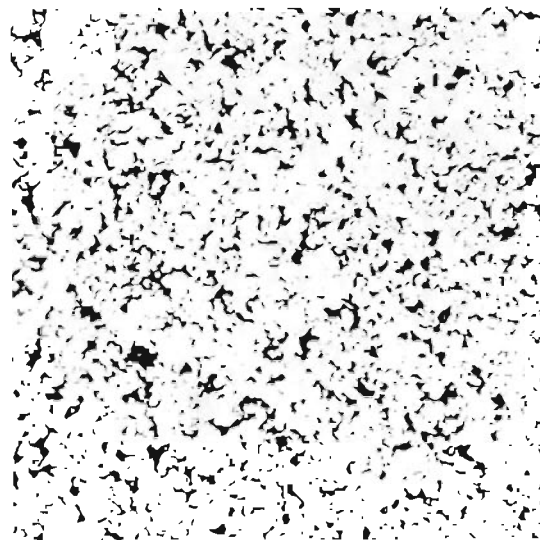
(a) $6.7 \mu\text{m}$ (b) $2 \mu\text{m}$ (c) $10 \mu\text{m}$

Figure 4.20 Microstructure of cemented carbide tips: (a) and (b) secondary electron image (SEI, Murakami's etchant etching for 2 minutes), and (c) backscattering electron image (BEI, as-polished and no etching) showing angular carbide particles embedded in a cobalt matrix.

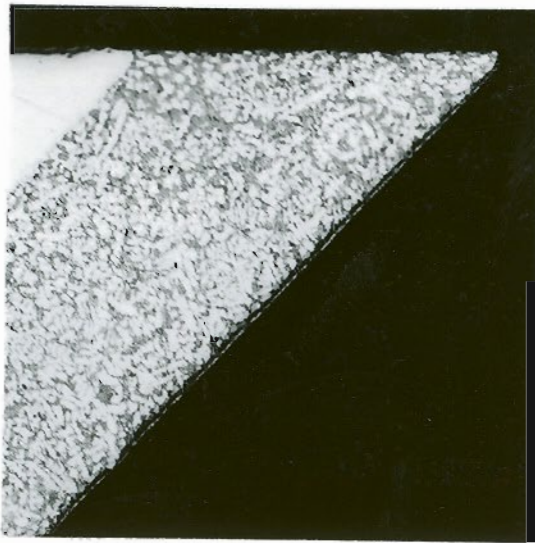
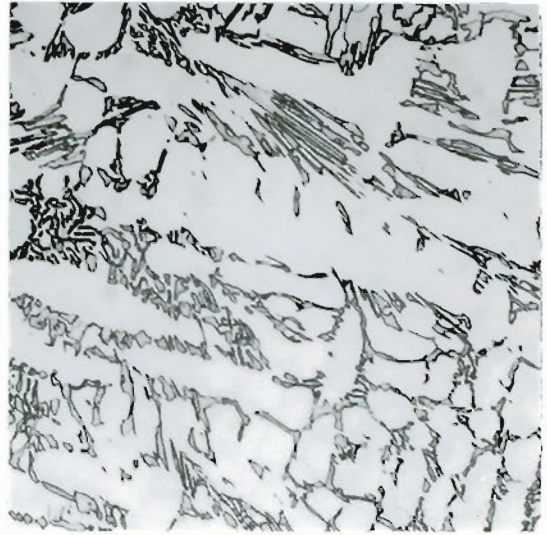
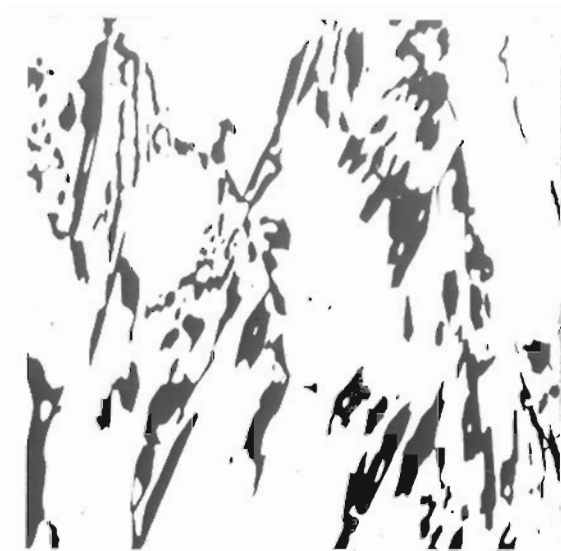
(a) 200 μm (b) 25 μm (c) 10 μm

Figure 4.21 Optical micrographs (a and b, Murakami's etchant etching for 2 minutes) and SEM backscattering electron image (c, as-polished and no etching) of Stellite tips showing a hypoeutectic microstructure with interdendritic arrays of carbides.

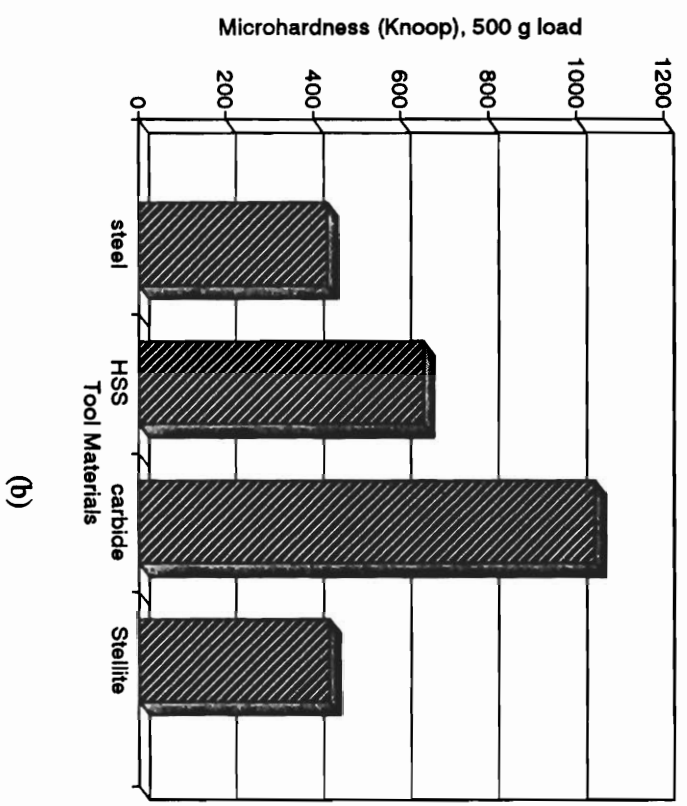
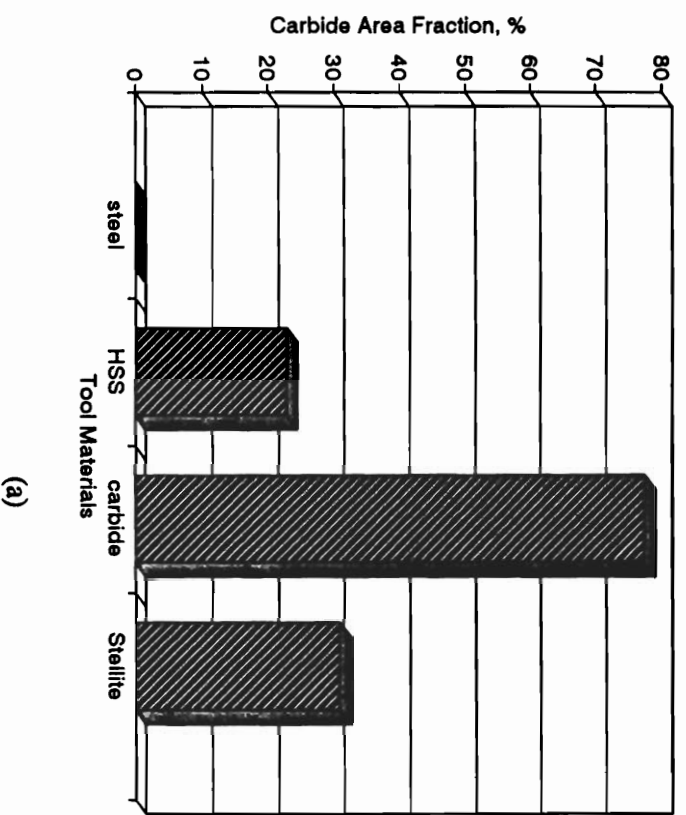


Figure 4.22 Carbide area fractions (a) and Knoop microhardnesses (b) of all four types of tested cutting edge materials.

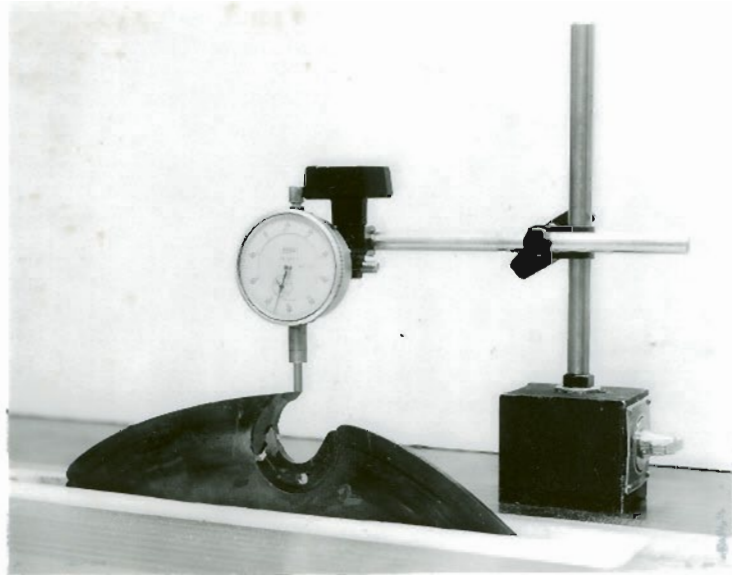


Figure 4.23 A dial indicator measuring a bit height.

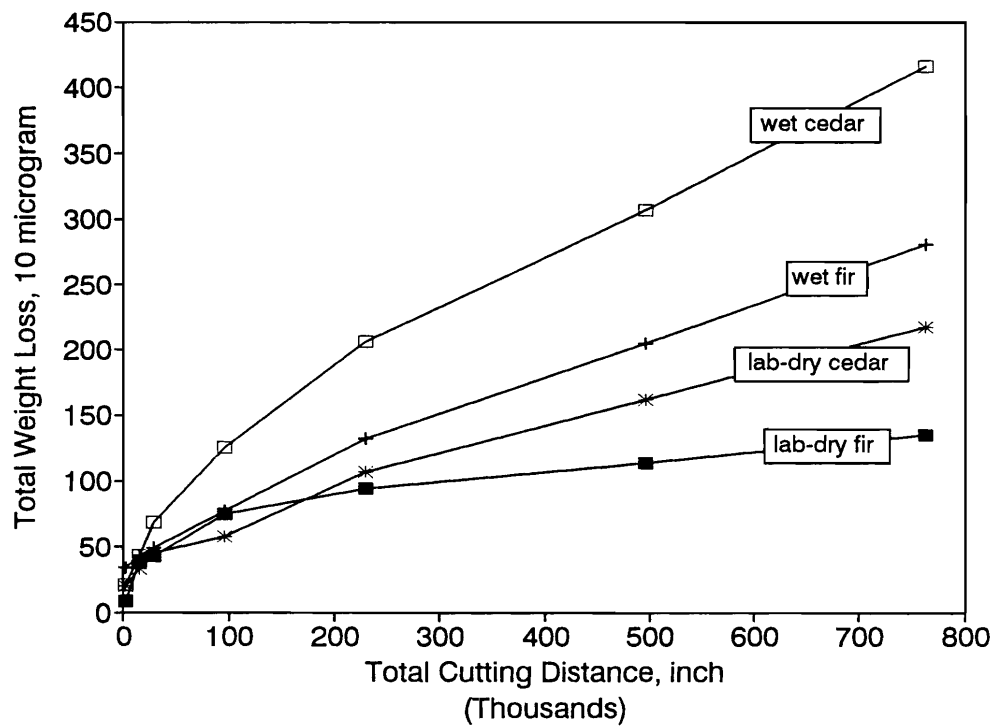
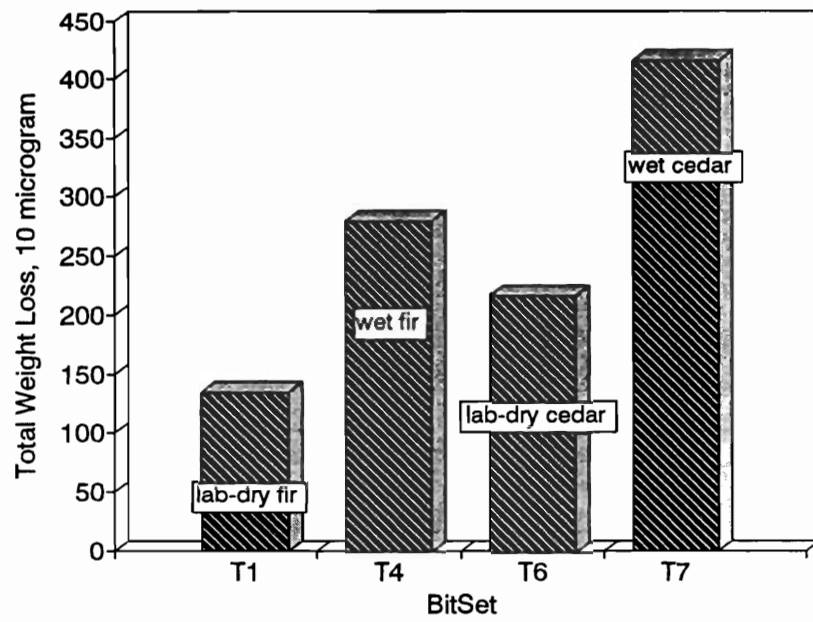
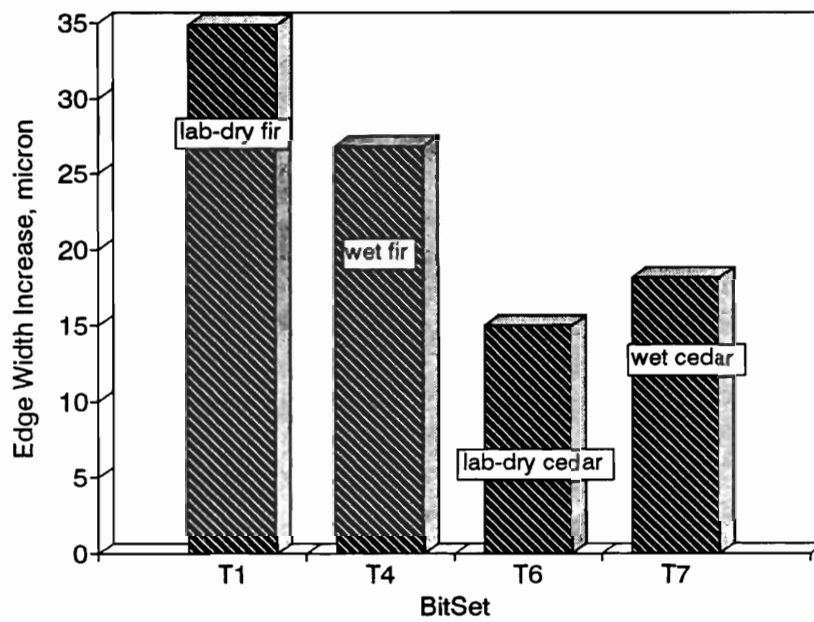


Figure 4.24 Total weight loss versus total cutting distance. Steel bits were used to cut wood at 0.0064 inch cutting tooth bite without air cooling.

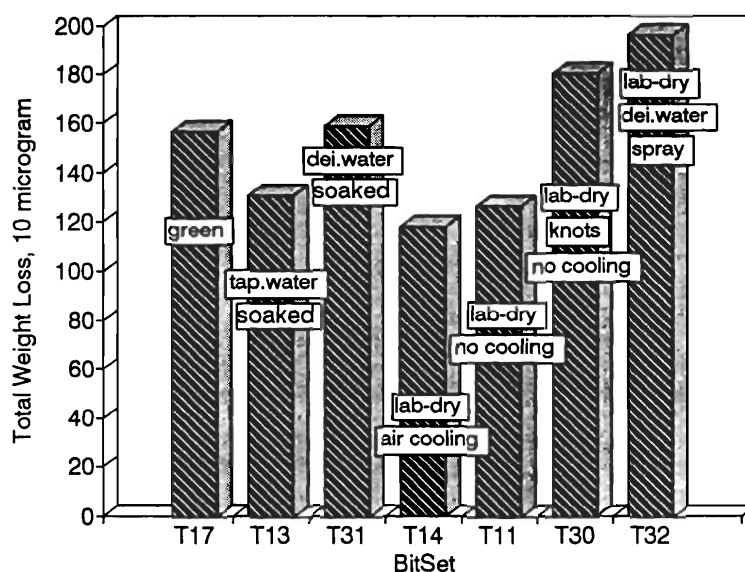


(a)

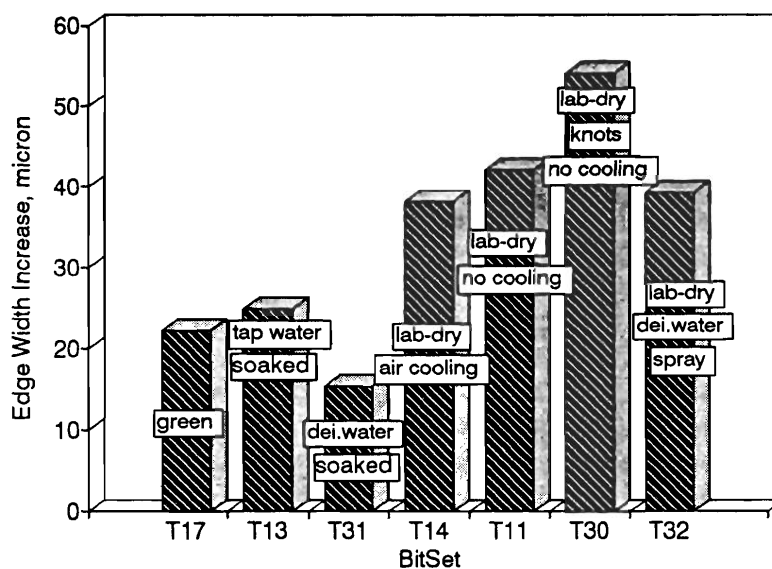


(b)

Figure 4.25 Weight loss (a) and edge width increase (b). Steel bits were used to cut wood at 0.0064 inch cutting tooth bite without air cooling for 800,000 inches cutting distance.

