INVESTIGATION OF WEAR BEHAVIOR OF CUTTING TOOL INSERT FOR Ti-ALLOY MACHINING USING CARBON COATED Al_2O_3 WITH SiC SANDBLASTING AND HF ACID PRETREATMENT

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ABSTRACT

In machining process, pretreatment of cutting tool surface helped to increase wear resistance of cutting tool. The tool insert used was carbon coated with Hydrofluoric acid (HF) and sand blasting pretreatment, while the machining workpiece was Titanium alloy. Sandblasting was conducted using Silicon Carbide (SiC) particles with 300 grit size. Carbon coating was deposited on the tool insert substrates by using Physical Vapor Deposition (PVD) technique. Morphological observation was conducted using optical microscope to observe the micrographs of tool insert surface in as-received condition and after pretreatment and to measure length of flank wear on the substrate after machining titanium. Parameters used for machining were cutting speed of 100 m/min, depth cut of 0.25 mm and feed rate of 0.1 mm/rev. The substrate surface after coating by different surface pretreatment was measured using Vickers Hardness machine. From the morphological observation, the as-received micrograph has a continuous 45° direction from the horizontal line. Sandblasted substrate showed white spots on the tool insert surface. Surface pretreatment combination with Hydrofluoric acid showed a non-uniform surface with a peak and valley image. Alumina coated with sand blast and hydrofluoric acid pretreatment was found to increase wear resistance by having the shortest wear length of 0.336 mm after machining a titanium alloy rod.

ABSTRAK

Dalam proses pemesinan, prarawatan permukaan alat pemotong membantu meningkatkan daya tahan haus memotong alat.Alat memasukkan digunakan adalah karbon bersalut dengan asid hidrofluorik (HF) dan prarawatan pasir yang letupan, sementara bahan kerja pemesinan aloi Titanium. Pembagasan pasir telah dijalankan menggunakan Silikon karbida (SiC) zarah dengan kersik saiz 300. Salutan karbon telah didepositkan pada substrat masukkan alat dengan menggunakan Pemendapan Wap Fizikal (PVD) teknik. Pemerhatian morfologi telah dijalankan menggunakan mikroskop optik untuk mematuhi mikrograf permukaan masukkan alat dalam keadaan seperti yang diterima dan selepas prarawatan dan untuk mengukur panjang haus rusuk atas substrat selepas titanium pemesinan. Parameter yang digunakan untuk pemesinan kelajuan pemotongan sebanyak 100 m/min, kedalaman pemotongan 0.25 mm dan kadar suapan 0.1 mm/putaran. Permukaan substrat selepas salutan dengan prarawatan permukaan yang berbeza telah diukur dengan menggunakan mesin Kekerasan Vickers. Dari pemerhatian morfologi, Mikrograf yang diterima sebagai mempunyai hala tuju berterusan 45° dari garis mendatar. Substrat sandblasted menunjukkan bintik putih pada permukaan masukkan alat. Permukaan gabungan prarawatan dengan asid hidrofluorik menunjukkan permukaan yang tidak seragam dengan imej puncak dan lembah. Bersalut alumina dengan letupan pasir dan prarawatan asid hidrofluorik telah didapati untuk meningkatkan rintangan haus dengan mempunyai haus panjang yang terpendek 0.336 mm selepas pemesinan rod aloi titanium.

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CVD	Chemical Vapor Deposition
d	Depth of Cut, mm
DOE	Design of Experiment
f	Feed Rate, mm/rev
HF	Hydrofluoric acid
Hv	Vickers hardness
mm	milimeter
PVD	Physical Vapor Deposition
SiC	Silicon Carbide
V_B	Flank wear, mm
V_C	Cutting Speed, m/min

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CHAPTER 1

INTRODUCTION

1.1 Background of study

In the last few decades, there have been great advancements in the developments of cutting tools, including coated carbides, ceramics and cubic boron nitride and polycrystalline diamond. Improvement in materials by hard Chemical Vapor Deposition (CVD) and Physical Vapor Deposition (PVD) coatings are widely used today in the metal-working industrial and provide the best alternative for most machining operations.

The revolution of coating technology into cutting tool still continuous by researchers can give a lot of improvement in their mechanical properties and wear resistance. Also, to increase the life and cutting speed ability of the cutting tools considerably. To achieve the machining performance of tool coating, the tool's material must have high strength at elevated temperature, good oxidation resistant, low coefficient of thermal, resistant to wear, chemical reactance resistance and high conductivity and can withstand for a long time (Kalpakjian and Schmid S.R, 2001).

