DEVELOPMENT OF CUTTING TOOL THROUGH SUPERPLASTIC BORONIZING OF DUPLEX STAINLESS STEEL

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ABSTRACT

In this work, cutting tool is developed from duplex stainless steel (DSS) using superplastic boronizing technique. The feasibility of the development process is studied and the cutting performances of the cutting tool are evaluated and compared with commercially available carbide and high speed steel (HSS) tools. The superplastically boronized (SPB) cutting tool promised dense boronized layer of 50.5 µm with surface hardness of 3956 HV. Coefficient of friction (COF) value of 0.62 is obtained which is lower than 1.02 and 0.8 of carbide and HSS tools respectively. When tested on aluminium 6061 surface under dry condition, the SPB cutting tool also is able to produce turning finishing below 0.4 µm, beyond travel distances of 3000 m that is comparable to carbide tool but far better than HSS tool. Through superplastically boronizing of DSS, a high quality metal base cutting tool that is comparable to the conventional carbide tool is possible to be produced.

ABSTRAK

Dalam kajian ini, alat pemotong dibangunkan daripada keluli tahan karat dupleks (DSS) dengan menggunakan teknik superplastik boronizing. Kemungkinan proses pembangunan dikaji dan pencapaian memotong oleh alat pemotong dinilai dan dibandingkan dengan karbida (carbide) dan keluli kelajuan tinggi (high speed steel) yang boleh didapati secara komersial. Alat pemotong superplastically boronized (SPB) menghasilkan lapisan boronized padat 50.5 µm dengan kekerasan permukaan 3956 HV. Pekali geseran (COF) dengan nilai 0.62 diperolehi yang mana lebih rendah daripada karbida dan alat keluli kelajuan tinggi (high speed steel) dengan masing-masing mempunyai nilai 1.02 dan 0.8. Apabila diuji pada permukaan aluminium 6061 dalam keadaan kering, alat pemotong SPB juga mampu menghasilkan pemotongan penyudah bawah 0.4 µm, melangkaui jarak perjalanan mata pemotong sehingga 3000 m yang setanding dengan alat pemotong karbida, tetapi jauh lebih baik daripada alat pemotong keluli kelajuan tinggi (high speed steel). Melalui superplastically boronizing keluli tahan karat dupleks, alat pemotong berasaskan logam yang berkualiti tinggi setanding dengan alat karbida konvensional adalah mungkin untuk dihasilkan.

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NOMENCLATURES

C	Carbon
Co	Cobalt
Cr	Chromium
Fe	Iron
Mn	Manganese
Mo	Molybdenum
Ni	Nickel
Si	Silicon
WC	Tungsten Carbide
T_m	Melting Temperature
Ra	Average Surface Roughness

CHAPTER 1: INTRODUCTION

1.4 General

High demands in machining industry today calls for the production of high performance cutting tools with respect to the substrates, processes and coating involved. The most established substrates or tool materials that widely used comprised of high-speed steels (HSSs), sintered carbide or cemented carbide, ceramic, and extra-hard materials. Most of these tool materials are processed at high pressure and high temperature in order to produce the cutting tools. For example, ceramic materials are molded from ceramic powder at a pressure of more than 25 MPa, to be sintered later at approximately 1973 K (1700 °C) (Lacalle *et* al., 2011). This shows that the process involves the use of high energy, which implies high cost.

Most of the cutting tools are coated by other materials to improve surface properties such as wear resistance, surface hardness, thermal shock, metal fatigue, reducing frictions and the lifetime of the tool. Chemical vapor deposition (CVD) and physical vapor deposition (PVD) are the most widely used coating technology nowadays. The CVD of films and coatings involves the chemical reactions of gaseous reactants on or near the vicinity of a heated substrate surface (Choy, 2003; Liu *et*., al 2016; Koseki *et*., al 2015). However, some problems encountered in the process, where it involved of complicated chemical systems and the films can be deposited at elevated temperature. Whereas in PVD coating, thin films are produced through solid or liquid source evaporated into the gas phase, then in turn deposited into the solid phase. One disadvantages found is this process's line of sight at which resulting in poor surface coverage. Thus makes even coating for complicated geometries challenging (Liu *et*., al 2016; Koseki *et*., al 2015; Montgomery, Kennedy & O'Dowd, 2010). From an industrial point of view, this shows that the methods are quite complicated with high capital cost. Apart from that, only simple geometries can be coated evenly.