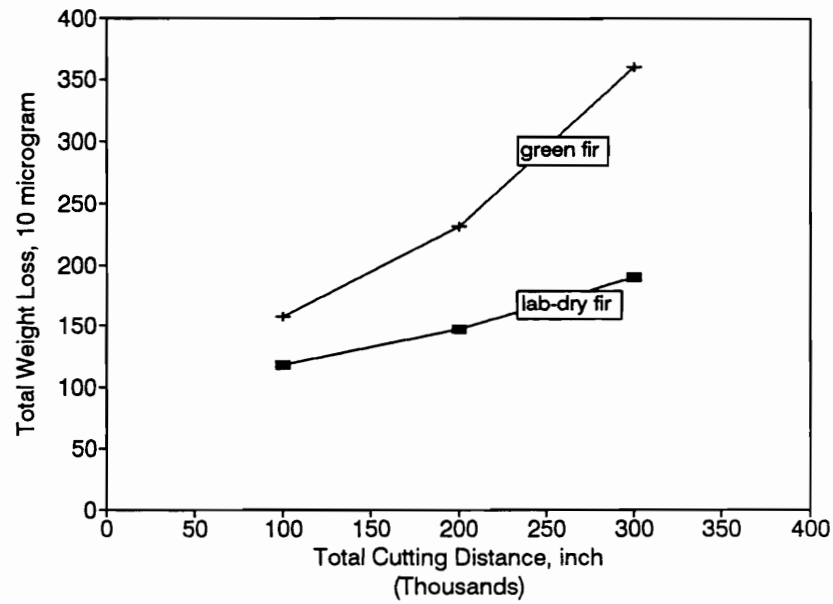


(a)

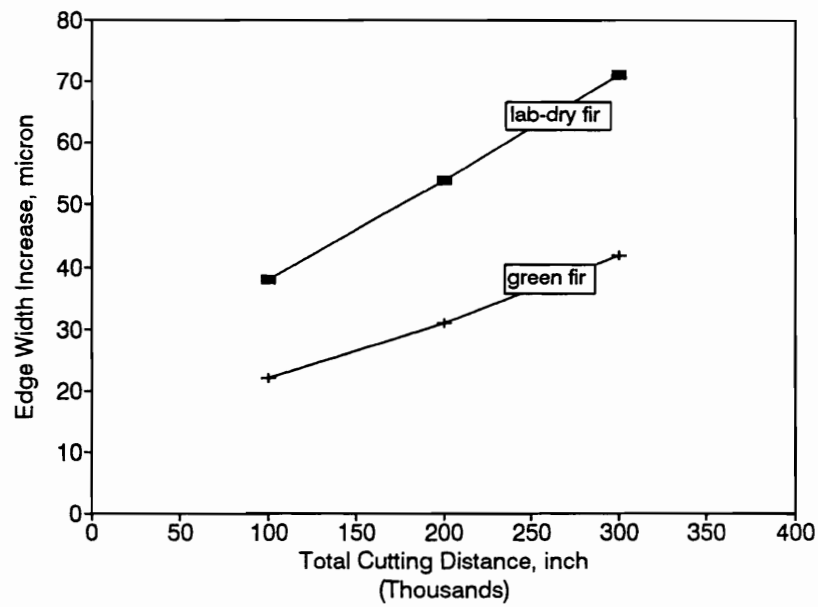


(b)

Figure 4.26 Total weight loss (a) and edge width increase (b). Steel bits were used to cut fir at 0.035 inch cutting tooth bite with (T14) or without (the rest) air cooling for 100,000 inches cutting distance.



(a)



(b)

Figure 4.27 Total weight loss (a) and edge width increase (b) versus total cutting distance. Steel bits were used to cut lab-dry (with air cooling) and green (without air cooling) fir at 0.035 cutting tooth bite.

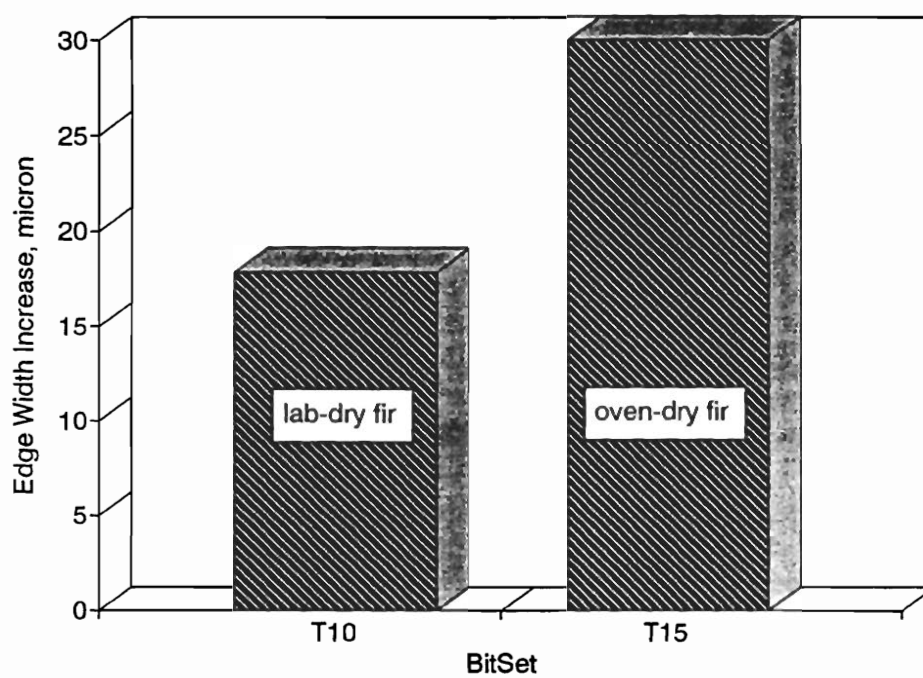
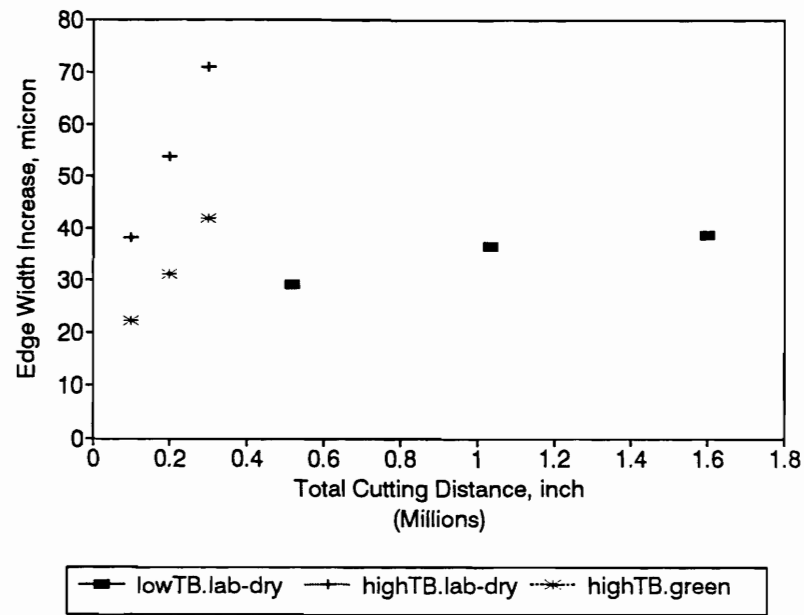
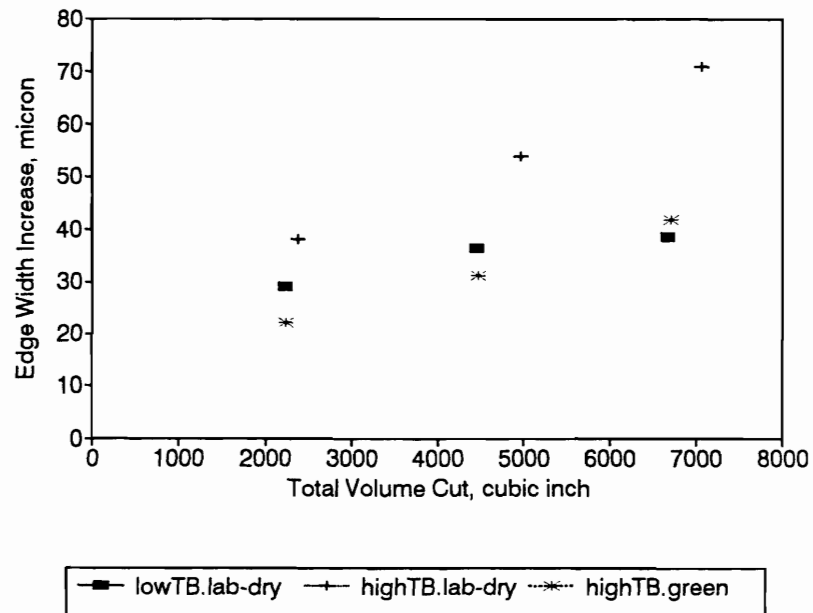


Figure 4.28 Comparison of edge width increase between steel bits cutting lab-dry and oven-dry fir at 0.035 inch tooth bite with air cooling for 5,000 inches cutting distance.

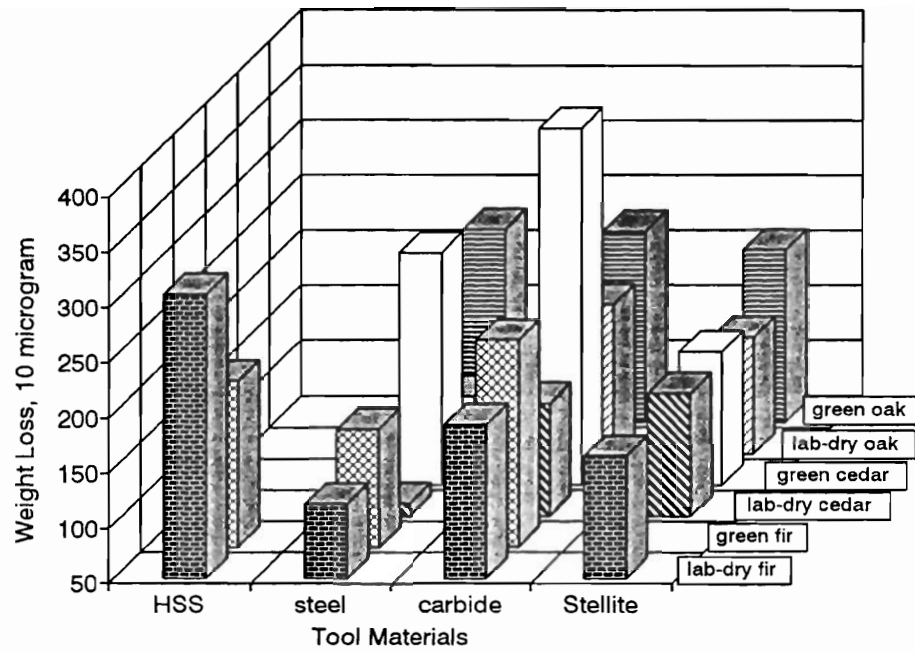


(a)

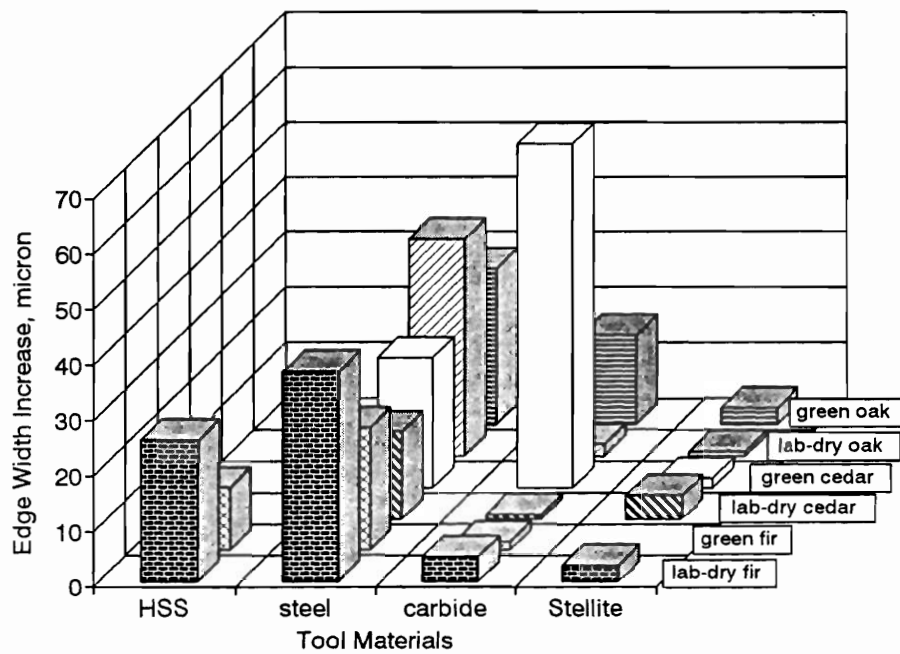


(b)

Figure 4.29 Edge width increase versus total cutting distance (a) and total volume of cut (b). Comparison is made between a low (0.0064 inch) and a high (0.035 inch) cutting tooth bites. Steel bits were used to cut fir at lab-dry (with air cooling) and green (without air cooling) conditions.



(a)



(b)

Figure 4.30 Total weight losses (a) and edge width increases (b) of steel, high speed steel (HSS), cemented carbide tip and Stellite tip. These bits were used to cut wood at 0.035 inch tooth bite with (lab-dry) or without (green) air cooling for 100,000 inches cutting distance.

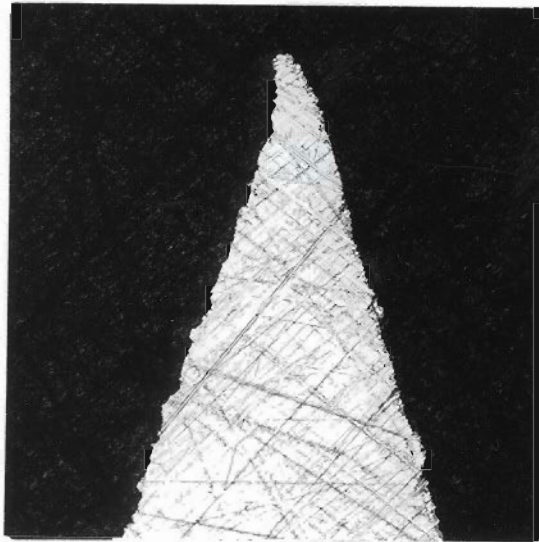
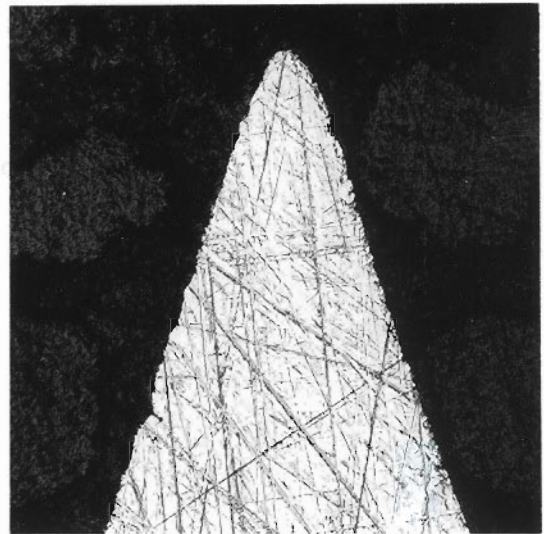
(a) $\overline{100\ \mu\text{m}}$ (b) $\overline{100\ \mu\text{m}}$ (c) $\overline{100\ \mu\text{m}}$

Figure 4.31 Cross-sectional profiles of steel bits: (a) as-received (new); (b) after cutting green fir at 0.035 inch tooth bite without air cooling for 300,000 inches; and (c) after cutting lab-dry fir at the same tooth bite and cutting distance and with air cooling (left-rake face, right-clearance face).

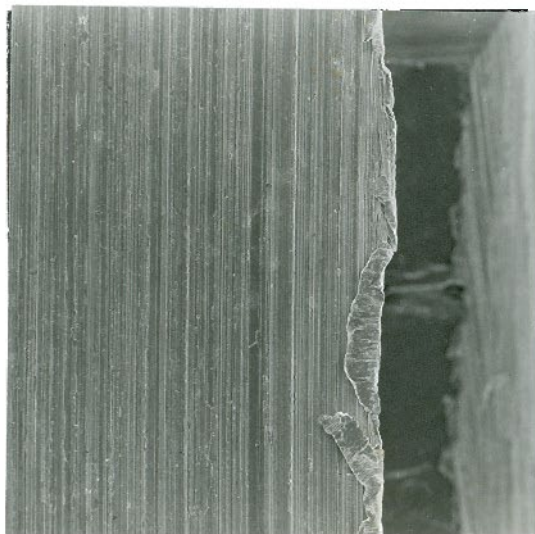
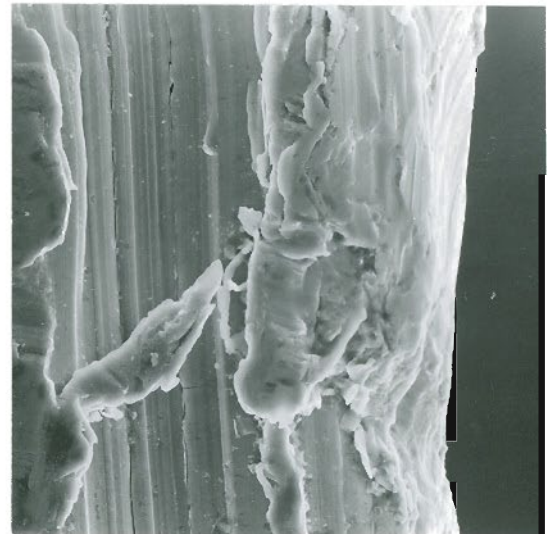
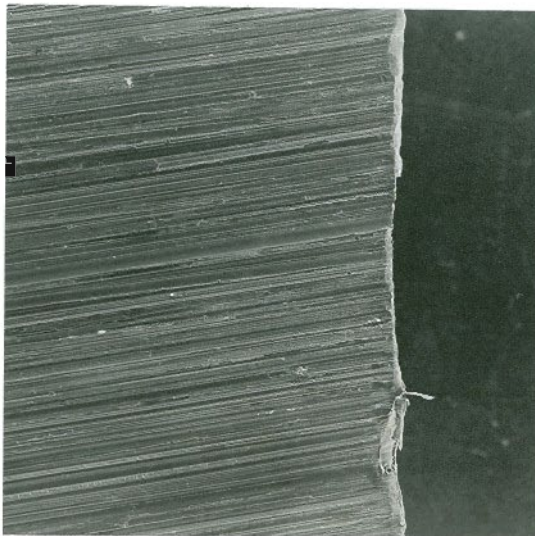
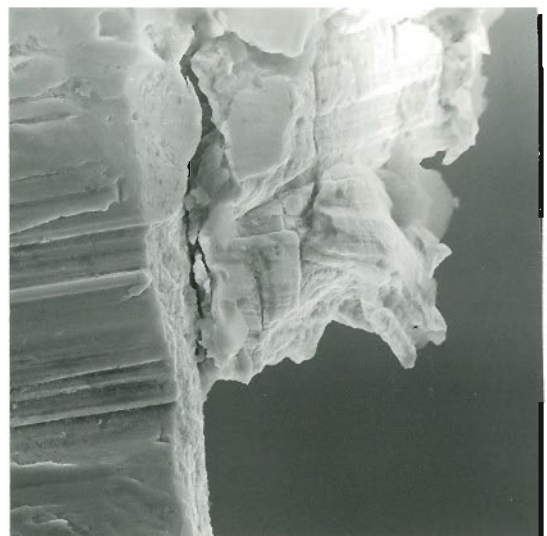
(a) $500\ \mu\text{m}$ (b) $10\ \mu\text{m}$ (c) $500\ \mu\text{m}$ (d) $10\ \mu\text{m}$

Figure 4.32 Rake (a and b) and clearance (c and d) face edges of an as-received (new) steel bit showing grinding burrs and marks (or grooves). These marks are parallel to the cutting edge at the rake face, and nearly perpendicular to the edge at the clearance face.