Normally, the flank wear in tools initially occurs due to abrasion and as the wear process progresses, the temperature increases causing diffusion to take place. Abrasive wear may occur in metal cutting tool even there are many hard abrasive particles present in metals, especially in steel.

In this study, an improvement of Aluminum Oxide (Al_2O_3) cutting tool was conducted. The Aluminum Oxide(Al_2O_3) tool insert was pretreated by Silica Carbide (SiC) sand blasting and Hydrofluoric acid etching. Tool inserts was carbon coated using Physical Vapor Deposition (PVD) technique. The coated tool insets were used to machine titanium alloy workpiece. Wear performance of the tool inserts was analyzed and compared with the uncoated Aluminum Oxide.

1.2 Problem statement

Machining of titanium alloys requires cutting forces only slightly higher than those needed to machine steel, but these alloys have metallurgical characteristics that make them somewhat more difficult to machine than steels of equivalent hardness.

Nowadays, hard coatings are commonly used to increase the wear resistance of cutting tools in metal machining (M. Van Stappen, M. Kerkhofs, L.M. Stals, C. Quaeyhaegens, 1995).

Uncoated cutting tool caused higher wear rate in machining process. Hence, in order to increase the wear resistance or tool life of that cutting tool, coating is necessary.

Cutting tools performance depends on surface pretreatment and coating technique. In addition, to further increase the properties of coated material, the substrate (cutting tool) can be sand blasted by silicon carbide. Hydrofluoric acid used for give strong coating adhesion with carbon coating. Besides that, hydrofluoric acid increase the substrate surface roughness cutting tool providing large surface area.

1.3 Objective of the Study

The objectives of this research were:

1. To investigate the effectiveness of PVD coating, sand blasting and acid etching on alumina cutting tool insert.
2. To quantify the effect of alumina insert wear resistance in machining of titanium alloy rod bar.

1.4 Scopes of the Study

The scopes of this study were limited as follows:

1. Alumina was used as cutting tool insert.
2. Surface pretreatment of alumina cutting tool insert using:
    - Sand blasting using silicon carbide
    - Acid etching using hydrofluoric acid (HF)
3. Conduct turning operation for 3 mm diameter titanium alloy rod bar work piece
4. Conduct characterization on cutting tool insert for morphology analysis, Vickers hardness and tool flank wear

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Background information was emphasizes about cutting tools material, ceramic, aluminum oxide, carbon coating, tool wear, pretreatment, sand blasting, Hydrofluoric acid, coating, PVD technique, machine turning and work piece titanium to highlight some of what has occurred in tool wear studies.

2.2 Cutting Tool Material

The cutting tool must meet several requirements, depending upon the cutting conditions and the work piece material (Inspektor, 1994). The tool has to have high hardness and high wear resistance at the metal cutting temperature. It also has to be tough, chemically stable over a wide range of temperatures and insert to the work piece material. It is difficult to satisfy all the demands in one material, and thus successful tools are often made of hard coatings on suitable substrate (Safari, 2010)

2.2.1 Tool Material for Precision Machining

The cutting tool materials must possess a number of important properties to avoid excessive wear, fracture failure and high temperatures in cutting (Valery Marinov). The following characteristics are essential for cutting materials to withstand the heavy conditions of the cutting process and to produce high quality and economical parts:

- Hardness: at elevated temperatures (so-called hot hardness) so that hardness and strength of the tool edge are maintained in high cutting temperatures.
- Toughness: ability of the material to absorb energy without failing. Cutting if often
  Accompanied by impact forces especially if cutting is interrupted, and cutting tool may fail very soon if it is not strong enough.
- Wear resistance: although there is a strong correlation between hot hardness and wear resistance, later depends on more than just hot hardness. Other important characteristics include surface finish on the tool, chemical inertness of the tool material with respect to the work material, and thermal conductivity of the tool material, which affects the maximum value of the cutting temperature at tool-chip interface.