Boronizing is thermo-chemical surface treatment processes that give high surface hardness through diffusion of boron atoms into the surface of the substrate material to form boride layer. Recent developments in boronizing have shown that it can be applied to the WC cutting tool to enhance titanium alloy machining (Matei *et*., al 2015). However, a high processing cost is expected in this method. Superplasticity is known as a phenomenon of solid material that exhibits large deformation at high temperature. Superplastic boronizing is a process of conducting boronizing while the specimen is concurrently superplastically deformed. The method of superplastic boronizing is likewise to hot isostatic pressing, where the process is conducted at an elevated temperature with pressure applied from all directions. Prior studies have been conducted on superplastic boronizing of duplex stainless steel (DSS) under initial pressure conditions, where it is superplastically deformed the surface of the subsrate and compacting the boron powder (Jauhari *et*., al 2007). Good results were obtained from the aspect of the surface mechanical properties, with a surface hardness up to 4000 HV.

Duplex stainless steel is well-known for its very good resistance to stress corrosion cracking, high tensile strength and fatigue strength with good toughness and ductility. To the authors' knowledge, there is no published work on the development of cutting tools from DSS. However, based on the promising results, including the practicality and simplicity of the process, it is worth applying the technique to developing a cutting tool for metal cutting purposes. Furthermore, the production of metal-based cutting tool is predicted to be greener and more economical since the process requires less time than the conventional method. Hence, in this work, a cutting tool is developed from DSS using the superplastic boronizing technique. The practicability of the development process is studied and the cutting performances of the cutting tool are evaluated and compared with those of the commercial one.

1.2 Objectives

The objectives of this work are:

1. To develop cutting tool through superplastic boronizing process on duplex stainless steel.
2. To evaluate microstructure and mechanical properties of superplastically boronized cutting tool.
3. To evaluate cutting performances by finishing operation turning test of superplastically boronized cutting tool.

1.3 Outline of Research

The outline of this dissertation is divided into five chapters which are elaborated as follows:

Chapter 1: The introduction briefly describes the overview of the cutting tool, including substrate materials, commercial process and coating method, with the related problem statement. It also reviews previous studies regarding the superplastic boronizing methods. The objectives of this study are presented followed by the research methodology. The dissertation outline is given at the end of the chapter.

Chapter 2: Literature Review is mainly based on the theories and summaries of superplasticity, boronizing, superplastic boronizing, duplex stainless steel, superplastic boronizing of duplex stainless steel and various type of commercial cutting tools and its coating method. It reviews from the various sources such as journals, proceeding papers, text books, previous dissertations reports, and the world wide webs.

Chapter 3: Material and methodology involved of the substrate used and experimental work. Experimental works are divided into five main stages. This involved: (I) the preparation of developing the superlastic boronizing process, (II) the superplastic boronizing process, (III) cutting test, (IV) characterization and mechanical evaluation and (V) collecting and analysing of data. This section depicts the details on each of the procedures. Some of the characterization and mechanical evaluation techniques such as field emission scanning electron microscopy (FESEM), X-ray diffraction analysis and Vickers hardness measurement, wear test to determine coefficient of friction through pin on disc tester are also described in this chapter. Cutting test and evaluation of sample after cutting test are also depicted in this chapter.

Chapter 4: Results and Discussions examination and discussion of all the results obtained are divided into several sections. These can be divided into (I) X-ray diffraction analyses, (II) microstructure analyses, (III) mechanical properties analyses (IV) cutting test evaluation including surface roughness analyses, wear analyses, elemental analyses and chip evaluation. This section compares the results obtained with other commercial cutting tool.

Chapter 5: Conclusion and Recommendation summarize all the obtained results. The possible future works that can be conducted are also recommended in this chapter.