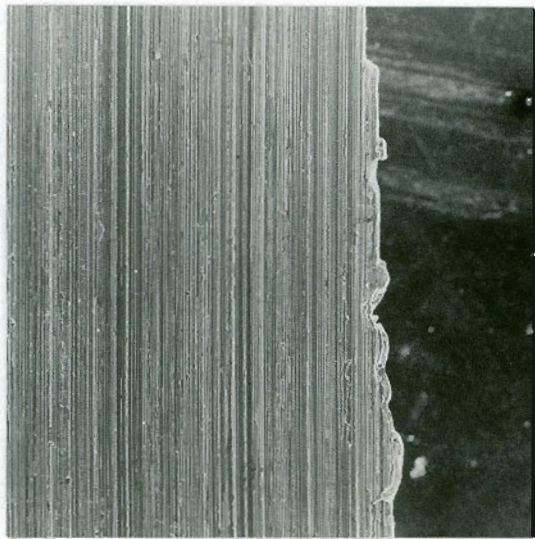
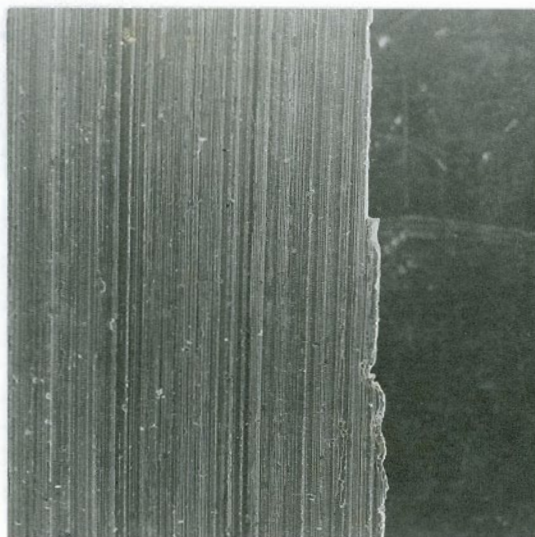
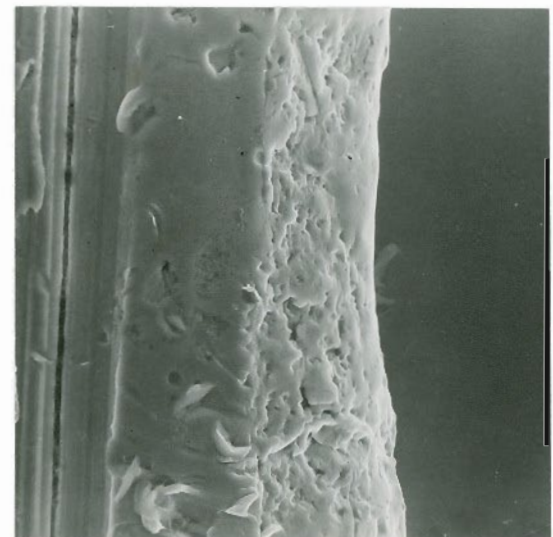
(a) 500 μm (b) 10 μm (c) 500 μm (d) 10 μm

Figure 4.33 Rake face edges of a steel bit after cutting lab-dry fir at 0.0064 inch tooth bite without air cooling for 16,000 inches cutting distance (a and b) showing removal of grinding burrs by fracture, and after 230,000 inches cutting distance (c and d) showing smoothed edge.

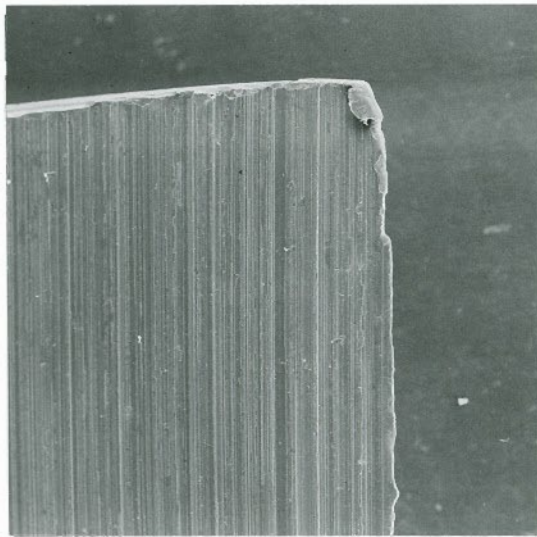
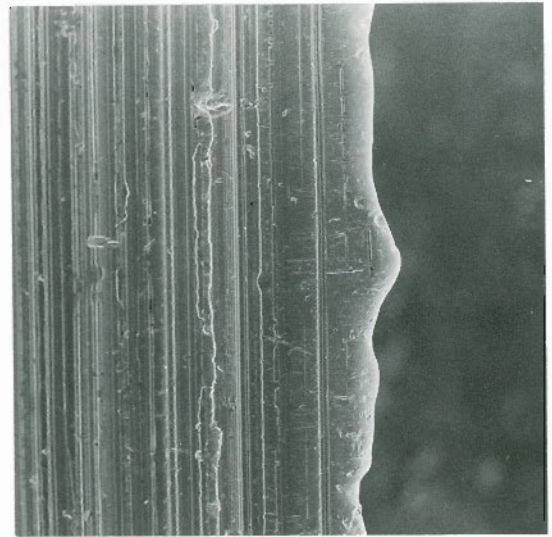
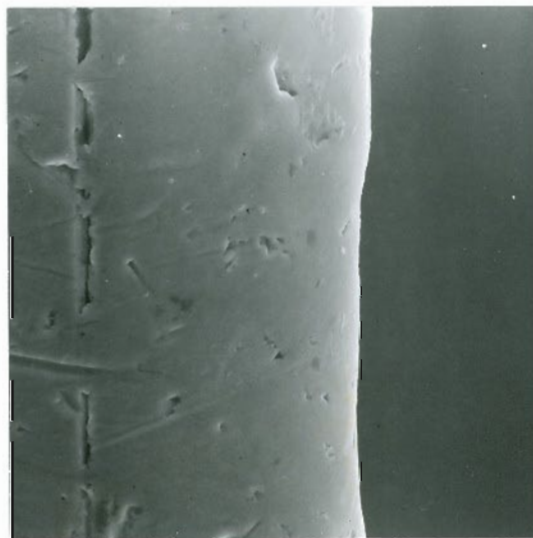
(a) $500\ \mu\text{m}$ (b) $100\ \mu\text{m}$ (c) $10\ \mu\text{m}$

Figure 4.34 The rake face edge of a steel bit after cutting lab-dry fir at 0.0064 inch tooth bite without air cooling for 230,000 inches cutting distance showing a smoothed edge with traces of wear grooves.

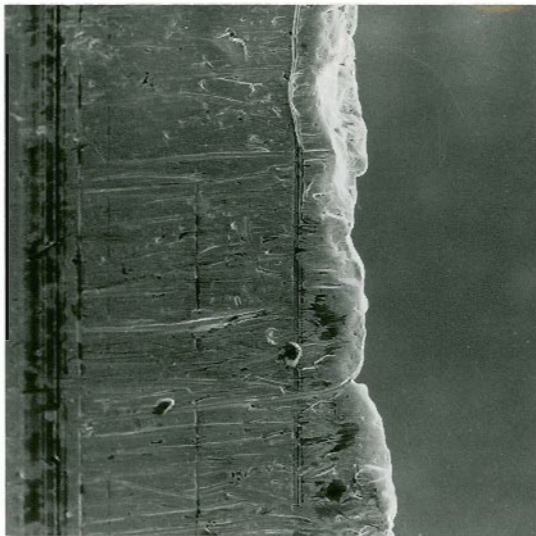
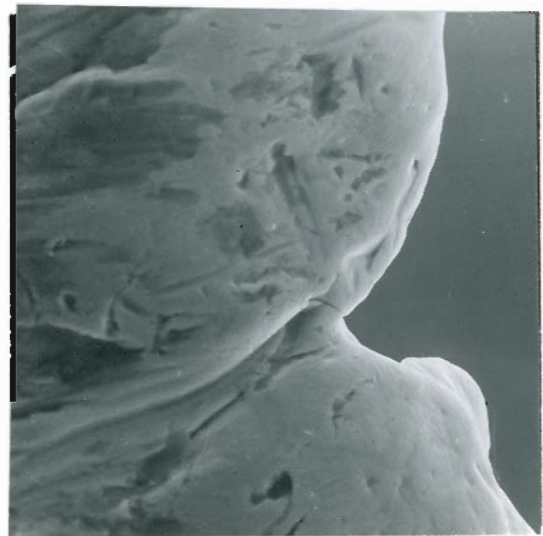
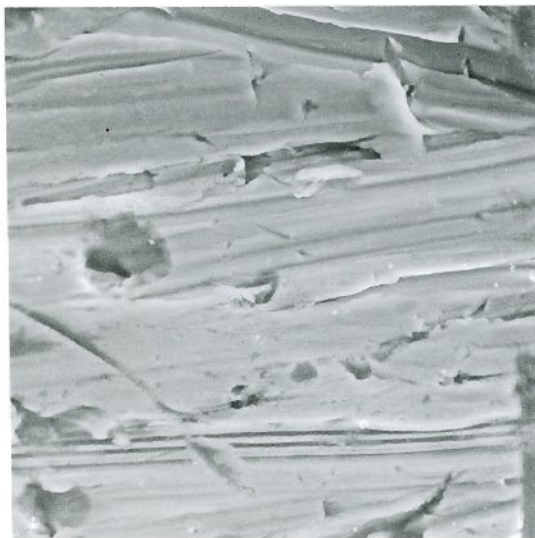
(a) $100\ \mu\text{m}$ (b) $10\ \mu\text{m}$ (c) $10\ \mu\text{m}$

Figure 4.35 The rake face edge of a steel bit after cutting lab-dry fir at 0.0064 inch tooth bite without air cooling for 760,000 inches cutting distance showing a rough edge with a high density of wear grooves.

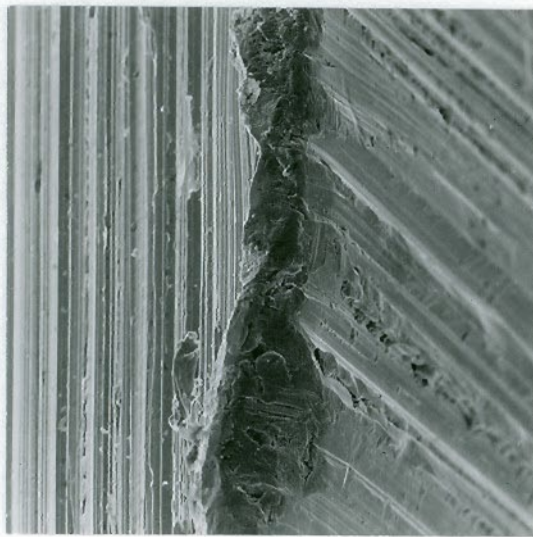
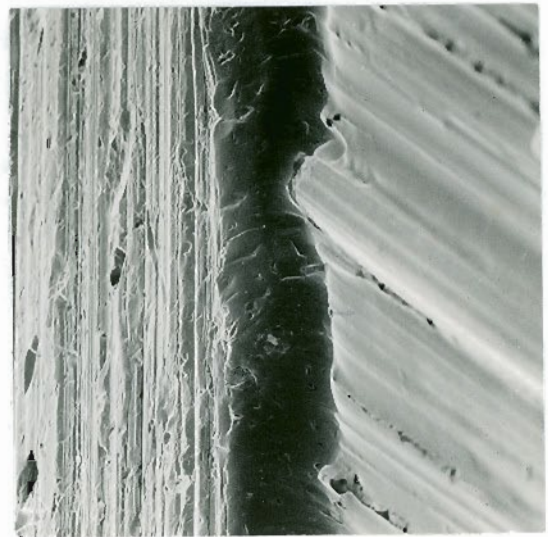
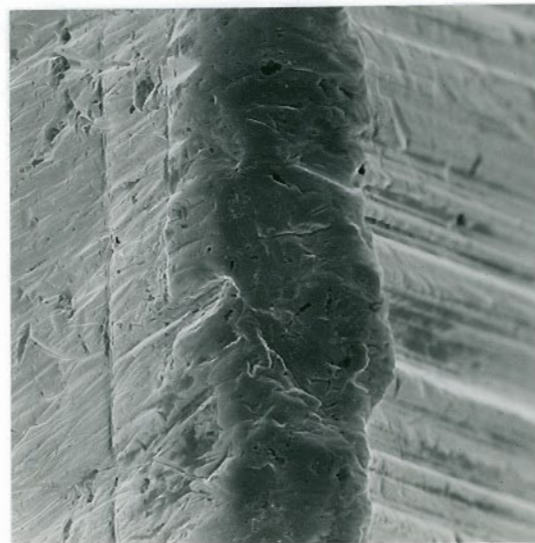
(a) $50\ \mu\text{m}$ (b) $50\ \mu\text{m}$ (c) $50\ \mu\text{m}$

Figure 4.36 Edges of steel bits from a top view: (a) as-received (new); (b and c) after cutting lab-dry fir at 0.0064 inch tooth bite without air cooling for 760,000 inches cutting distance.

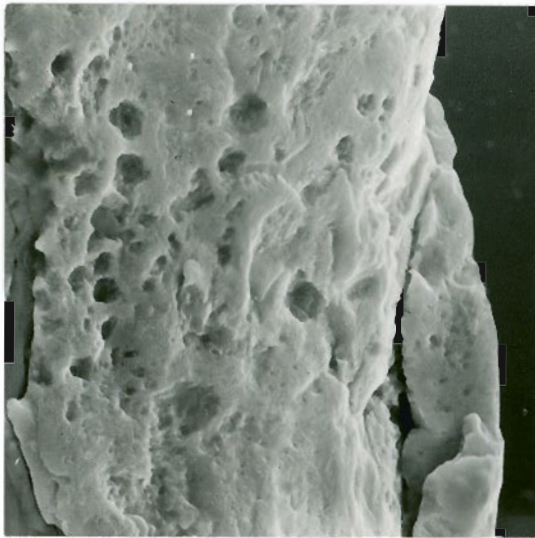
(a) $3.3 \mu\text{m}$ (b) $10 \mu\text{m}$ (c) $10 \mu\text{m}$

Figure 4.37 Rake face edges of steel bits after cutting wet (tap water soaked) fir at 0.0064 inch tooth bite without air cooling for 16,000 inches cutting distance (a and b), and 760,000 inches cutting distance (c).

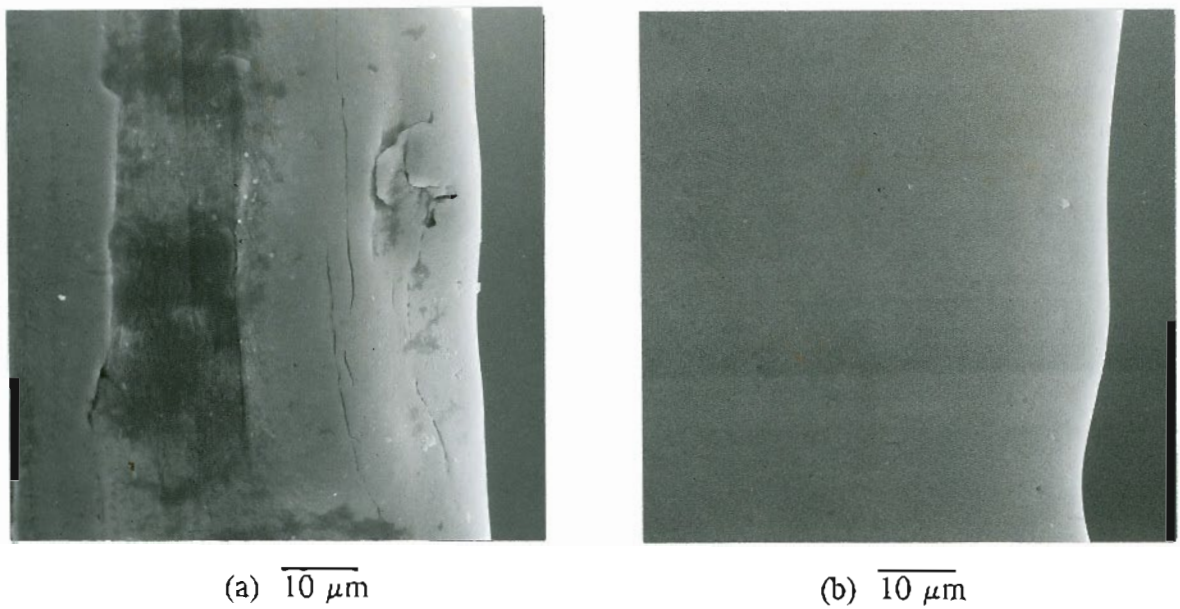


Figure 4.38 Rake face edges of steel bits: (a) after cutting lab-dry cedar at 0.0064 inch tooth bite without air cooling for 228,000 inches cutting distance; and (b) after cutting wet (tap water soaked) cedar at the same condition.

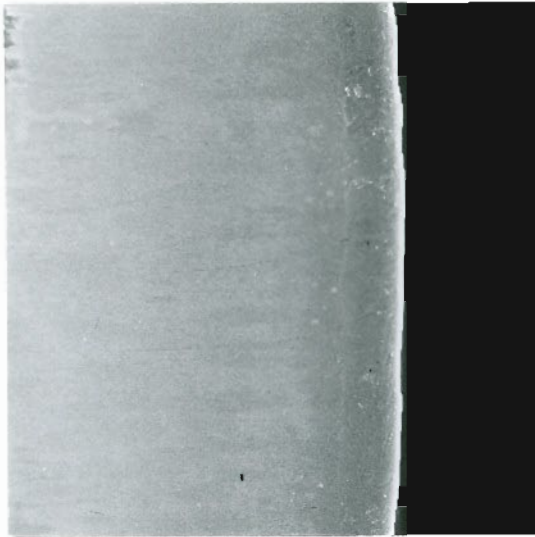
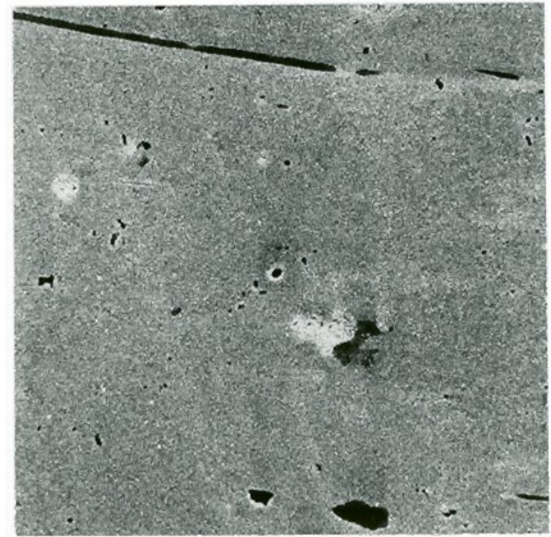
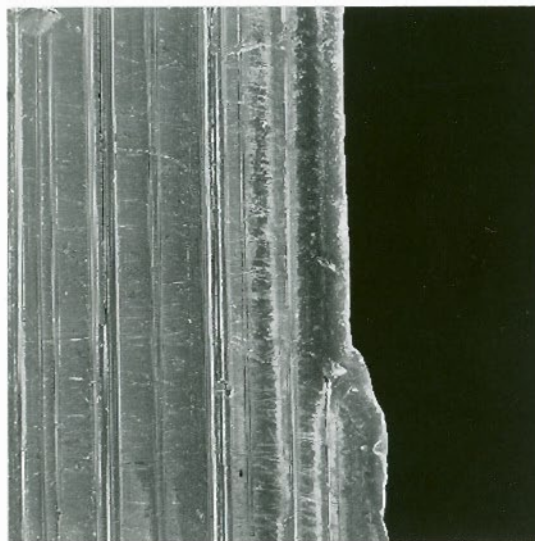
(a) $100\ \mu\text{m}$ (b) $10\ \mu\text{m}$ (c) $100\ \mu\text{m}$ (d) $10\ \mu\text{m}$

Figure 4.39 Rake face edges of steel bits: (a and b) after cutting green fir at 0.035 inch tooth bite without air cooling for 300,000 inches cutting distance showing a smoothed surface and traces of wear grooves; (c and d) after cutting lab-dry fir at the same tooth bite and cutting distance with air cooling showing relatively rough edge and many wear grooves.