A comparison between hot hardness, wear resistance and toughness is shown in Table 2.1 (Izman Venkatesh, V C Venkatesh, 2007). It indicates that single-crystal diamond which is widely used for ultra-precision applications has the highest hot hardness and wear resistance, but it lacks toughness in terms of which it is quite surprising that this earliest tool material still holds an edge over other materials (Anon, 2009). A clearer picture can be obtained from Table 2.2 that indicates the relative values of several properties for each of the cutting tool materials of the major classes of tool materials, carbon steels, high speed steels and cast alloys are seldom used in precision applications. Carbon steel is the earliest tool material that was widely used for making drills, taps, reamers, and broaches. The use of carbon steel is restricted to low cutting speeds and temperatures.

Table 2.1: Comparison between hot hardness, wear resistance and toughness for cutting tool

Source: Anon, 2009

Hot hardness ↓	Wear resistance ↓		Toughness ↑
		1. Carbon steels	
		2. High-speed steels	
		3. Cast alloys	
		4. Tungsten Carbides	
		5. Cermets	
		6. Titanium carbides	
		7. Ceramics	
		8. Polycrystalline diamond and cubic boron nitride	
		9. Single-crystal diamond	

Table 2.2: Properties of cutting tool materials

Source: Anon, 2009

Property	High-speed steel	Cast alloys	Tungsten carbides	Titanium carbide	Ceramics	Cubic boron nitride	Single-crystal diamond
Hardness	83–86 HRA	82–84 HRA	90–95 HRA	91–93 HRA	91–95 HRA	4000–5000 HK	7000–8000 HK
Compressive strength, MPa	4100–4500	1500–2300	4100–5850	3100–3850	2750–4500	6900	6900
Transverse rupture strength, MPa	2400–4800	1380–2050	1050–2600	1380–1900	345–950	700	1350
Impact strength, J	1.35–8	0.34–1.25	0.34–1.35	0.79–1.24	< 0.1	< 0.5	< 0.2
Modulus of elasticity, GPa	200	–	520–690	310–450	310–410	850	820–1050
Density, kg/m^3	8600	8000–8700	10,000–15,000	5500–5800	4000–4500	3500	3500
Volume of hard phase (%)	7–15	10–20	70–90	–	100	95	95
Melting of decomposition temperature, °C	1300	–	1400	1400	2000	1300	700
Thermal conductivity, W/mK	30–50	–	42–125	17	29	13	500–2000
Coefficient of thermal expansion, × 10^{-6}/°C	12	–	4–6.5	7.5–9	6–8.5	4.8	1.5–4.8

2.2.2 Ceramic

Ceramic tools cannot compete favorably with the best grades of carbides, and it was not until the 1950s, when new techniques for their manufacture were developed, that the significant application of oxide ceramic tools to machining was made (Anon. 2009). Ceramics are artificial man-made products obtained by sintering pure alumina Al_2O_3 at a high temperature (1,500–1,900 °C) but below its melting point at a pressure of 150–200 atm.

The optimum cutting performance is obtained using pure oxide ceramic tools with as small a grain size as possible. However, the strength value is affected, as the maintenance of smaller grains would mean lowering the firing time or temperature, which can thus give rise to a decrease in the density of the tool. The crystal growth of pure oxide ceramics can be affected by the addition of grain growth inhibitors such as magnesium oxide which keep the grain size of sintered pure oxide at low values of 5–10 μm. Recently, ceramic tools with an average grain size as low as 3–4 μm have been manufactured.

Density is closely related to the method of manufacture. From theoretical calculations based on X-ray data of the crystal structure of alpha-alumina, the theoretical density was calculated to be 3.90, and some data yielded a value as high as 4.00. The porosity of pure oxide ceramic tools, whether hot sintered or cold sintered, depends on the firing temperature. The higher the firing temperature, the denser is the product obtained, but a higher firing temperature necessitates a longer firing time, which in turn results in an accelerated grain growth. Hence, it becomes essential to use grain growth inhibitors such as magnesium oxide. Porosity and therefore density have a considerable influence on tool life. The lower the porosity, the higher is the tool life.