CHAPTER 2: LITERATURE REVIEW

2.1 Superplasticity

Superplasticity is known as a phenomenon of solid material that can show a very large deformation at high temperature (Hasan et al., 2006). In a simpler definition, superplasticity is a phenomenon by which a material shows very large plastic deformation during tensile loading, under a certain strain rate and temperature (Hasan, 2006). For tensile deformation, a traditional metal alloys can only be deformed up to 20%, but elongations in excess of 200% are usually indicative of superplasticity (Hassan, 2006). As reported by Higashi, the current world record for elongations in metals stands at 8000% elongation in commercial bronze as shown in Figure 2.1.

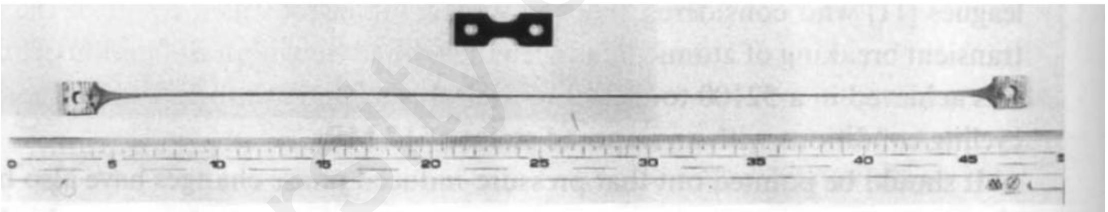


Figure 2.1: A dramatic demonstration of superplasticity in Cu-Al alloy (8000% elongation) (Chandra, 2002)

As reported by Chandra, 2002 not all materials exhibit superplasticity. However a wide range of materials including metals, ceramics, metallic/ intermetallic/ ceramics matrix composites, intermetallics and nanocrystalline materials show superplasticity at some specific loading conditions. Most of these materials do require some special processing conditions to achieve the microstructural requirements necessary for superplasticity.

2.1.1 Characteristic of Superplastic Deformation

It has been reported that superplastic behavior in most metals, alloys and ceramics are associated with three main characteristics: (1) a strain rate sensitivity factor m which is more than 0.3, (2) a fine grain size (on the order of 1-10µm) and (3) deformation temperature > 0.5 Tm (Hertzberg, 1996).

A high strain rate sensitivity of flow stress (m) is the most important mechanical characteristic of a superplastic The high strain rate sensitivity of a material imparts high neck resistance which in turn results large elongation (Reddy et al., 2012). Most of superplastic materials, m lies in the range 0.4 to 0.8. The characteristic mechanical behavior observed is a strong dependence of flow stress, σ on strain rate, $\dot{\varepsilon}$ at the superplastic temperature.

Fine grain size is one of the main characteristic of superplasticity. It has been well understood that ductility of materials increases as the grain size becomes finer. It is critical for the material to have fine grain structure in order to create superplasticity in the material or to deform material in the superplastic condition. Superplasticity in most materials commonly occurs at elevated temperature. The optimal temperature of superplastic forming is systematically higher than 0.5 T_m (T_m is the melting point of material expressed in Kelvin). Most alloys are only superplastic when the deformation temperature is greater than 0.4 T_m. There is equilibrium between recovery and hardening at these temperatures, so that the metal does not strain harden.

2.1.2 Mechanism of Superplasticity

Superplastic gives high ductility through its grain boundary sliding and fine equiaxed microstructure. Grains are observed to change their neighbors and seen to emerge at the free surface from the interior (Chandra, 2002). Several models of mechanisms have been proposed for superplastic deformation (Langdon, 1970; Mukherjee, 1971; Gifkins, 1976; Arieli & Mukherjee, 1980). Figure 2.2 (a) explains the mechanism of microstructure during superplastic deformation. However, strain in a given direction is due to the motion of individual grains or clusters of grains relative to each other by sliding and rolling. During deformation, the grains remain equiaxed or become equiaxed. Although there is some differences in grain shape during the accommodation, the grain shape and size remains identical before and after deformation.

One characteristic feature of superplastic flow is that grains retain equiaxed or nearly equiaxed shape after being deformed for several hundred percent elongations (Zelin & Mukherjee, 1996). Grains are observed to change their neighbors and seen to emerge at the free surface from the interior (Chandra, 2002). This is different with plastic deformation where grains become elongated and the location of grain neighborhood remains unchanged when a tensile force is applied. Figure 2.2 (b) explains the evolution of microstructure during plastic deformation.