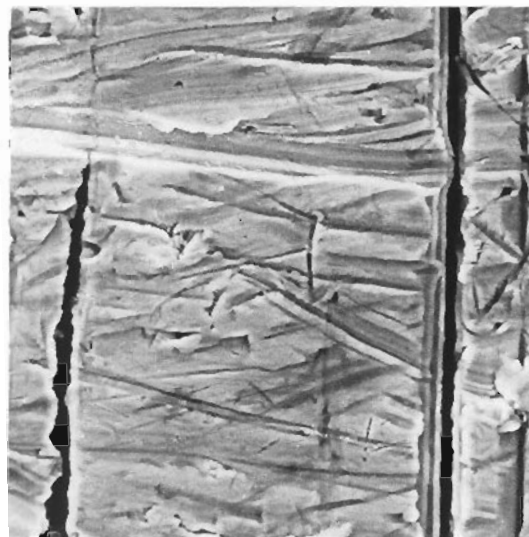
(a) $100\ \mu\text{m}$ (b) $10\ \mu\text{m}$ (c) $10\ \mu\text{m}$

Figure 4.40 The rake face edge of a steel bit after cutting lab-dry fir with a high density of knots at 0.035 inch tooth bite without air cooling for 100,000 inches cutting distance showing a rough edge and many wear grooves.

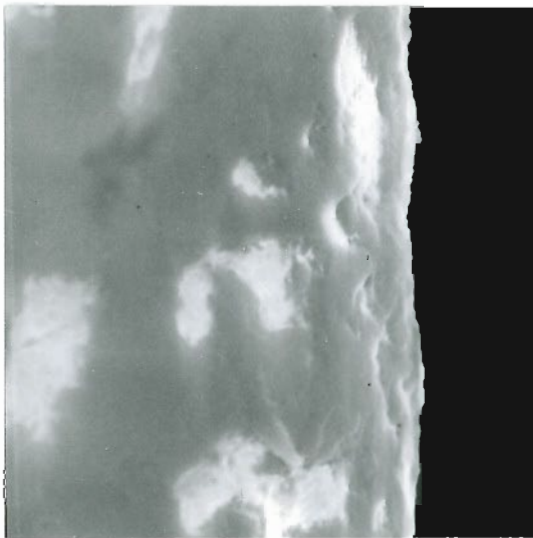
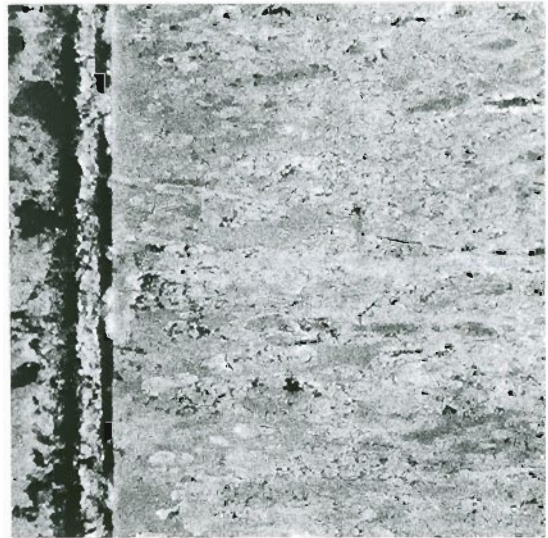
(a) $100\ \mu\text{m}$ (b) $10\ \mu\text{m}$ (c) $2\ \mu\text{m}$ (d) $10\ \mu\text{m}$

Figure 4.41 The rake face edge of a steel bit after cutting green cedar at 0.035 inch tooth bite without air cooling for 100,000 inches cutting distance showing a rounded edge and areas of stains (d-rake face about $100\ \mu\text{m}$ away from the extreme edge).

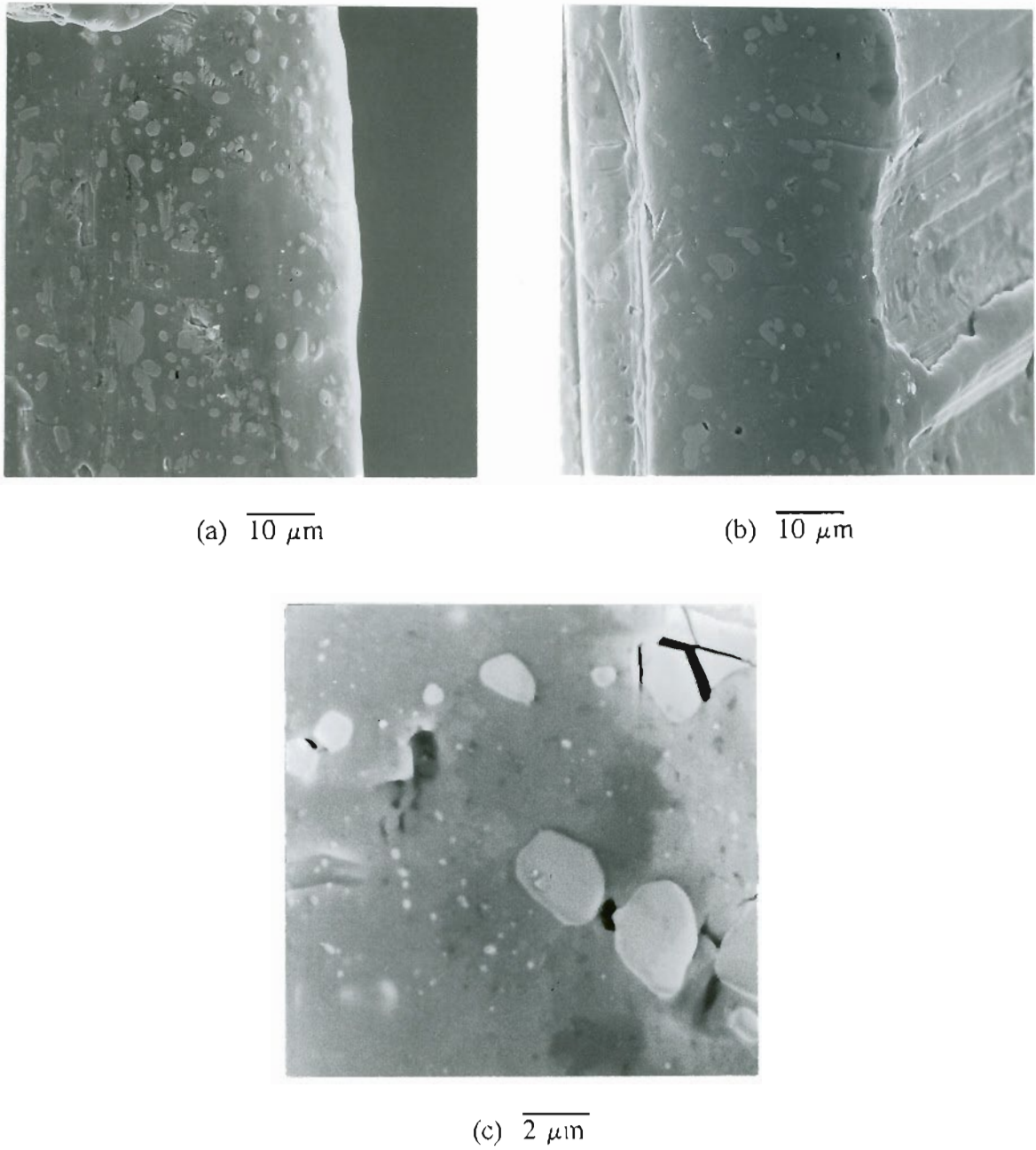


Figure 4.42 The cutting edge of a HSS bit (a-rake face; b and c-top view) after cutting green fir at 0.035 inch tooth bite without air cooling for 100,000 inches cutting distance showing a smoothed edge.

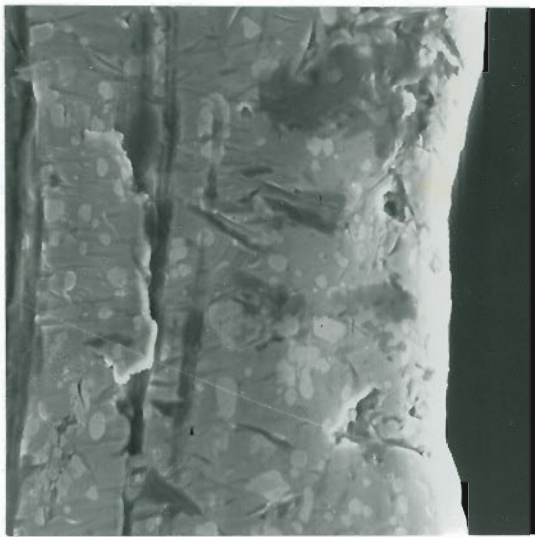
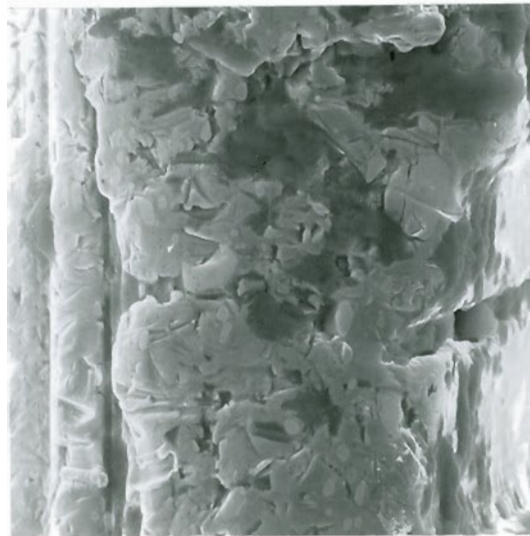
(a) $10\ \mu\text{m}$ (b) $10\ \mu\text{m}$ (c) $10\ \mu\text{m}$

Figure 4.43 The cutting edge of a HSS bit (a and b-rake face, c-top view) after cutting lab-dry fir at 0.035 inch tooth bite with air cooling for 100,000 inches cutting distance showing a rough edge with wear grooves.

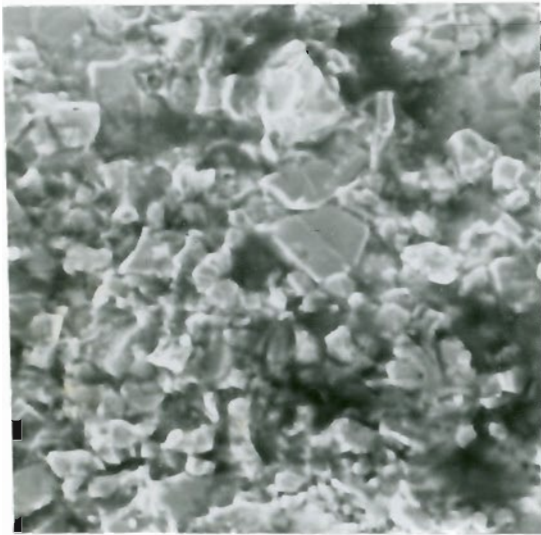
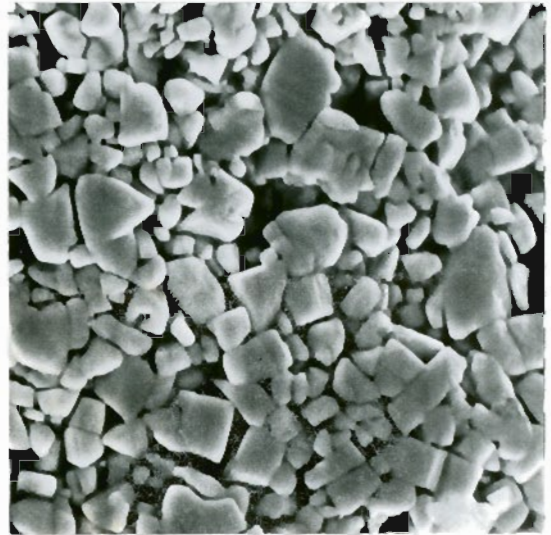
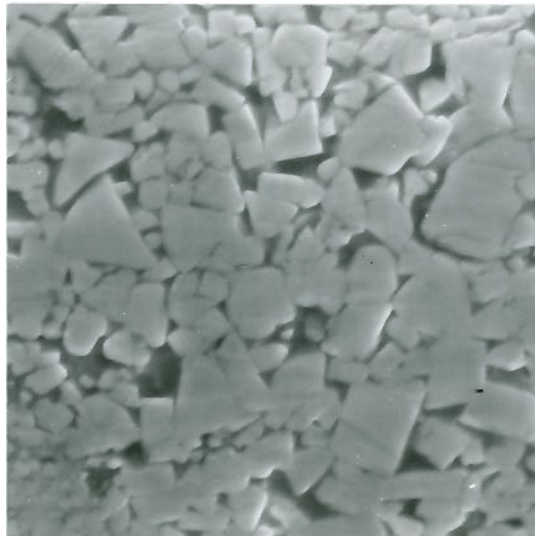
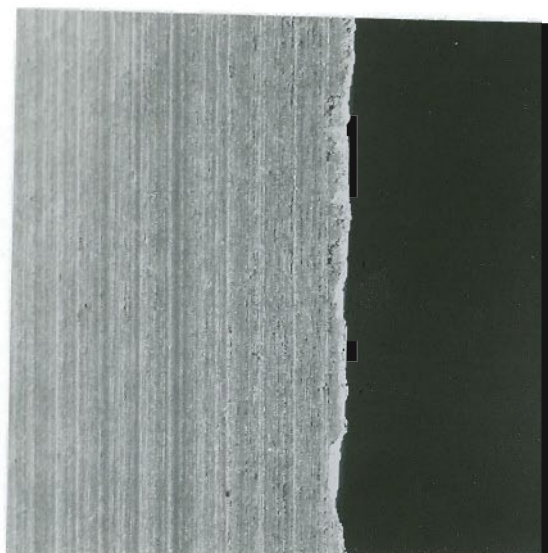
(a) $2\ \mu\text{m}$ (b) $2\ \mu\text{m}$ (c) $2\ \mu\text{m}$

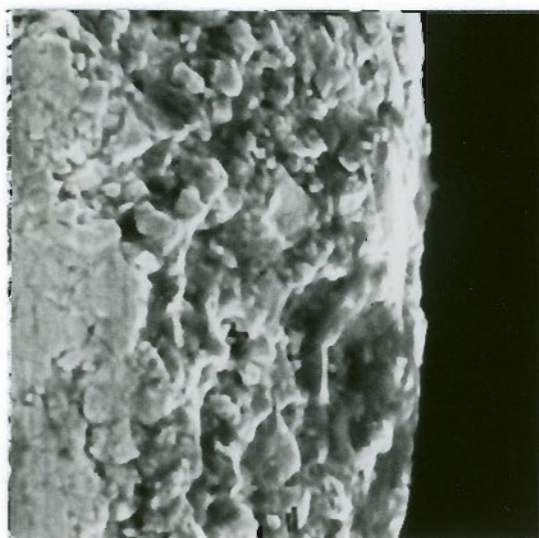
Figure 4.44 Edges of cemented carbide tips from a top view: (a) as-received; (b) after cutting green fir at 0.035 inch tooth bite without air cooling for 100,000 inches cutting distance showing exposed carbide particles; and (c) after cutting lab-dry fir at the same tooth bite and cutting distance with air cooling showing flattened carbide particles.



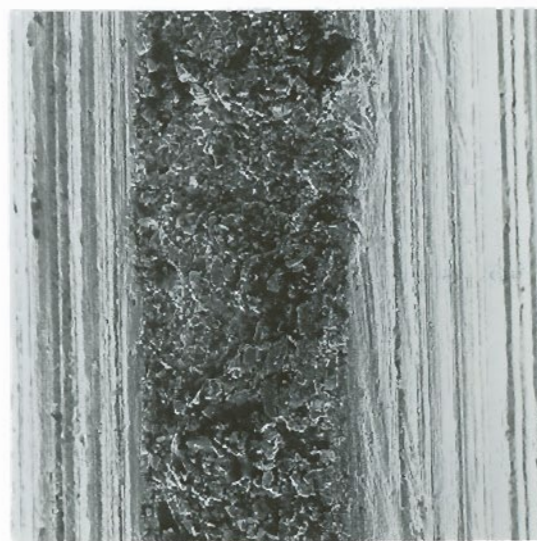
(a) $100\ \mu\text{m}$



(b) $10\ \mu\text{m}$



(c) $2\ \mu\text{m}$



(d) $10\ \mu\text{m}$

Figure 4.45 The edge of an as-received (new) cemented carbide tip (a, b and c-rake face; d-top view)

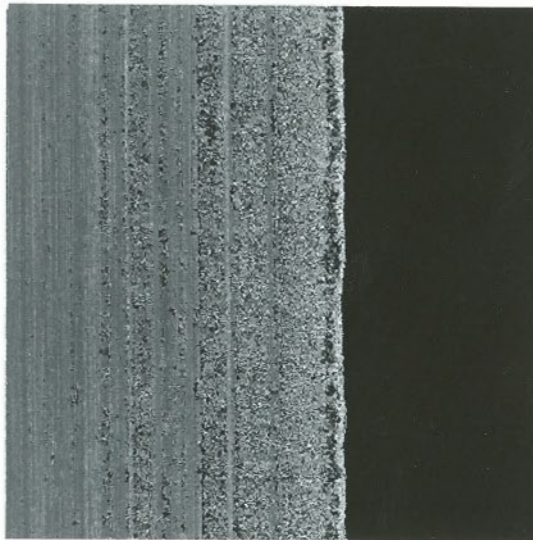
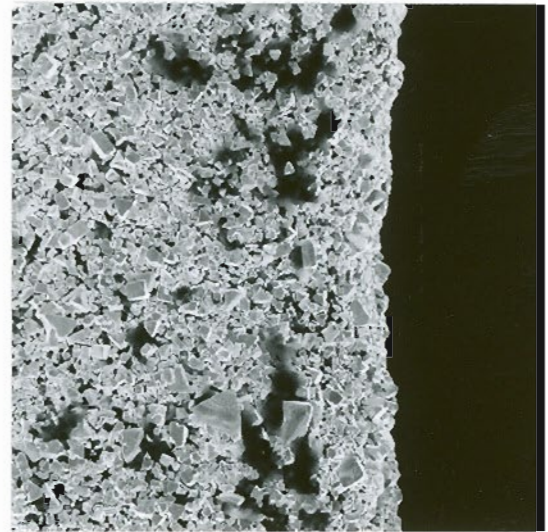
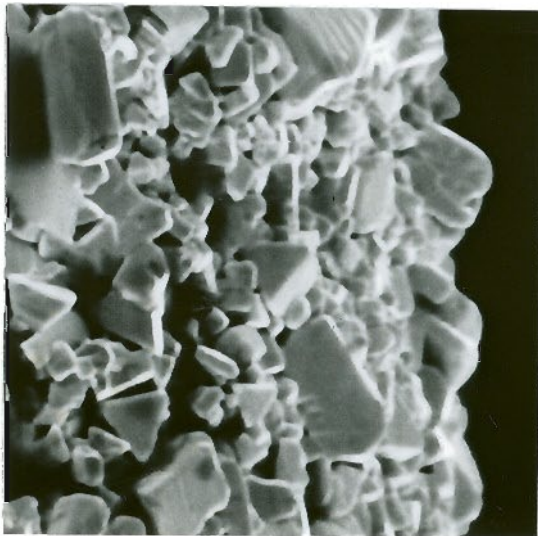
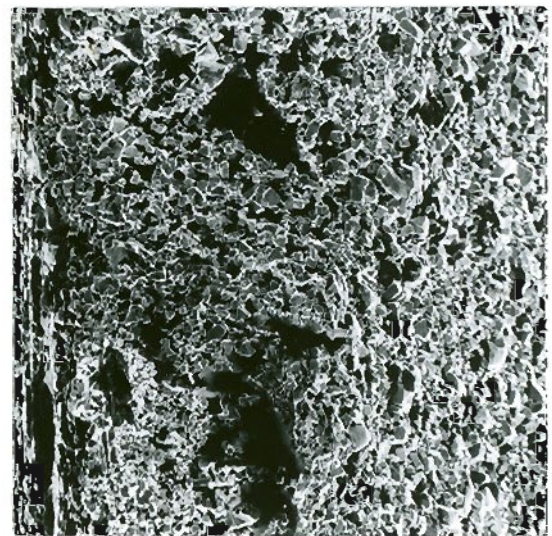
(a) $100\ \mu\text{m}$ (b) $10\ \mu\text{m}$ (c) $2\ \mu\text{m}$ (d) $10\ \mu\text{m}$

Figure 4.46 The edge of a cemented carbide tip: (a, b and c-rake face; d-top view) after cutting green cedar at 0.035 inch tooth bite without air cooling for 100,000 inches cutting distance showing exposed sharp carbide particles.