Oxide ceramics retain their hardness at higher temperatures as compared with other materials. Ceramics have a very low tensile strength of 370–600 N/mm2. Hence, they need to be supported on steel shanks as in the case of carbides, and the shank design detailed earlier is also valid for these tools. Because of its high compressive strength and low bending strength, negative rakes for ceramic tools are essential, except in finishing operations of plastic and graphite where a positive rake is used. Ceramics have a low coefficient of thermal expansion so that heat is conducted to a great depth in the tool as in the case of High Speed Steel. tools. This property has the further advantage that thermal shock is reduced. But the low coefficient of expansion gives rise to difficulties when brazing tool bits on to steel shanks and these difficulties have largely contributed to the development of clamped tools not only for ceramic tools but for carbide tools as well. Oxide ceramics have two other important chemical properties, namely, (a) a high resistance to oxidation and (b) a low affinity for most metals, which reduce the tendency to adhesion and also bring about reduction in friction. Resistance to cratering is therefore high.

Oxide ceramics however function well only at high cutting speeds preferably above 500 m/min. The rate of chip removal is high, necessitating machine tools of a larger power capacity and a high spindle rotation, which in turn calls for a very high rigidity. Further modifications are necessary, such as a variable speed for the gradual increase in speed, and a variable feed to minimize the shock while the tool enters and leaves the work piece

2.2.3 Aluminum Oxide

Aluminum oxide is a chemical compound of aluminum and oxygen with the chemical formula Al_2O_3 .Alumina is the most cost effective and widely used material in the family of engineering ceramics. The raw materials from which this high performance technical grade ceramic is made are readily available and reasonably priced, resulting in good value for the cost in fabricated alumina shapes. With an excellent combination of properties and an attractive price, it is no surprise that fine grain technical grade alumina has a very wide range of applications. Aluminum oxide, commonly referred to as alumina, possesses strong ionic interatomic bonding giving rise to its desirable material characteristics. It can exist in several crystalline phases which all revert to the most stable hexagonal alpha phase at elevated temperatures. This is the phase of particular interest for structural applications and the material available from Accuratus (I.S. Ahmed Farag, 2004).

Key Properties

- Hard, wear-resistant
- Excellent dielectric properties from DC to GHz frequencies

- Resists strong acid and alkali attack at elevated temperatures
- Good thermal conductivity
- Excellent size and shape capability
- High strength and stiffness
- Available in purity ranges from 94%, an easily metallizable composition, to 99.5% for the most demanding high temperature applications.

Alpha phase alumina is the strongest and stiffest of the oxide ceramics. Its high hardness, excellent dielectric properties, refractoriness and good thermal properties make it the material of choice for a wide range of applications.

High purity alumina is usable in both oxidizing and reducing atmospheres to 1925°C.Weight loss in vacuum ranges from 10–7 to 10–6 g/cm2.sec over a temperature range of 1700° to 2000°C. It resists attack by all gases except wet fluorine and is resistant to all common reagents except hydrofluoric acid and phosphoric acid. Elevated temperature attack occurs in the presence of alkali metal vapors particularly at lower purity levels.

The composition of the ceramic body can be changed to enhance particular desirable material characteristics. An example would be additions of chrome oxide or manganese oxide to improve hardness and change color. Other additions can be made to improve the ease and consistency of metal films fired to the ceramic for subsequent brazed and soldered assembly.

2.3 Tool Wear

Wear resistance is the ability of the coating to protect against abrasion. Although a material may not be hard, elements and processes added during production may aid in the breakdown of cutting edges or forming lobes. The rate of tool wear depends on tool and work piece materials, tool shape, process parameters and the machine tool itself (Kalpakjian and Schmid, 2001). Wear is related to interactions between surfaces and more specifically the removal and deformation of material on a surface as a result of mechanical action of the opposite surface (Rabinowicz, E., 1995).

Types of wear include:

- Flank wear: in which the portion of the tool in contact with the finished part erodes. Can be described using the Tool Life Expectancy equation.
- Crater wear: in which contact with chips erodes the rake face. This is somewhat normal for tool wear, and does not seriously degrade the use of a tool until it becomes serious enough to cause a cutting edge failure.

Flank wear occurs on the relief face of the cutting tool and is generally attributed to the rubbing of the tool along the machined surface and high temperatures causing abrasive and/or adhesive wear, thus affecting tool materials properties as well as work piece surface (A. Senthil Kumara, A. Raja Duraia, T. Sornakumarb 2005). Abrasion, diffusion and adhesion are the main wear mechanisms in flank wear. Flank wear in the ceramic cutting tools is a mechanically activated wear usually by the abrasive action of the hard work piece material with the ceramic cutting tools. The severity of abrasion increases in cases, where the work piece materials contain hard inclusions, or when there is hard wear debris from the workpiece or the tool, at the interface. The flank wear is usually characterized by the abrasive grooves and ridges on the flank face.