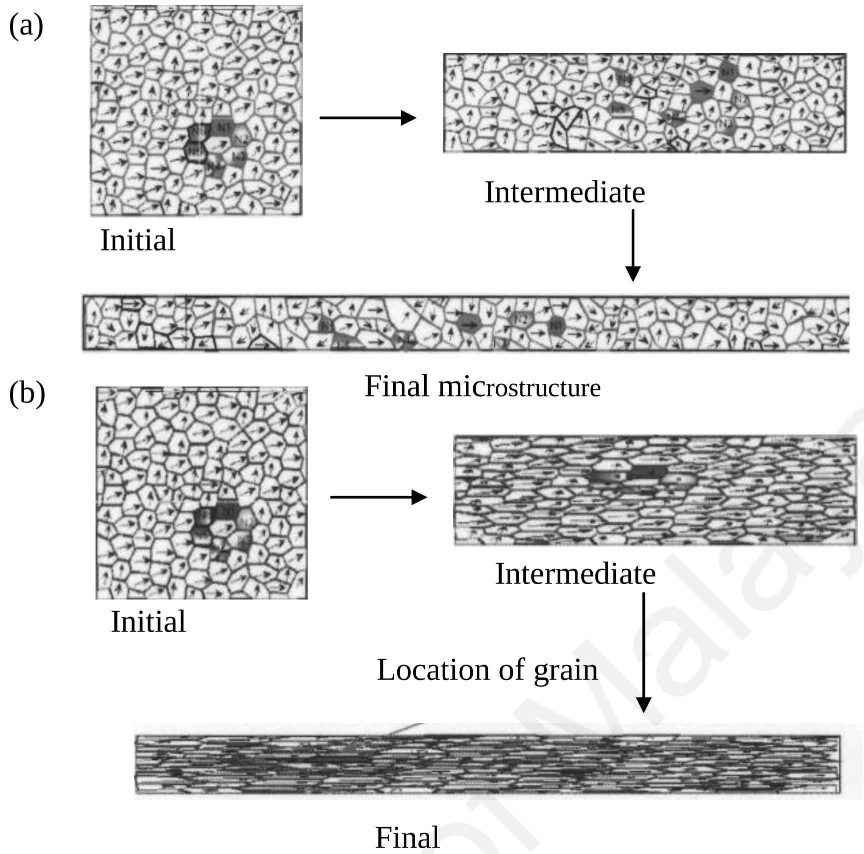


Figure 2.2: Evolution of microstructure during (a) superplastic and (b) plastic deformation (Chandra, 2002)

Whereas accommodation mechanisms can be divided into three general groups (Mukherjee, 2002): (a) diffusional accommodation, (b) accommodation by dislocation motion and (c) combined model with elements of dislocation and diffusional accommodation. Diffusional accommodation occurs when the mass flow is due to the diffusion process at the vicinity of grain boundary. When a load is given to a material, the deformation is due to grain boundary diffusion and sliding, as a result of strain. The process is indicated in Figure 2.3.