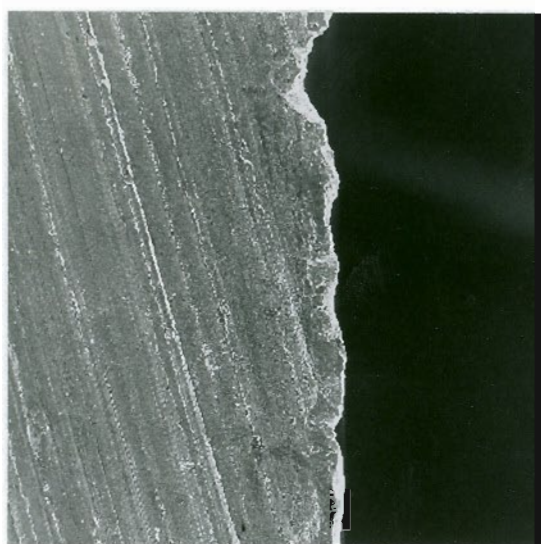
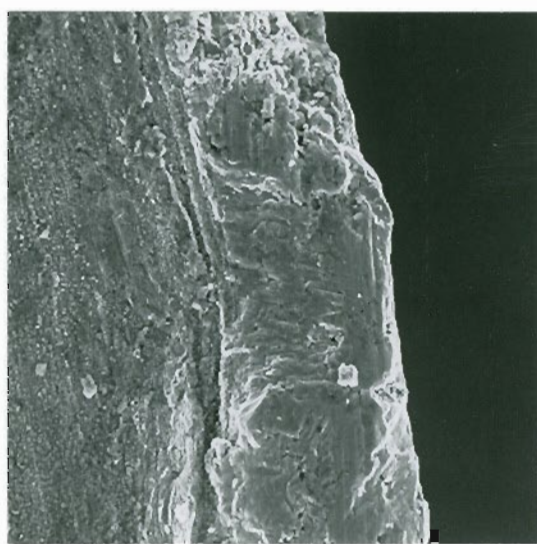
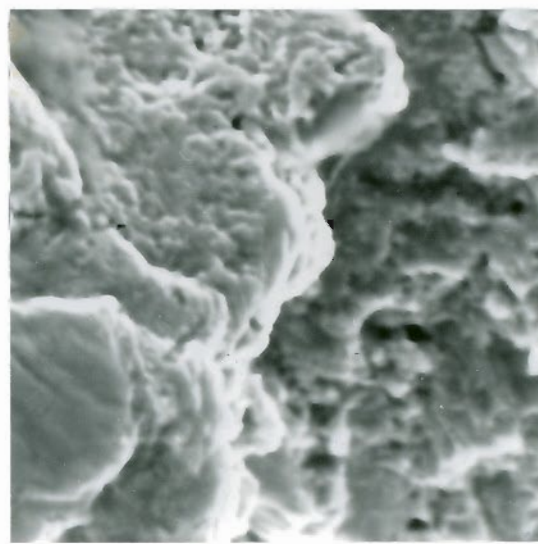
(a) $100\ \mu\text{m}$ (b) $10\ \mu\text{m}$ (c) $10\ \mu\text{m}$ (d) $2\ \mu\text{m}$

Figure 4.47 The edge of an as-received (new) Stellite tip (a and b-rake face; c and d-top view).

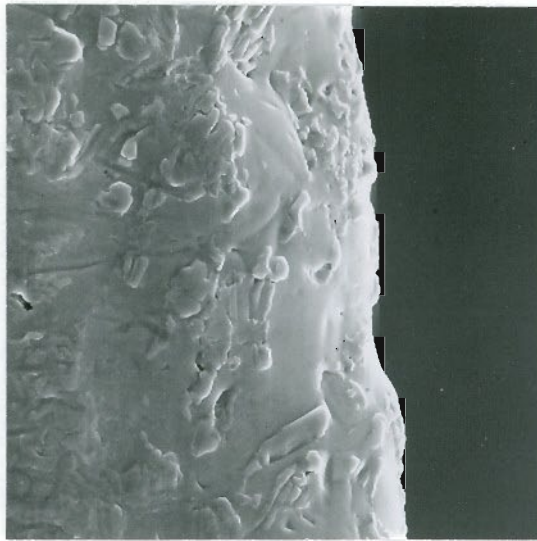
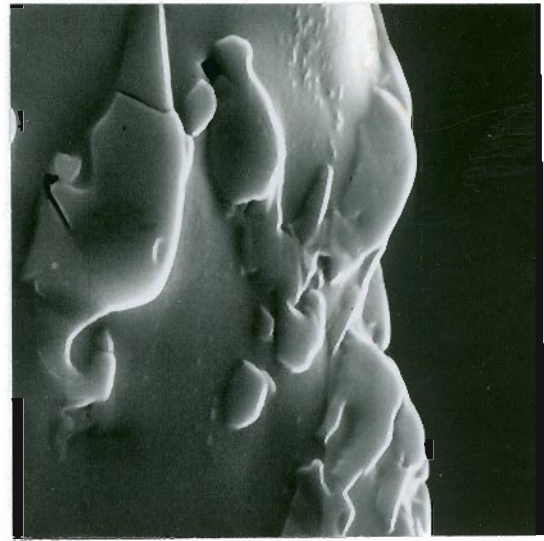
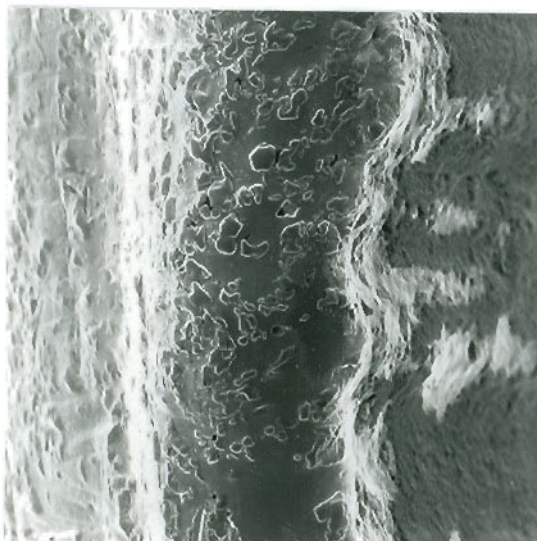
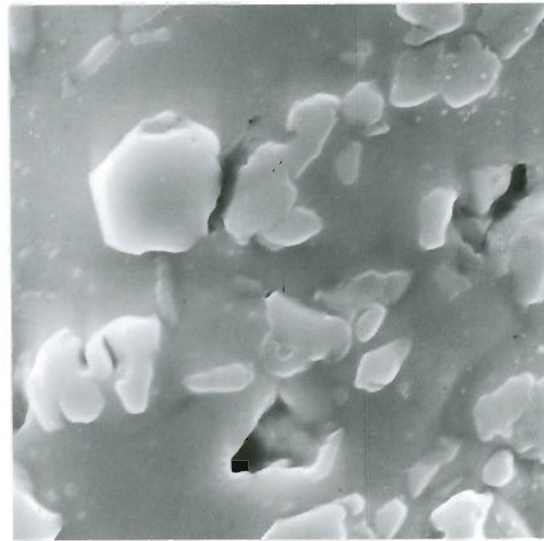
(a) $10\ \mu\text{m}$ (b) $2\ \mu\text{m}$ (c) $10\ \mu\text{m}$ (d) $2\ \mu\text{m}$

Figure 4.48 The edge of a Stellite tip (a and b-rake face; c and d-top view) after cutting green oak at 0.035 inch tooth bite without air cooling for 100,000 inches cutting distance.

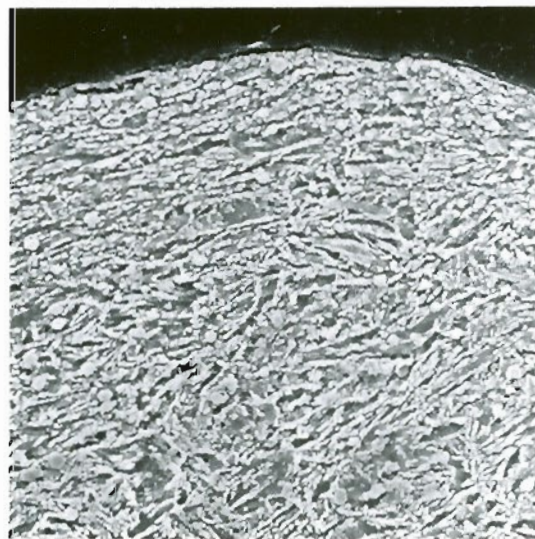
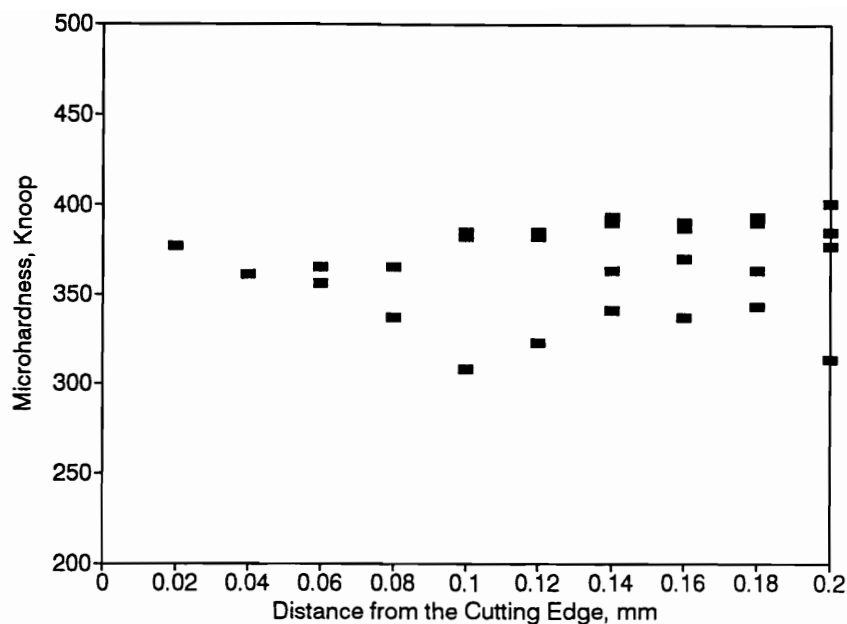
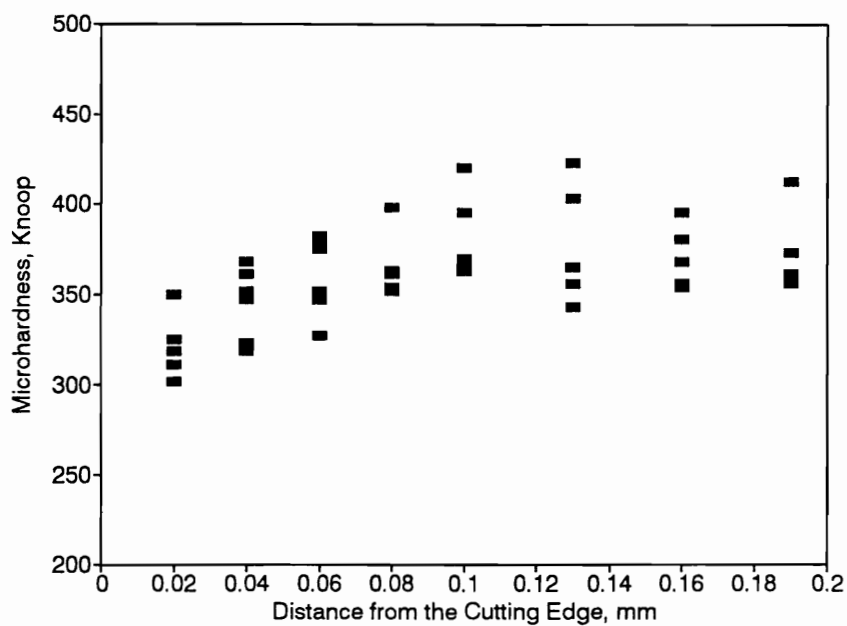
(a) $50\ \mu\text{m}$ (b) $3.3\ \mu\text{m}$ (c) $3.3\ \mu\text{m}$

Figure 4.49 The edge cross-sectional profile and microstructure of a steel bit after cutting lab-dry fir with knots at 0.035 inch tooth bite without air cooling for 100,000 inches cutting distance showing plastic deformation.



(a)



(b)

Figure 4.50 Microhardness at cutting edges of (a) an as-received steel bit and (b) a steel bit after cutting lab-dry fir with knots at 0.035 inch tooth bite without air cooling for 100,000 inches cutting distance.

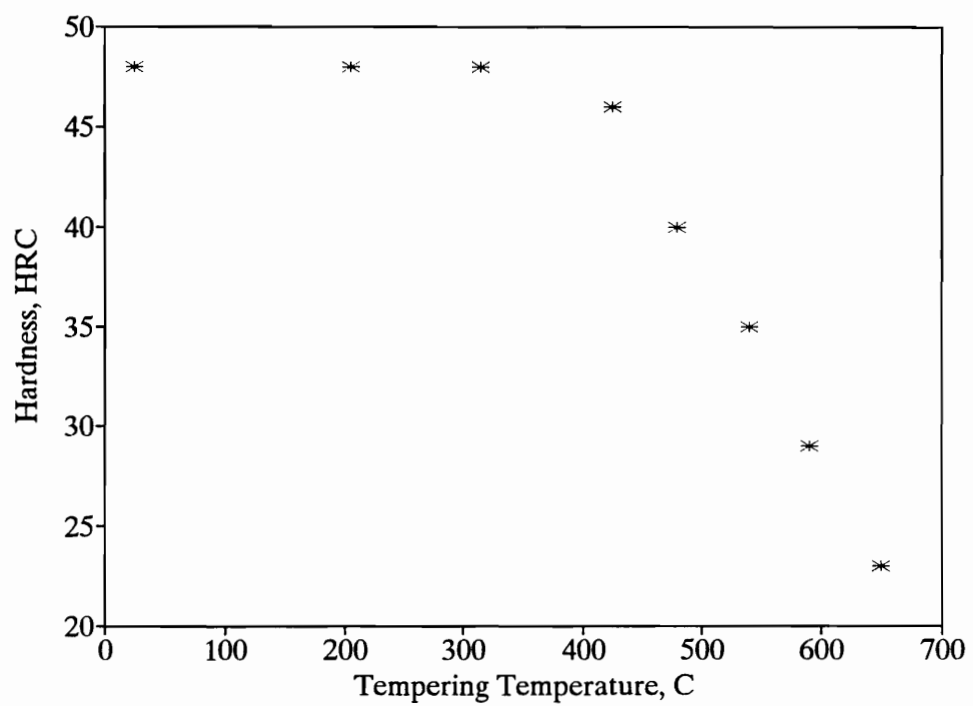
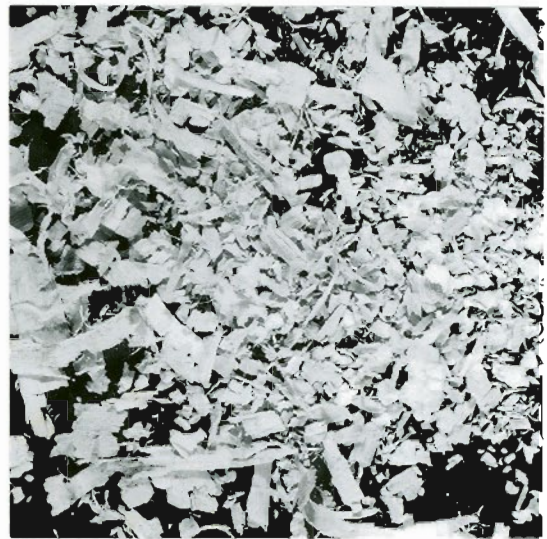


Figure 4.51 Hardness versus tempering temperature plot of as-received steel bits.



(a) 10 mm



(b) 10 mm

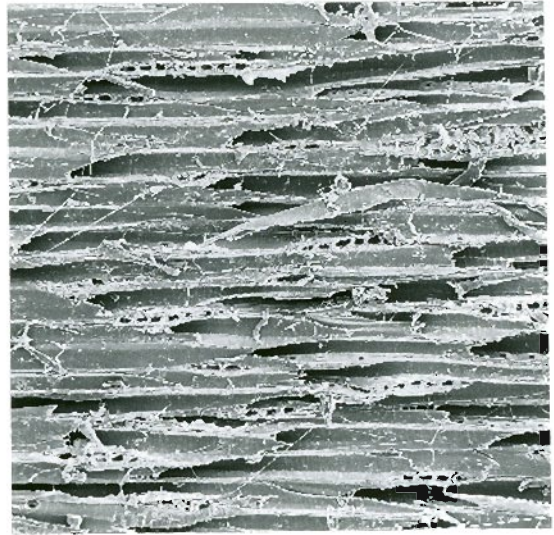


(c) 10 mm

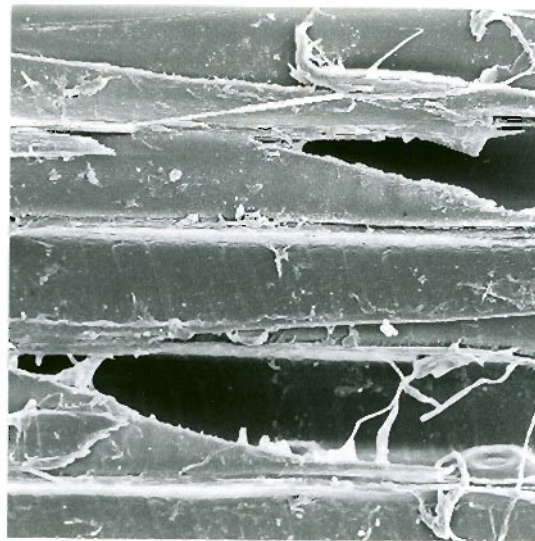
Figure 4.52 Optical photographs of sawdust/wood chips: (a) green fir; (b) lab-dry fir and (c) oven-dry fir.