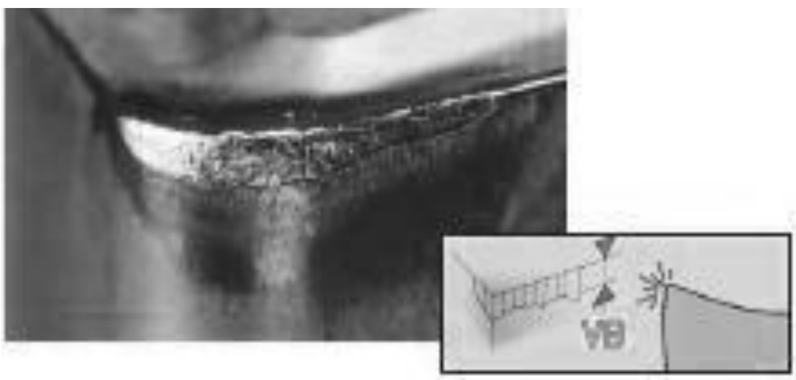

Figure 2.1: Flank wear.

Source: www.sandvik.coromant.com

Crater wear which occurs on the rake face is caused by welding and galling action between the work material and the cutting tool that tends to wash out small particles of the tool material (Donaldson and LeCain, 1957). It can be reduced by increasing the chemical stability of the tool material, decreasing solubility in the work piece or barrier protection by substrate alloying or coating. The position of the crater relative to the cutting edge is also important as a deep and wide crater far away from the cutting edge may be less dangerous to the tool than a less deep, narrow crater close to the cutting edge. Excessive crater wear changes the geometry and weakens the edge (Black et al., 2004).

(A. Senthil Kumara, A. Raja Duraia, T. Sornakumarb 2005) said crater wear occurs on the rake face of the tool, changing the tool–chip interface geometry, thus affecting the cutting process.. The most significant factors influencing crater wear are the temperature at the tool–chip interface and the chemical affinity between the tool and the work piece materials. Additionally the factors influencing flank wear also influence crater wear. The main wear mechanisms in crater wear of ceramic tools are diffusion, adhesion and abrasion. Crater wear involves a chemical reaction between the work piece chip material and the ceramic tool material, and the process is activated by high speeds and temperatures. It is thus a tribochemical wear as a result of the chemical affinity between the work piece materials and the cutting tool materials.

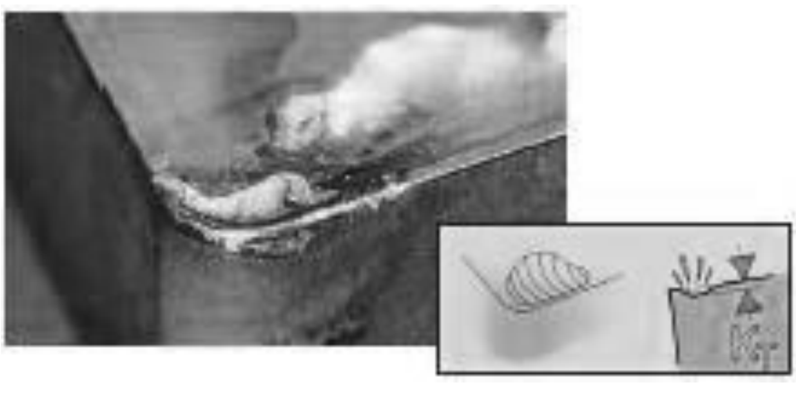

Figure 2.2: Crater wear.