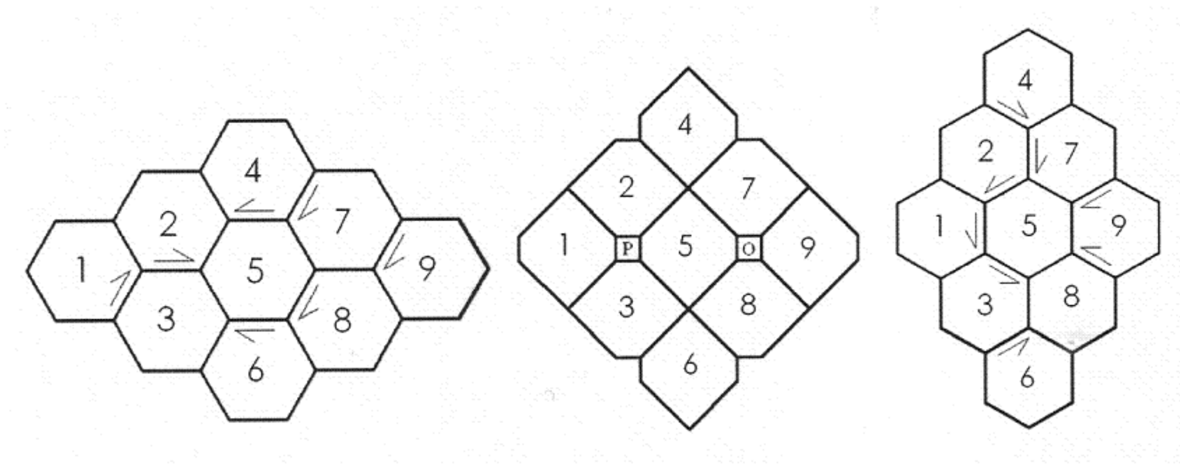


Figure 2.3: The process of diffusional accommodation (Zelin & Mukherjee, 1996)

For accommodation by dislocation motion, it can be understood by dividing the grain into two parts; the core inside the grain and mantle at the grain boundary, as shown in Figure 2.4 (a). In order for the grain to slide, initially the dislocations which move onto the grain boundary are accumulated at the triple point of grain boundary. From there, the dislocations move into the mantle due to stress concentration. Finally, the dislocation motion inside the mantle resulted in the grain rotation. Figure 2.4 (b) shows the process of accommodation by dislocation motion. The accommodation which combines dislocation and diffusion process is illustrated in Figure 2.5.

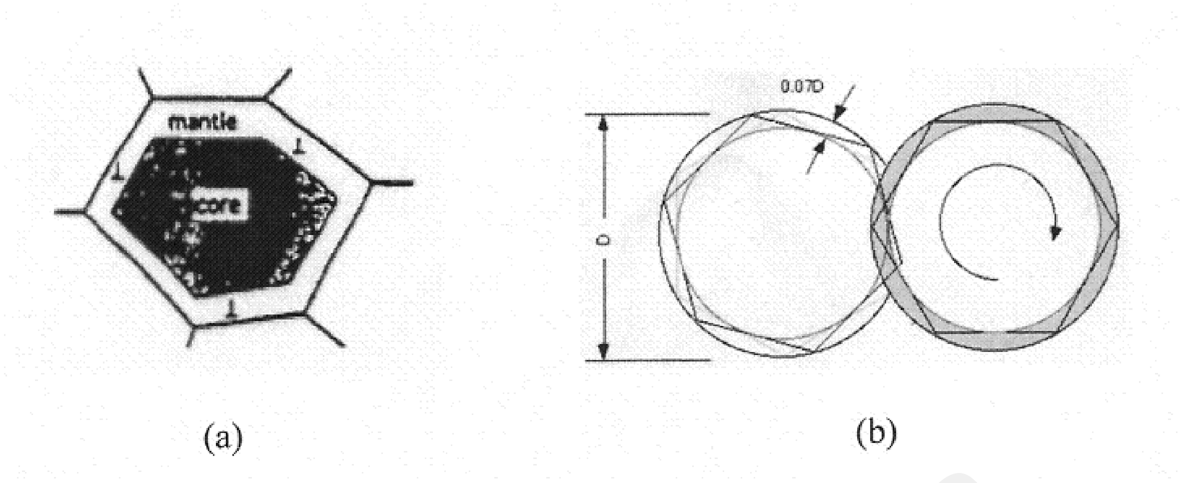


Figure 2.4: (a) core inside the grain and mantle at the grain boundary (b) dislocation motion inside the mantle results in the grain rotation (D = diameter) (Zelin & Mukherjee, 1996)