(a) 1.25 mm



(b) 100 μm



(c) 20 μm

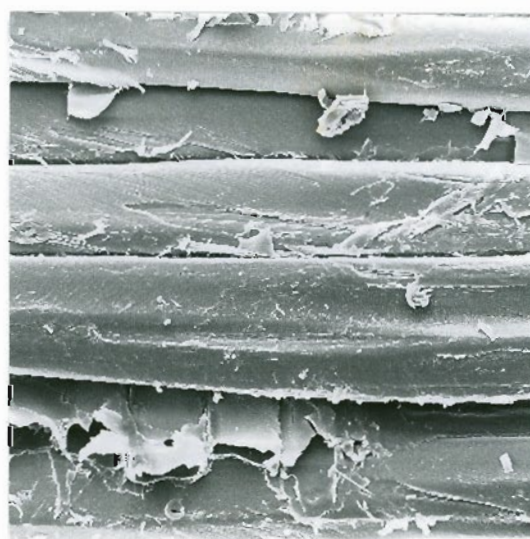
Figure 4.53 SEM micrographs of green fir chips cut by steel bits at 0.035 inch tooth bite without air cooling for 200,000 inches cutting distance showing intrafiber breakage.



(a) 1.25 mm



(b) 100 μm



(c) 20 μm

Figure 4.54 SEM micrographs of lab-dry fir chips cut by steel bits at 0.035 inch tooth bite with air cooling for 200,000 inches cutting distance showing small chips and fiber interfaces indicating interfiber breakdown.

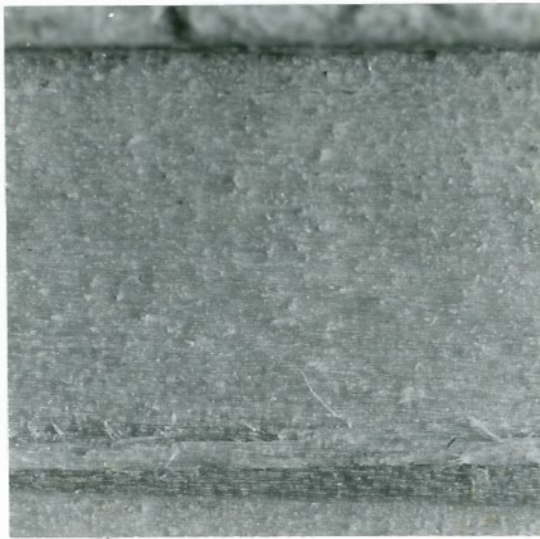
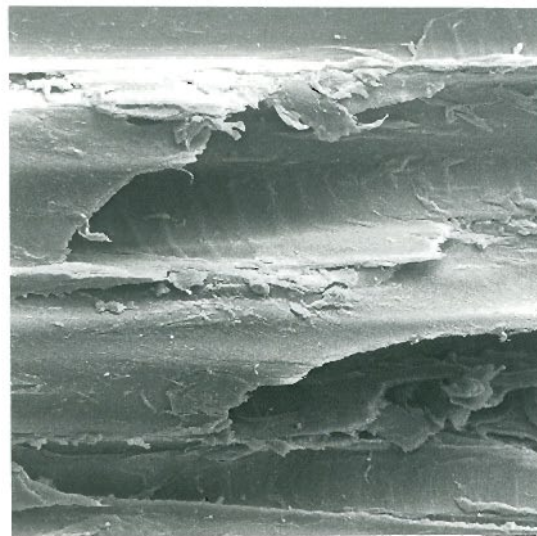
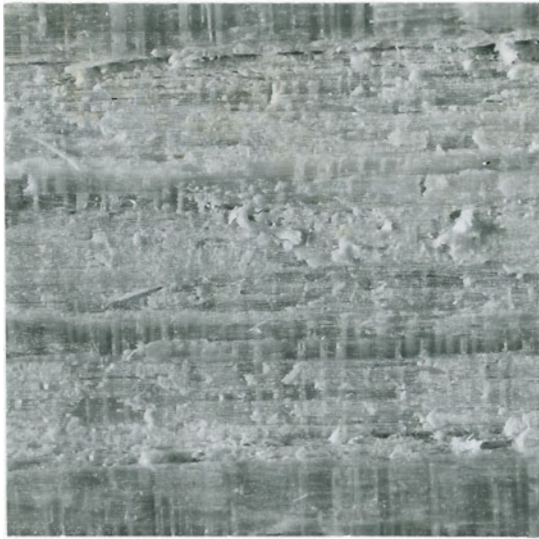
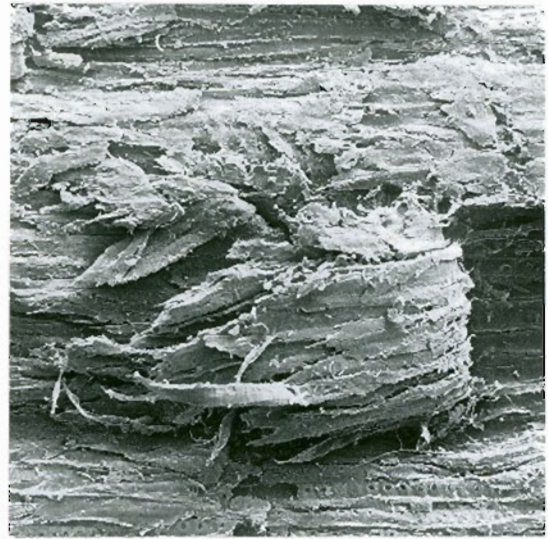
(a) $\overline{2.5 \text{ mm}}$ (b) $\overline{100 \mu\text{m}}$ (c) $\overline{20 \mu\text{m}}$

Figure 4.55 SEM micrographs of saw kerf end faces from green fir cut by steel bits at 0.035 inch tooth bite with air cooling for 200,000 inches cutting distance showing intrafiber breakage.



(a) 2.5 mm



(b) 100 μm



(c) 20 μm

Figure 4.56 SEM micrographs of saw kerf end faces from lab-dry fir cut by steel bits at 0.035 inch tooth bite with air cooling for 200,000 inches cutting distance showing rough surface (a), fiber pull-out and breakdown in groups (b) and intercellular breakdown (c).

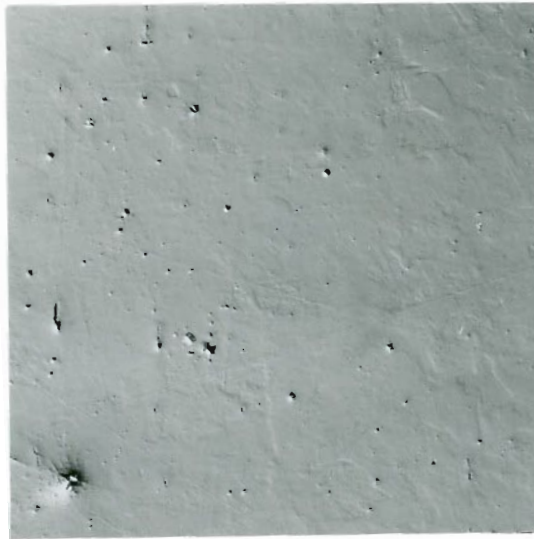
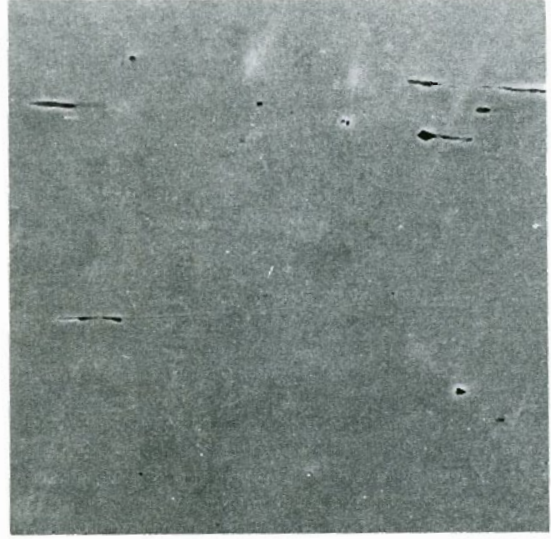
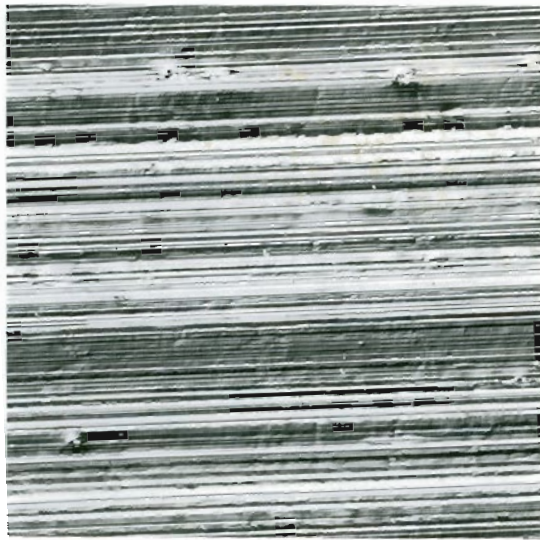
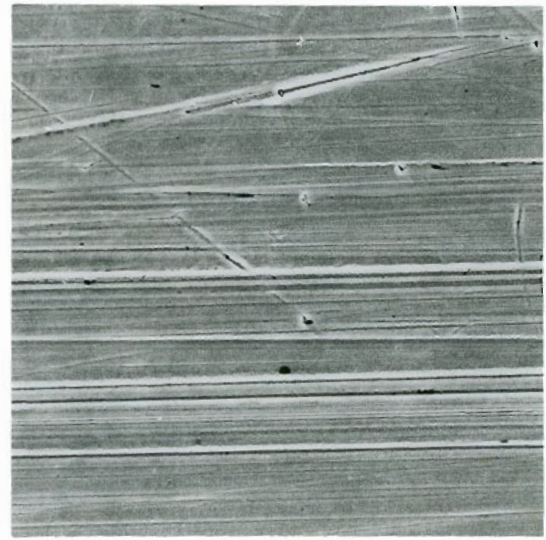
(a) $50\ \mu\text{m}$ (b) $10\ \mu\text{m}$ (c) $50\ \mu\text{m}$ (d) $10\ \mu\text{m}$

Figure 4.57 Surface topographies of AISI 1065 steel samples: as-polished (a-optical and b-SEM); after 500 revolutions of abrasion testing (c-optical and d-SEM).

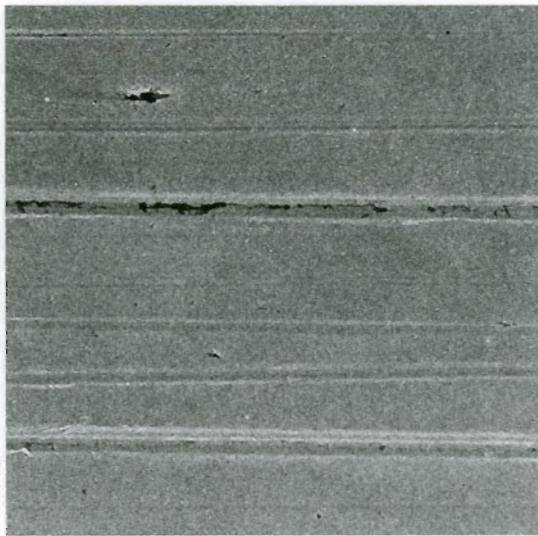
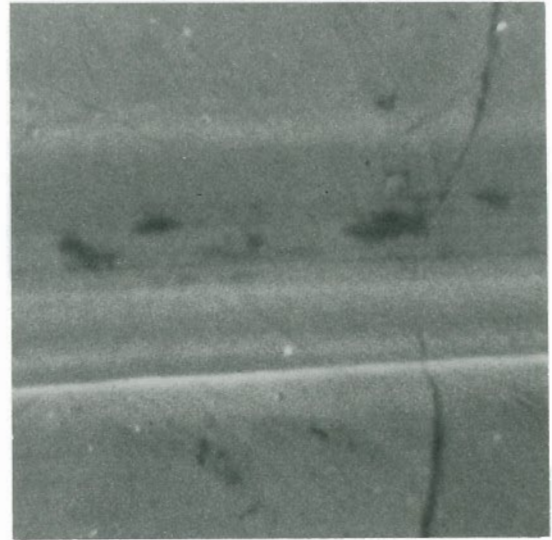
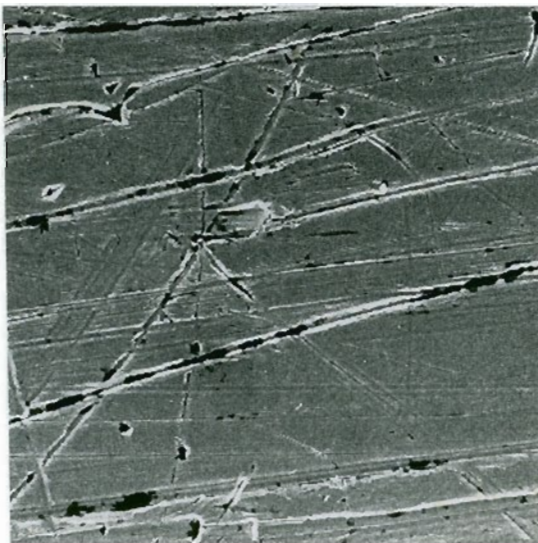
(a) $10\ \mu\text{m}$ (b) $1\ \mu\text{m}$ (c) $10\ \mu\text{m}$ (d) $1\ \mu\text{m}$

Figure 4.58 Surface topographies of AISI 1065 steel samples after 5,500 revolutions of testing: wear scar starting areas where the abrasive were flowing into the rubber and sample contact area (a and b); wear scar ending areas where the abrasive were flowing out (c and d).

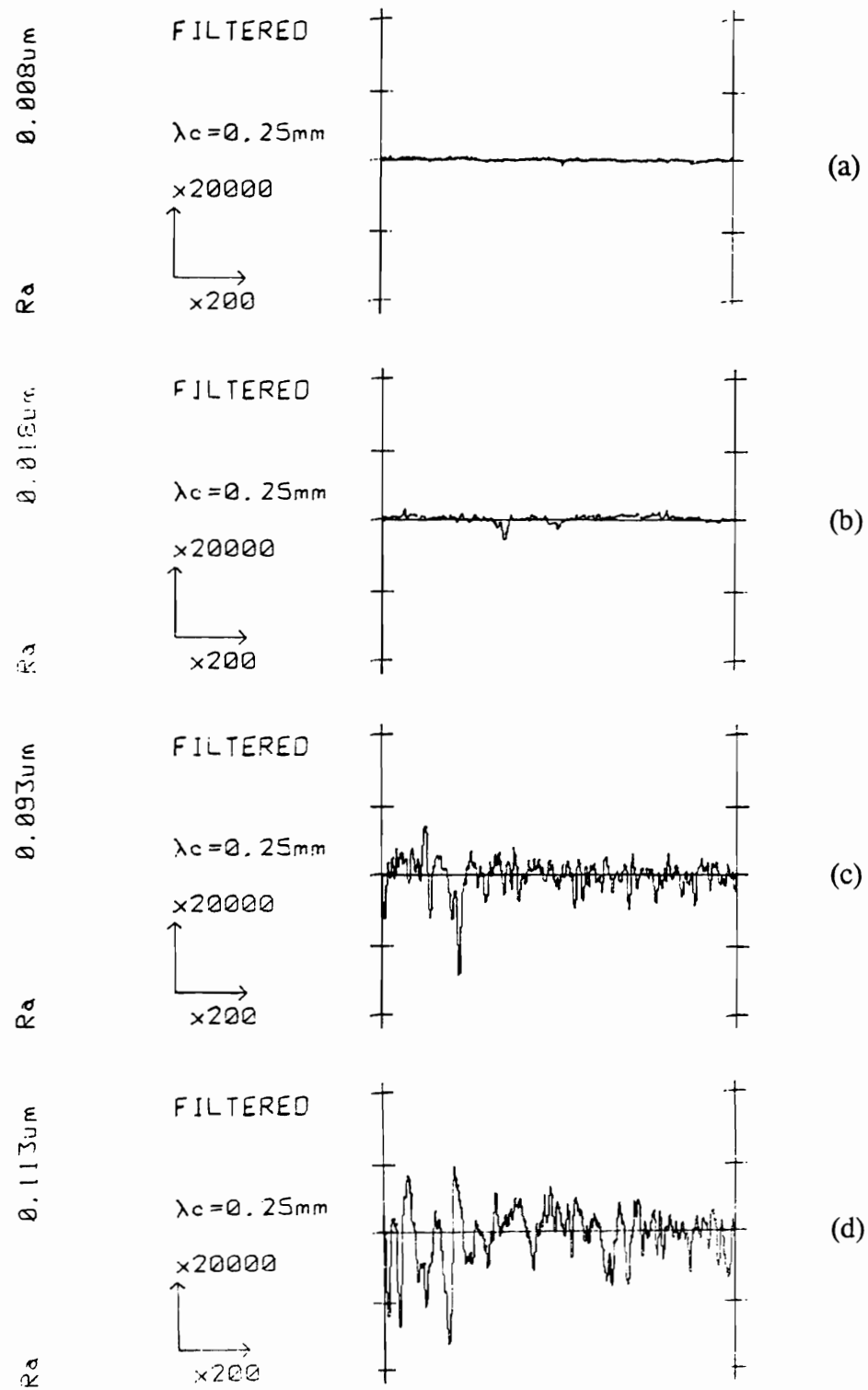


Figure 4.59 Surface roughness profiles of AISI 1065 steel samples: (a) as-polished; (b) after 500 revolutions; (c) after 3,500 revolutions and (d) after 5,500 revolutions of abrasion testing.

CHAPTER 5. DISCUSSION

5.1 The Field Study

The field study involved a total of 22 saws or pieces of tools covering different types of woodworking tools cutting three wood species, from three independent sawmills in Oregon and Washington. It was a broad based and unique study in the sense that no similar work has been reported before. It was revealed that the overall differences in surface appearance were related more to the cutting edge materials than the tool type. The field study results established a background database which helped the development of the laboratory cutting test, and thus were quite important.

Steel

Steel cutters, including tool steel and high speed steel, showed a common surface wear pattern: extensive grooving perpendicular to the cutting edge at both the rake and the clearance faces. Additionally, the worn surfaces appeared to be smoothed since the number of grinding marks was reduced. These surface appearances suggest that some sort of abrasive wear had occurred during wood cutting. However, it is impossible to know the source of abrasives based on these observations alone. Sizes of wear grooves varied, from submicron to 2 μm . Large grooves shown in Figures 4.4 and 4.5 appear to be caused by ploughing. The surfaces of tool steel canter and chipper knives appeared slightly different, with more wear grooves than those of steel band saws. This could be due to the fact that the knives were working under more aggressive conditions, often dealing with wood bark where highly abrasive substances were more likely to be present.