Source: www.sandvik.coromant.com

2.3.1 Tool Wear Measurement

According to the (American National Standard "Tool Life Testing With Single-Point Turning Tools" ANSI/ASME B94.55M-1985", 1985), there are certain criteria that need to be considered when measuring tool wear and there are different type of instruments that can be used to measure tool wear. Tool wear geometry is the most important criteria in measuring the wear and all those criteria are shown in Figure 2.4. As suggested, the major cutting edge is divided into three zones, as shown in Figure 2.4, for the purpose of the wear measurements: (1) Zone C is the curved part of the cutting edge at the tool corner, (2) Zone N is the quarter of the worn cutting edge length b_w farthest from the tool corner, (3) Zone B is the remaining straight part of the cutting edge between Zone C and Zone N. As such, the following criteria for carbide tools are normally recommended: (a) the average width of the flank wear land VB_B=0.3 mm, if the flank wear land is considered to be regularly worn in Zone B; (b) the maximum width of the flank wear land $VB_{B\max}$=0.6 mm, if the flank wear land is not considered to be regularly worn in Zone B. Besides, surface roughness for finish turning and the length of the wear notch VBN=1 mm can be used. However, these assessments are subjective and insufficient. They do not account for the tool geometry (the flank angle, the rake angle, the cutting edge angle, etc.) so they are not suitable to compare cutting tools having different geometries. They do not account for the cutting regime and thus do not reflect the real amount of work material removed by the tool during the time over which the measured flank wear is achieved.

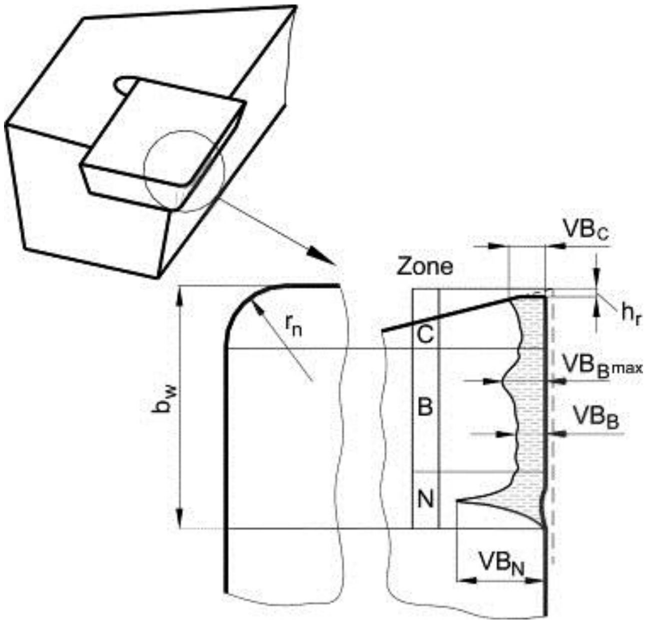

Figure 2.3: Flank wear characteristics according to ANSI/ASME B.94.55M-1985 standard

Source: American National Standard "Tool Life Testing With Single-Point Turning Tools" ANSI/ASME B94.55M-1985", ASME, New York, 1985.

2.4 Vickers hardness test

It is the standard method for measuring the hardness of metals, particularly those with extremely hard surfaces: the surface is subjected to a standard pressure for a standard length of time by means of a pyramid-shaped diamond. The diagonal of the resulting indention is measured under a microscope and the Vickers Hardness value read from a conversion table (Smith, 2004)

Vickers hardness a measure of the hardness of a material, calculated from the size of an impression produced under load by a pyramid-shaped diamond indenter. Devised in the 1920s by engineers at Vickers, Ltd., in the United Kingdom, the diamond pyramid hardness test, as it also became known, permitted the establishment of a continuous scale of comparable numbers that accurately reflected the wide range of hardnesses found in steels.

The indenter employed in the Vickers test is a square-based pyramid whose opposite sides meet at the apex at an angle of 136°. The diamond is pressed into the surface of the material at loads ranging up to approximately 120 kilograms-force, and the size of the impression (usually no more than 0.5 mm) is measured with the aid of a calibrated microscope. The Vickers number (HV) is calculated using the following formula:

$$HV = 1.854(F/D2),$$

With F being the applied load (measured in kilograms-force) and D2 the area of the indentation (measured in square millimeters). The applied load is usually specified when HV is cited.

The Vickers test is reliable for measuring the hardness of metals, and it is also used on ceramic materials. (Encyclopædia Britannica Online)

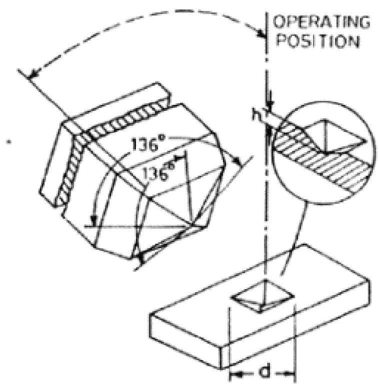

Figure 2.4: Vickers hardness.

Source: www.calce.umd.edu