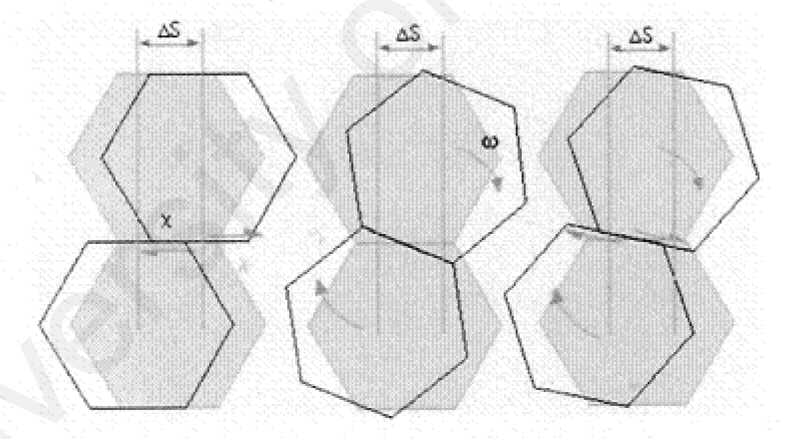


Figure 2.5: The accommodation which combines dislocation and diffusion processes (Zelin & Mukherjee, 1996)

2.1.3 Applications of Superplasticity

Superplastic has been widely applied in many field of industrial application. Most of the applications are in the aerospace area (Friedrich and Winkler,1991; Tsuzuka et al., 1991: Hefti, 2004; Li and Guo, 2005). But there is also non aerospace application such as superplastic aluminum alloys that has been used in the complex surface profile and decorative panels for internal and external cladding of buildings and high speed train (Superform Metals Limited, 1988). All of these applications come under the well known processes of superplastic forming (SPF) and superplastic diffusion bonding (SDB).

The superplastic forming (SPF), conducted under controlled temperature and strain rates, dramatically increases the formability of materials and allows production of highly integrated, net shape components that often consolidate many parts into one (Li and Guo,2005). Superplastic forming processes can provide products with integral structure, light weight and superior strength, all of which are of particular importance for aerospace and automotive components (Balasubramaniam et al., 2012). Figure 2.6 shows illustrations of (a) Superplastic forming (SPF) process and (b) SPF applications for Ti-6A1-4V high pressure vessel used to fill coolant for soldier-carrying infrared detectors.

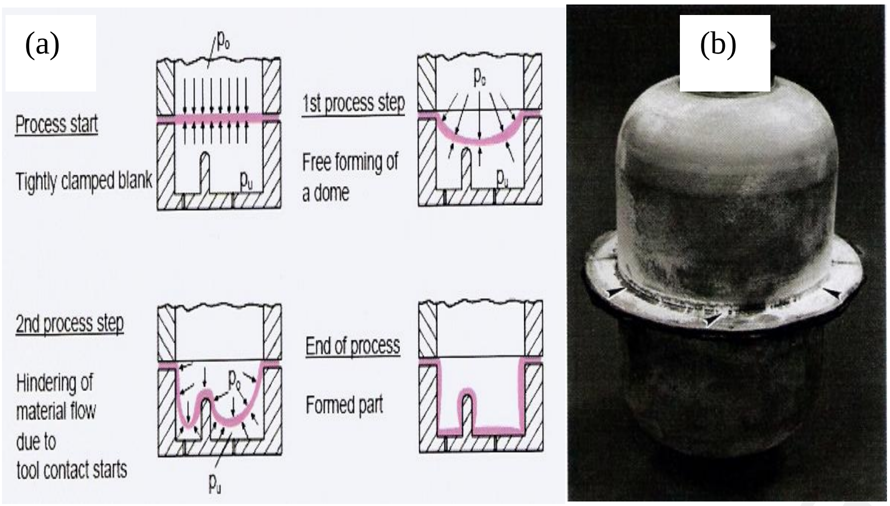


Figure 2.6: Superplastic application (a) Superplastic forming (SPF) process and (b) SPF applications for TS-6A1-4V high pressure vessel (Huang and Chuang, 1999)

Superplastic also plays an important role in solid state diffusion bonding (DB) process. It was reported that superplastic deformation accelerates the solid state diffusion bonding process while obtaining effective bonding (high strength) with minimum material deformation (Jauhari et al., 2002). The acceleration of solid state joining by superplastic deformation is closely related with the development of fine grain boundary sliding in the material (Lutfulin et al., 1995). The superplastic diffusion bonding (SDB) is often combined with superplastic forming (SPF) in the manufacture of complex cellular structures. Compared to other diffusion bonding processes, the SDB process offers a shorter joining time at lower pressure, with parent metal strength (Jauhari et al., 2002). In the aerospace application, superplastic forming and diffusion bonding techniques have been widely used in aero engines for civil usage and aircraft in military as shown in the Figure 2.7.