The degree of wear was prominent from a top view (Figure 4.3) and a cross-sectional view (Figure 4.15) of the cutting edges. A wide strip, or flat top band, on the worn cutting edges, compared with those of the sharpened ones, clearly indicates the occurrence of materials loss or wear at the cutting edges after wood cutting. No obvious sign of corrosion, such as round spots or stains, was observed. The effect of corrosion, nevertheless, can not be excluded on these observations alone.

Cemented Carbide

Wear, or blunting, of cemented carbide tips was observed by comparing the surfaces and cross-sections of as-sharpened and worn edges. The surfaces of as-sharpened cemented carbide cutting edges show the occurrence of fracture during the sharpening process, carbide particles at the fractured edges and grinding marks, or grooves (Figure 4.7). Unlike steel cutting edges, where wear grooves were present after woodcutting, no trace of abrasive wear grooves was observed on cemented carbide cutting edges. However, complete removal of grinding marks, a rounded rather than fractured edge, and rounded rather than angular carbide particles, indicate the occurrence of wear during woodcutting (Figures 4.7 vs 4.8). As shown in Figure 4.9, material was lost at the cutting edges during woodcutting, as indicated by the flat cutting edge being three times wider than that of an as-sharpened cutter.

A high magnification (5,000X) examination revealed areas of depressions on the worn surface (Figure 4.8b). An analysis of backscattering electron images, combined with topography and composition, indicated a high cobalt concentration in these areas. This suggests a preferential removal of the cobalt binder over the cemented carbide. There are two possible reasons for this: (a) cobalt was attacked preferentially by corrosion; or (b) cobalt was preferentially removed by abrasion. Bailey and his coworkers [43] proposed that preferential cobalt removal (by oak extractives) exposed carbide particles which were then easily removed by a mechanical action due to a weaker bond between carbides and cobalt binders. During the current examination, however,

carbide particles also suffered wear and were not fully exposed. This indicates that some other wear mechanisms were acting on both the carbide and the cobalt simultaneously. The flattened carbides and rounded corners suggest that each particle was worn by a progressive wearing process. Although acetic or other acids are mentioned in the literature, there is no direct experiment evidence to prove their existence, particularly in wood species such as fir, pine or hemlock. The element tungsten has an atomic number of 74, and its carbide, WC, is essentially a non-conductor, which means no galvanic cell (for corrosion to occur) can be established. The occurrence of corrosion, if any, is questionable. Abrasion was most likely responsible for the progressive wearing process. Cobalt binders suffered more wear than carbide particles by abrasion, possibly because the cobalt was softer than the WC carbide.

Stellite

Compared with the as-sharpened steel and cemented carbide edges, the as-sharpened Stellite edge had a much rougher profile (Figure 4.10a). Fractures and cracks in various orientations were observed along the Stellite edge (Figure 4.10b and c). This demonstrates the susceptibility of further fracture upon impact during woodcutting. A smoothed edge profile (Figure 4.11a) after woodcutting in comparison with that of as-sharpened (Figure 4.10a) and rounded particles (Figure 4.11c) indicate a process of material loss at the cutting edge. It is not known whether the smoothed edge profile was due to fracture and subsequent abrasive wear, or entirely abrasive wear or others. A small number of wear grooves, seen on the surfaces, do indicate the occurrence of abrasive wear. Again, no direct sign of corrosion, such as round spots, pits or stains was observed.

Two types of tipping processes, Vollmer-tipping and Wright-tipping, were found to produce different tip chemistries and microstructures. The former generates a much higher base metal dilution and has a dendritic structure associated with cracks. This suggests that the Vollmer-tipping may be inferior to the Wright-tipping, at least

technically, since the dendrites are detrimental to the mechanical properties. In practice, the relative cost has also to be considered in drawing comparison. Vollmer-tipping costs more than Wright-tipping.

Almost all the worn tools received had served their life prior to a resharpening. In future work, interrupted life cycle tests, would be very valuable in understanding the wear progression.

5.2 The Laboratory Woodcutting Test

The laboratory cutting test was felt to be valid based on a number of reasons. The 16-inch inserted tooth sawbody was driven by a 5 hp and 3480 rpm motor which yielded a cutting speed of 14,600 feet per minute (4,443 meters per minute). This cutting speed was in the range of most commercial practices. This is unlike those of most laboratory tests reported in the literature, often running at much lower speeds (up to ten times less).

There were four variables for the experiments: tool, wood feed rate (leads to various cutting tooth bites), wood species and conditions (moisture content). Previously, in most studies, either a single wood species or a single type of cutting edge material was used. The current experiments are more comprehensive involving four types of the most widely used tool materials in the woodworking industry and three wood species of major commercial importance in North America. Wood was cut at moisture contents ranging from 0% in the oven dried condition to 110% in the green condition. This range of moisture content covers that of most commercial practice in sawmills. Since green wood was cut in a natural state, the current test is fundamentally sound compared with other reported tests when acids, such as tannic acid or acidic acid, were sometimes artificially sprayed onto the cutting edge during cutting. Additionally, few published papers provide quantitative information on wood moisture content, tests on oven-dried wood have not been reported.

Although it is generally recommended that a low tooth bite be used for dry wood and a high tooth bite for green wood, no information about the moisture content of 'green' and 'dry' wood was available. The cutting tooth bite is expected to have a great effect on cutting edge wear. Instead of using a low tooth bite, a high tooth bite was used in cutting dry wood in the current experiment. It is believed, from an academic point of view, that only in this way can apples be compared with apples. A concern of thermal effects is one of the reasons for cutting dry wood at low tooth bites in industry. Since thermal effects were eliminated during dry wood cutting through air spray cooling, the high tooth bite (same as green wood cutting) used during lab-dry wood cutting is considered well justified.

Perhaps the most important fact validating the laboratory cutting test was that the surface appearance of cutting edges from the laboratory tests were similar to those observed on tools from the field. For example, round and smooth extreme edges, wear grooves and removal of grinding marks were observed on steel cutting edges from both the field and the laboratory after cutting fir. There were two extreme cases in the laboratory test, one with a very smooth surface and few grooves after cutting green fir, and one with a rough surface and a high density of wear grooves after cutting lab-dry fir. The surface appearances of steel tools from the field seem to suggest that the firs cut in the field were at neither oven-dry nor fresh green condition, with their moisture content close to but higher than that of the lab-dry fir in the current laboratory experiment.

Interrupted tests were performed to allow the examination of cutting edges at all stages of their lives. This makes this laboratory cutting test unique. Similar tests have not been reported before in the literature. Results showed that grinding burrs' breaking down from the cutting edges and subsequent edge fracture were the primary edge degradation mechanisms during tool early life. This information may be useful for improving grinding techniques and quality, and thus tool life.

The results from the current test form a matrix from which an expansion can be made on more wood species or cutting edge materials towards an overall understanding of edge degradation mechanisms.

5.3 Tool Wear Evaluation-Weight Loss, Edge Width Increase and Others

A big hurdle in studying tool wear is the lack of means to quantify wear. In the current work, both weight loss and edge width measurements were used to quantify edge wear. The cross-sectional examination, which should be the most reliable method of evaluating edge wear, was in agreement with the edge width measurement, but not with the weight loss measurement. This shows that edge width measurement was an effective method. However, results from the weight loss measurement did provide information on corrosion. Edge width measurements were useful particularly for interrupted tests where sample sectioning for cross-section examination was not feasible. Other methods, such as making a cast of edge and then measuring the edge recession were limited to edge corners while edge profiles often vary along the edges. Edge width increase measurement, on the other hand, provides wear information along the whole edge.

Figure 4.30a shows that HSS, carbide tipped and Stellite tipped bits, had greater weight losses than steel bits when cutting green and lab-dry fir. Even considering the density of these tool materials, the volume loss of the other materials would be still greater than that of the steel bit. This would suggest that the steel bit was more wear resistant than other, harder, materials. However, the weight loss from areas other than the extreme cutting edges needs to be considered as well. Figure 4.26a demonstrates that cutting fir soaked in deionized water caused greater weight loss to steel bits than either green or tap water soaked fir. In addition, cutting lab-dry fir with a deionized water spray resulted in the highest weight loss compared to all other conditions. It does not seem possible that deionized water would be more aggressive than tap water if aqueous corrosion is predominant. Tap water and deionized water differ primarily by the chloride concentration. The chloride concentration in tap and deionized water were tested by a commercial testing kit and the tap water chloride concentration was found to be 3 to 4 ppm while less than 0.1 ppm was detected in deionized water, a difference of more than 30 times. If weight loss was due to corrosion at the cutting edges during the cutting process, tap water with a greater chloride concentration would have caused more weight

losses than deionized water. The fact is that the bit sets used to cut fir at the two conditions were not immediately cleaned and weighed as other bit sets, but after an interval of about two weeks. The incident indicates that the high weight loss was most likely associated with areas other than the cutting edge. As there was no mechanical action after wood cutting, the weight loss must be due to corrosion, and, corrosion must have affected other areas of the bit other than the cutting edge. The edge width measurement was thus more specific than the weight loss measurement, as changes elsewhere on the bit did not affect the results.

5.4 Wear Mechanisms-Abrasion, Abrasives, Corrosion and Corrosives

Previous publications concerning wear mechanisms appear to indicate, overwhelmingly, the significance of corrosion. Other wear mechanisms, such as abrasion, are discussed in a limited number of reports, yet evidence appears limited. This creates confusion to sawmill operators as to what types of tools would be appropriate for a particular cutting operation. Results from the current laboratory woodcutting experiment indicate that either corrosion or abrasion could be dominant depending strongly on cutting edge materials, wood species and moisture content, while other mechanisms are minor.

Abrasion is a rather vague term. It is generally defined as the phenomena that occur when two bodies are in relative sliding contact with or without a third body in between, and one penetrates and scratches the other resulting in a loss of materials or wear. Grooving is generally taken to be an indication of abrasion or abrasive wear. In this experiment, the surface grooves observed on many tested bits, particularly steel bits used to cut lab-dry wood, clearly indicate abrasive wear. However, stains, round pits, higher weight loss of steel bits associated with high wood moisture content, and severe damage to the cemented carbide cutting green cedar, also suggested the influence of corrosion.

For example, consider the behavior of steel cutting edges. Abrasion was the dominant edge wear mechanism, except when cutting green cedar. Green wood caused less wear than dry wood, as indicated by the edge width measurement. This means that corrosion was not the dominant mechanism since corrosion should be proportional to the wood moisture content. The primary question concerns the nature of the abrasive, and secondarily, why there was a difference in results from different wood conditions (various moisture contents) using identical steel bits. Possible abrasive sources are foreign hard particles such as nails and rocks, extraneous materials within the wood, including both organic and inorganic crystals, such as calcium compounds and silica, metal particles from the tool materials, sawdust or any foreign particles in the air and the wood itself. In the current test series, the lumber was carefully examined before testing and no foreign particles were found. Microscopic examination of wood samples so far showed no sign of silica, or other particles/solid chemical compounds, in the tested wood. Foreign hard particles in the air would have the same effect as the particles from the tool materials. They could cause abrasive damage to the cutting tool yet the hypothesis that they play a primary abrasive role is questionable. It could be that a three-body wear process was significant during the initial cutting periods when fracture occurred quite often. However, as cutting continued to long distances and edge fracture had ceased, massive grooves were still observed (such as shown in Figure 4.39c and d). The argument that third party, or non-wood particles, if any existed, caused such a large amount of wear grooves is again in question.

Consider now the case of green fir versus dry fir. The primary difference between them is the moisture content. If any three body wear had occurred, the consequence of damage to the cutting edge should have been the same. As the result showed a significant difference of wear (based on both surface appearances and edge width increase) in cutting green and dry wood, the suggestion of wear by foreign particles as a primary mechanism should be ruled out. The only thing left is the wood itself. Water in wood may act as a lubricant, and the wood moisture content may affect the frictional force between the cutting edge and the wood. The effect of lubrication,

however, needs further experimental study.

Wood mechanical properties are strongly dependent on wood moisture contents. Table 5.1 lists selected mechanical properties of western red cedar, Douglas fir and Oregon white oak, the three wood species used. For almost every property listed in the table, dry wood has greater mechanical strength than green wood. Since cutting was done either parallel, or at a small acute angle to the grain (longitudinal or primary) direction, the properties of maximum crushing strength (compression parallel to grain), maximum shearing strength (shear parallel to grain) and maximum tensile strength (tension perpendicular to grain) are most relevant to the current wood cutting tests. The maximum crushing strength (compression parallel to grain) was 7,230 psi for dry fir and 3,780 psi for green fir, a difference of almost two. Taking red cedar as another example, the maximum crushing strength is 4,560 psi for dry cedar versus 2,770 psi for green cedar while maximum shearing strength is 990 psi for dry cedar versus 770 psi for green cedar. In fact, it is almost universally true for all wood species that mechanical properties of dry wood are superior to those of green wood. The strength difference between green and dry wood sometimes exceeds 100 percent. The combined effect from all relevant properties would be much more significant than a single property. Dry wood would therefore be expected to be much stronger in overall mechanical strength. A tool cutting lab-dry fir would, therefore, face greater resistance due to higher loading of the cutting edge, and thus more likelihood of 'wear', if any, than tools cutting green fir. Similarly, a tool cutting fir in green or dry condition would face greater resistance, and thus more wear, than that cutting cedar in green or dry condition respectively, since fir is mechanically stronger than cedar. The same hypothesis would hold true in comparing fir with oak. Figure 5.1 shows the wood maximum crushing strengths of the three wood species tested and compares with the edge width increases of the steel bits used to cut these woods. Except for green cedar, the two graphs clearly demonstrate the relationship between edge wear and wood strength, i.e., greater strength wood leads to greater edge wear. Considering also the higher density of surface wear grooves on steel bits associated with dry wood cutting than that of green wood cutting, the above facts would

suggest that the wood itself is the primary source of abrasive wear to the steel cutting tools.

Mechanically stronger wood led to greater wear to steel bits than mechanically weaker wood. To further verify this, wood species that are either weaker than cedar or stronger than oak should be tested. For example, balsam poplar, a cottonwood, has a maximum crushing strength of 1,690 psi in the green and 4,020 psi in the dry condition, versus 2,770 psi of green western red cedar and 4,560 psi of dry western red cedar. Cedar is among those wood species which have the lowest mechanical properties, and few selections of further weaker mechanical properties are available. In contrast, relatively more stronger wood species than Oregon white oak are available. Examples include red cherrybark, red scarlet, white live and swamp white, all within the oak family. Others such as bitternut pecan hickory, long leaf and splash pine are also good choices. However, one of the strongest wood species is black locust, with a maximum crushing strength of 6,800 psi in green and 10,180 psi in dry, compared with Oregon white oak of 3,560 psi in green and 7,440 in dry condition. Some imported species offer even higher mechanical properties, such as kaneelhart (botanical name *Licaria* spp.) with a maximum crushing strength of 17,400 psi (dry) [3]. Tropical wood species, particularly any wood supposedly containing high concentrations of silica, are also good choices for laboratory cutting tests.

Current cutting tests were performed closely parallel to the grain direction. Due to the heterogeneous nature of wood, cutting perpendicular to the grain directions (cross-cutting) may generate further evidence of the effect of wood mechanical properties on cutting edge performance. In cutting parallel to the grains (known as $90^\circ - 0^\circ$ cutting in wood machining industry [1]), resistance to the cutting edge depends on one or more of the following wood mechanical properties: compression parallel to grain - maximum crushing strength, shear parallel to grain - shearing strength and tension perpendicular to grain - maximum tensile strength. During cross-cutting (known as 0° to 90° cutting), however, other wood mechanical properties may have some relevance: static bending - modulus of rupture, compression perpendicular to grain - fiber stress at proportional

limit and side hardness - load perpendicular to grain. Because loading to the cutting edge is a mixed effect of wood mechanical properties, it is hard to predict the consequential difference between cross-cutting and cutting parallel to grains.

When a very soft material interacts with a relatively hard one, it is often the soft one that loses material by wear. Direct evidence showing that soft abrasives cause wear to a hard counterpart is rare. However, consider the result from the dry abrasive rubber wheel test. The small, 2 mm in diameter, walnut shells caused massive wear grooves on the AISI 1065 steel sample. Since the walnut shells were dry (lab dry), it was not possible for corrosion to be a factor. The walnut shells were from a commercial source and very clean. No foreign abrasive particles were found and the walnut shell was the only possible abrasive. The steel sample was tested in the annealed condition with a hardness of about HRC 20. The microhardness of the walnut shell was also tested for comparison. Samples were mounted in an epoxy, ground and then tested using the lowest indentation of 10 g from a Knoop microhardness testing machine. After converting the hardness values from both the steel sample and the walnut shell to the same scale (approximately in Knoop), the walnut shell, though among the hardest woods available, was found to have a hardness of only 4% of the steel sample. This raises the question regarding the fundamentals of wear by soft abrasives against a hard counterpart. Although wood itself is very soft, impact momentum due to the high moving speed at cutting edges could be sufficient to cause edge surface deformation at possibly atomic levels. Repeated interactions, or fatigue, may lead to the accumulations of damage which results in, eventually, wear.

Stains and round pits, as observed on some bit cutting edges, are generally taken as signs of corrosion. Green or wet wood caused a greater weight loss but often with a lower edge width increase than lab-dry wood, with the exception of green cedar and oak. This would suggest that the higher weight loss from cutting wood with high moisture content was due to material loss at locations other than the extreme cutting edge. Since there is no mechanical interaction nor any contact between wood and the bit at areas other than the cutting edge, the most probable explanation for the higher weight

loss associated with high moisture content wood (green and wet) is due to general corrosion. At a similar cutting distance, 300,000 inches, cutting green fir removed almost all the grinding marks on the rake face near the cutting edge of a steel bit while cutting lab-dry fir did not. This appears to indicate that additional degradation mechanism other than abrasion is operating when cutting green fir. Corrosion is the most likely candidate. However, considering the greater edge width increase cutting dry wood than cutting green wood, it would appear that the magnitude of corrosion at the extreme cutting edge with respect to abrasion is small.

Tap water soaked fir caused greater edge width increase to steel bits than deionized water, suggesting the possibility of corrosion damage to the cutting edges. This seems reasonable considering the fact that tap water contains more chloride ions than deionized water. It was also found that soaking fir for three weeks does not change the chloride concentration in the soaking solution, with either tap water or deionized water.

Western red cedar is known for its high corrosivity and complexity of chemistry [15,17,66,84,98], and organic acids such as acetic acid and polyphenolic extractives are often blamed for its high corrosivity. However, the exact mechanism or chemical reaction is not clear. The cemented carbide bit behaved very well in terms of wear resistance compared with steel bits cutting lab-dry wood (Figure 4.30). However, the cutting edge was severely damaged after cutting green cedar and oak. Cutting edge surface appearances clearly demonstrated that corrosion (or chemical attack) was responsible for the greatest edge width increase or wear of cemented carbide cutting green cedar (Figure 4.46). Corrosive attack on carbide cutting edges was observed as the cobalt binder was preferentially removed and thus exposing the sharp angular carbides. This type of surface appearance was very similar to that observed by Kirbach [84] and Bailey [43]. With reduced matrix support, carbide particles are susceptible to removal. Green oak resulted in a similar corrosion effect on carbide tips, though to a lesser degree than green cedar. In these two specific situations, corrosion was the primary source of edge degradation. The stains or deposits observed on steel surfaces

(Figure 4.41), together with the higher edge width increase after cutting green cedar than cutting dry cedar, suggest that corrosion was also significant to the steel cutters during green cedar cutting.

Although green cedar caused greater edge width increase and thus more wear than lab-dry cedar on steel bits, it still caused less wear than lab-dry fir and lab-dry oak. Oven-dry fir caused more wear than lab-dry fir, as shown in Figure 4.28. Since oven-dry fir has almost zero moisture content, the corrosion effect would be eliminated completely, and abrasion should, therefore, play the dominant role.

Results from the laboratory cutting test demonstrate how wood moisture content may affect tool wear. For certain woods, such as fir, the higher the wood moisture content, the less the tool wear (true for all four types of tools tested). For others with more complex chemistries, such as cedar, the opposite may be true. The wood moisture content serves as a 'softener' (mechanically) in the first situation, and as an 'activator' (chemically) in the latter case. Again, a broader base of wood species is recommended for future experiments to further verify this.

5.5 Steel vs HSS vs Carbide vs Stellite

Figure 4.30b is a summary of the laboratory cutting test which shows a comparison of four types of bits cutting three wood species in green and lab-dry conditions. Overall, the Stellite bit appeared to offer superior performance based on its very low edge width increase. Except for when cutting green cedar and green oak, the cemented carbide had equivalent wear resistance to Stellite. The cobalt-based cemented carbide tools should be definitely avoided for cutting green cedar and oak. The high speed steel bit was only used to cut green and lab-dry fir, and showed a better performance than the steel bit, yet was worse than the cemented carbide and Stellite. The steel bit demonstrated different behavior when being used to cut fir, cedar and oak in green and dry conditions. Experimental results and discussion above indicates that abrasion was often responsible for the steel bit edge degradation, and that wood is the

abrasive. The steel bit should not be used to cut high density or potentially abrasive wood, such as oak. However, the steel bit offered competitive performance over cobalt based cemented carbide when cutting corrosive wood species such as green cedar, considering also economic aspects. The high abrasion resistance cemented carbide tool, however, should be good at cutting high density and abrasive wood, and in particular, would offer maximum performance when wood is cut under dry conditions.

Although the Stellite had a lower carbide area fraction than cemented carbide and an equivalent microhardness to that of steel, it demonstrated a far better performance than both the high speed steel and the cemented carbide. Possible factors for this difference should be traced back to carbide composition, morphology and distribution, as well as carbide and matrix (or binder) bonding strength. In the cemented carbide, WC (Vickers hardness about 2,100) is the primary carbide, mostly in angular shapes separated by the cobalt binder (Figure 4.20). Similarly, yet slightly different, a variety of carbides exist in high speed steel, including M_6C , $M_{23}C_6$, M_2C and MC types. The M could be either W, Mo, Cr, V or combined. There are primary carbide particles, large in sizes and separated in the matrix, as shown in Figure 4.19, and secondary carbide particles which precipitate during tempering in the high speed steel. The secondary carbides are small in size and can only be seen at high magnification. The cobalt-chromium alloy, Stellite, has hard particles, M_7C_3 and M_6C (Vickers hardness about 1,600 for Cr_7C_3), dispersed in the cobalt rich matrix. As shown in Figures 4.19 to 4.21, the morphology and distribution of carbides in Stellite is quite different from those of the high speed steel and the cemented carbide. Instead of being separated by the binder, most carbides in Stellite are loosely connected in the form of arrays, appearing as a skeletal structure. Because these carbides are connected, they are expected to offer more rigidity or support, and thus resistance to load or pressure than separated carbides. Antony [30] showed that the abrasive wear resistance measured in a dry sand rubber wheel test dropped by 5 to 10 times when the carbide morphology was changed to a uniform distribution of relatively coarse M_7C_3 carbides in a fine-grained matrix from a network-like structure, even with the same composition. Strain hardening

is possibly another factor contributing to the Stellite performance. Pure cobalt exists in two allotropes, a high temperature face-centered-cubic (FCC, α) allotrope and a low temperature hexagonal-close-packed (HCP, ϵ) allotrope. The α - ϵ allotropic transformation temperature in pure cobalt is 417 °C. In practice, most Co-Cr-W-C Stellite matrix alloys exhibit a FCC structure implying that the alloys are generally used in a metastable condition. Low temperature deformation can induce a martensitic α to ϵ transformation. This strain induced transformation absorbs energy and increases the rate of work hardening [30].

The Stellite showed little sign of wear based on both surface appearance and edge width increase measurement after cutting green cedar. EDX analysis on the Stellite indicated that the Stellite had a chromium concentration of about 30 wt% overall, and about 19 wt% in the matrix. This matrix chromium concentration is higher than that in a typical stainless steel, about 18 wt%. This would suggest that the Stellite should perform well in a corrosive environment such as cutting green cedar. However, wear had certainly occurred on the Stellite surface when the green oak was cut, as shown in Figure 4.48. The matrix was apparently preferentially removed leaving carbides exposed. If corrosion were the only, or the primary edge degradation mechanism, the green cedar might have caused at least equal, if not more, wear as the green oak. Green cedar is believed to be more complex in chemistry and generally more corrosive than green oak. One possible explanation is that green oak is mechanically stronger, and potentially more abrasive, than green cedar. However, it can not be ruled out that different substances may exist in green cedar and oak which were responsible for the attack of green cedar on the cemented carbide and green oak on the Stellite. The wear process of Stellite cutting green oak needs to be further studied by testing to longer distances.

The difference of edge width increases between the cemented carbide and the Stellite after cutting lab-dry wood was very small after 100,000 inches cutting distance, which was likely due to data scatter. Comparison of the two cutting lab-dry wood should only be made at longer cutting distances. Fundamental studies on Stellite alloys, to

determine the effect of chemistry and microstructure, are highly recommended for future work, and should be useful in developing alternative, economically more favorable materials.

5.6 Thermal Effects and Edge Fracture

Microstructural change was not observed at the edges of worn steel band saw teeth in the field study. Additionally, the microhardness near the extreme cutting edges (about 20 μm from the extreme edge) was greater, instead of lower, than at areas 5 and 10 mm away from them in both worn and as-sharpened steel tools. These facts indicate that, thermal effects, if any, were not significant in the wear of the examined cutting tools. The greater microhardness near the extreme cutting edges was more likely due to the sharpening process, however, this may need further study.

Thermal effects were also studied by measuring the microhardness at edge cross-sections of steel bits before and after laboratory cutting tests. Microhardness drops were found near the extreme cutting edges (about 20 μm from the extreme edge) of steel bits during lab-dry fir cutting without air cooling, and particular when exposed to the most aggressive cutting condition, i.e., cutting lab-dry fir with a high density of knots and without air cooling. Since no significant hardness decreases were observed in other testing conditions such as green wood cutting, thermal effects, or cutting edge softening, is not believed to play a major role in edge deterioration. However, this conclusion may not be extended into wood composite cutting, such as when particle board is cut at high speed and without air cooling, as in the tests of Banshoya [45] and Stewart [133].

Fracture was observed at the edges of steel bits during an initial period of cutting. Grinding burrs were observed at the edges of as-sharpened steel bits, and were found to initiate edge fracture during this period. However, fracture was not observed as cutting extended to long distances. For carbides, edge corner fracture was observed during the laboratory cutting test only on a few bits among the 6 sets (a total of 42) of cemented carbide bits tested. Although the as-sharpened cutting edges of Stellite from the field

showed very rough profiles and numerous cracks along the edges, direct evidence of fracture was not observed. For the cutting edge of Stellite tested in the laboratory cutting test, no fracture was observed. Fracture is not believed to have a dominant role in edge degradation.

5.7 Effect of Grinding (Sharpening)

No grinding information is available for any of the commercial tools/bits used. It is believed [150,151] that different grinding methods commercially available in industry have an impact on the degree of edge sharpness or dullness for any length of cutting. The cutting performance obtained with these methods has been found to differ widely, and is believed to be one of the reasons for mill to mill performance variations [151]. The variables that are known or can be expected to significantly influence edge sharpness and surface finish of a tool are type of abrasive material, type and size of grit, concentration of abrasive material, type of wheel bond, wheel type (cup or periphery wheel), grinding pressure, grinding speed, direction and speed of feeding, wheel translation (retracting wheel), vibration, grinding depth, and grinding condition (dry or wet grinding) [150].

The current experiments demonstrate some effect of grinding on the initial edge deterioration process. For example, grinding burrs or edges appear to break easily along the existing cracks from the grinding process, which is demonstrated on the cutting edges of Stellite in the field test and steel bits in the laboratory cutting test. Specifically, cracks parallel to the edges of the steel bits tested would suggest that grinding parallel to the edge should be avoided. This observation is in agreement with the result obtained by Kirbach and Bonac [150]. Their experiment results show that the most suitable grinding direction for practical applications is at an angle of 45° or larger to the cutting edge. The current experiment indicates that grinding can affect the initial cutting condition and potentially, the life of a cutting edge. In the laboratory cutting test, the initial period was observed to be very short compared with the overall bit life. After this initial edge

breakage, or 'run-in' period, the effect of grinding is significantly reduced and does not alter the fundamental wear mechanisms.

5.8 Wood and Tool Interaction

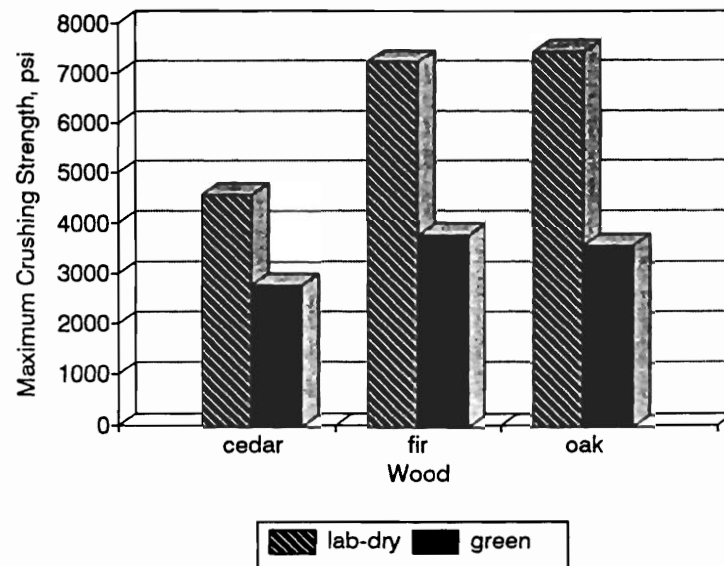
The surface appearances of both saw kerf and wood chips (fir only) were examined and found to be quite different between green and dry conditions. The examinations offered information on the interaction between the tool and the wood, and seem to further back up the suggestion that wood is the primary source of steel tool wear. Cutting is believed to be primarily the shearing of individual fiber (breakdown) in the green condition, and fiber debonding at fiber-fiber interface (interfiber breakdown) and fiber fracture in groups in the dry condition. One possible explanation is that each individual fiber is stronger in the dry condition than in the green condition. The next question which arises then is, why does the dry wood fiber fail at the fiber interface while the green wood fiber does not. To help answer this, sections of dry and green fir were examined. Numerous cracks were found to be present along fiber interfaces in the dry condition, and yet almost none were observed in the green state. The cracks are possibly due to the shrinkage of the wood cells and the consequences of residual stress release caused by drying. Small samples were cut from the bulk wood and then examined in the SEM. The crack surface was found to be mostly at the fiber interface (Figure 5.2). This would indicate that the fiber interface is the weakest point in the wood structure. Existing cracks would then extend in favorable conditions and thus act as crack initiation points during the dry wood cutting process. The consequence was that groups of fibers were pulled away from the fiber interfaces by the cutting tools, bent and eventually fractured. Apparently, cutting along a different orientation, such as with a cross-cut, may generate a different tool-wood interaction compared with the cutting parallel to the wood grains. Only fir chips and sawkerfs were examined in this study, surface and microstructural examination of cedar, oak or any wood to be tested, are also recommended for the future.

Wood fiber walls are rich in cellulose, with hemicellulose molecules orientated in various directions and encrusted within lignin. The fiber interfaces (or middle lamella) are, on the other hand, rich in lignin. The dry wood fiber behavior seems to suggest that cellulose and hemicellulose are stronger than lignin. Considering the wood as a natural composite, cellulose and hemicellulose as the reinforced fibers while lignin as the binder, the binder is apparently the weakest part (mechanically).

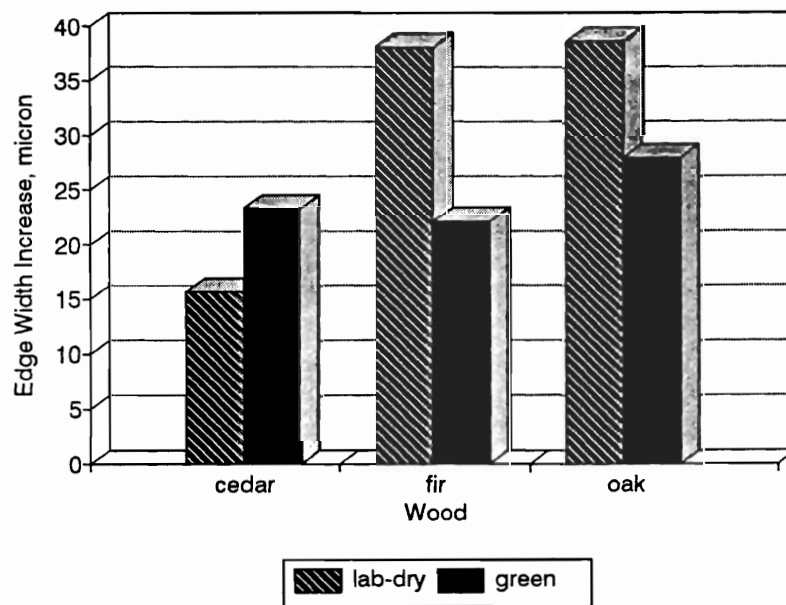
5.9 Tooth Bite Effect

A higher cutting tooth bite led to a greater edge width increase to the steel bit than a lower tooth bite, as shown in Figure 4.29b, after cutting lab-dry fir. There are two possible reasons. A higher feed rate (leading to a higher tooth bite) would generate a greater impact momentum or cutting force upon the cutting edge than a lower feed rate (leading to a lower tooth bite). Secondly, a higher tooth bite means that a thicker chip was cut during each interaction between the cutting edge and the wood. This would lead to a greater pressure and again a higher cutting force on the cutting edge since a larger volume of wood has to be pressed. In future experiments, it would be useful to monitor the cutting force variations for different cutting tooth bites. Additionally, the power consumption increase may also be used as an indicator of cutting edge-wood interaction.

Table 5.1 Selected mechanical properties of tested woods [3]						
Wood Properties	Western red cedar		Douglas fir		Oregon white oak	
	green	dry	green	dry	green	dry
Static bending Modulus of rupture (psi)	5200	7500	7700	12400	8300	15200
Compression $\parallel$ to grain maximum crushing strength (psi)	2770	4560	3780	7230	3560	7440
Compression $\perp$ to grain fiber stress at proportional limit (psi)	240	460	380	800	670	1070
Shear $\parallel$ to grain maximum shearing strength (psi)	770	990	900	1130	1250	2000
Tension $\perp$ to grain maximum tensile strength (psi)	230	220	300	340	770	800
Side hardness load $\perp$ to grain (lb)	260	350	500	710	1060	1360
Specific Gravity	0.31	0.32	0.45	0.48	0.60	0.68



(a)



(b)

Figure 5.1 Maximum crushing strength (compression parallel to wood grains) of western red cedar, Douglas fir and Oregon white oak under green and dry conditions (a), and edge width increase of steel bits cutting these woods (b).

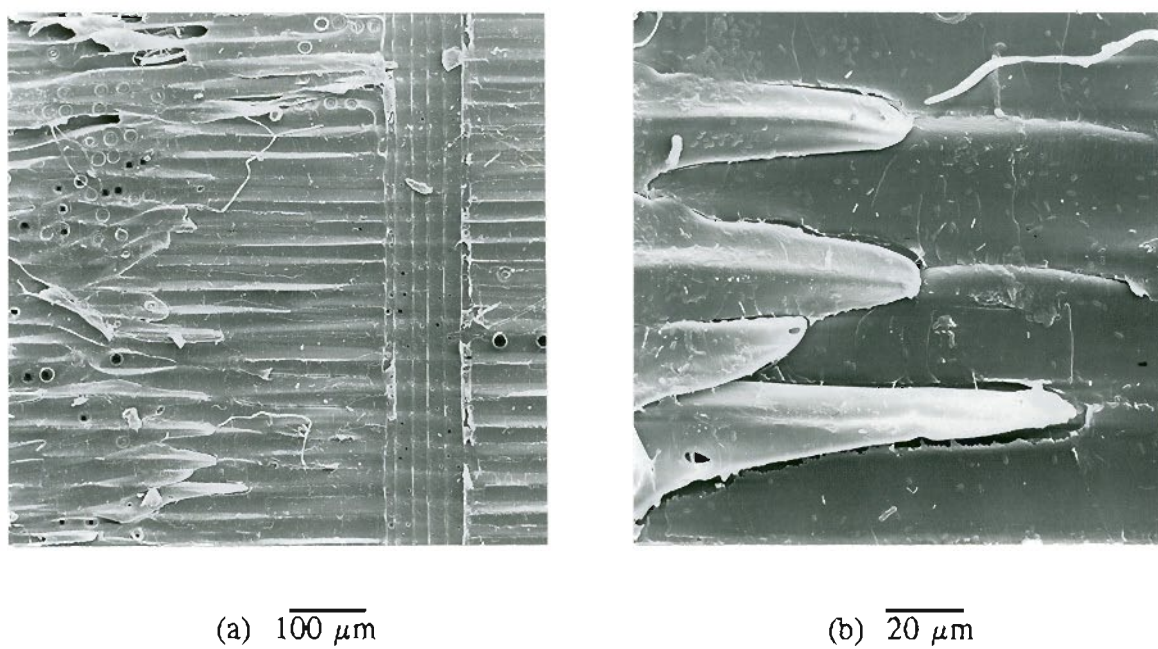


Figure 5.2 SEM micrographs of fir at naturally cracked surface showing interfiber breakage.

CHAPTER 6. CONCLUSIONS

1. Surface topography of field-used commercial tool cutting edges is more related to the cutting edge material than to the tool type.
2. The laboratory wood cutting test provides cutting conditions similar to those encountered in the field.
3. Cutting edge width increase is the most effective and reliable method of quantifying wear.
4. Either abrasion or corrosion could be the dominant edge wear mechanism depending on the wood species, moisture content (green or dry) and cutting edge materials.
5. Stellite is superior to steel, high speed steel and cemented carbide in wear resistance, especially under corrosive cutting conditions.
6. Fracture and thermal effects have little influence on the overall cutting edge degradation.
7. A high cutting tooth bite results in a greater edge wear than a low cutting tooth bite to steel cutting edges.
8. Green fir fibers fracture individually and dry fir fibers break in groups.

9. A soft dry abrasive (walnut shells) can cause scratching grooves to a hard steel surface.

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