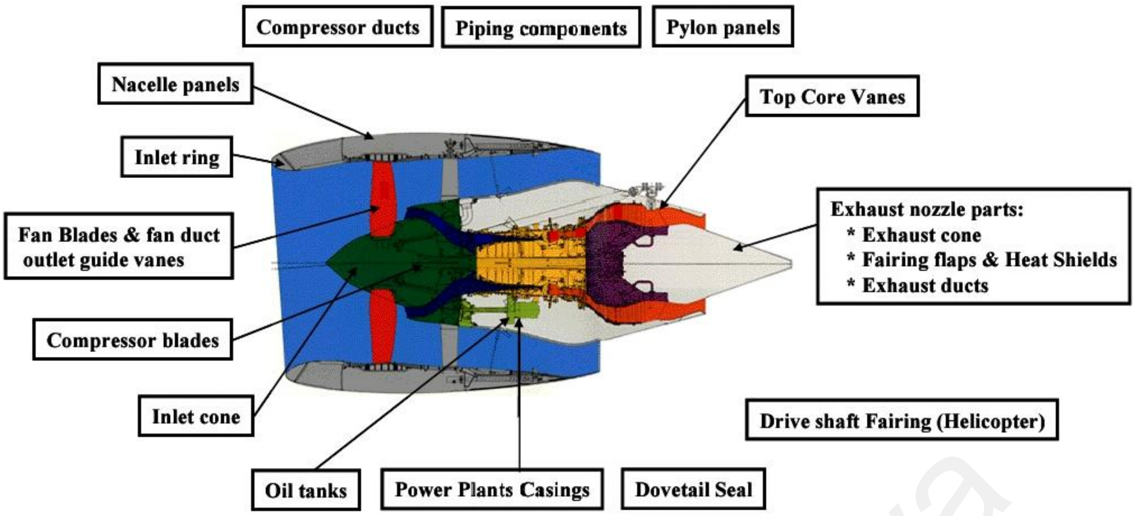


Figure 2.7: Possible part of SPF in aero engines (Serra, 2008)

SPF together with DB has been implemented to produce hollow engine blades, fan and compressor blades for aero engines (Xun and Tan, 2000; Xing *et al.*, 2004). Figure 2.8 is an example of the three layer slanting-rid strengthened Ti-6A1-4V structure fabricated using SPF/DB technique.

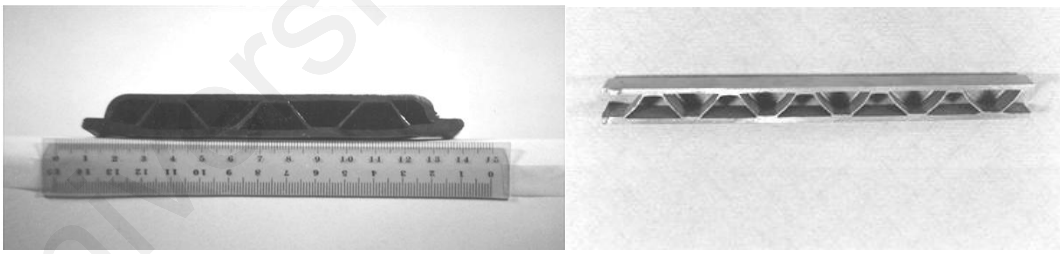


Figure 2.8: Example of the three layers slanting-rid strengthened using SPF/DB technique (Huang and Chuang, 1999)

2.2 Boronizing

Boronizing is a thermo-chemical surface hardening process through diffusion of boron atoms into the substrate material, forming boride layer that give high surface hardness within substrate material. This process can be performed in solid, liquid or gaseous medium and the most frequently utilized method is pack boronizing. The pack boronizing has the advantages in terms of simplicity and cost-effectiveness in comparison with other boronizing processes (Keddam and Chentouf, 2005; Celebi et al., 2005; Ozdemir et al., 2006). Unnecessary used of many handling component, thus is an ease and providing low cost for this process. In pack boronizing, substrates is immersed in the container with the boron powder, then it is heating to boronizing temperature and time. Boronizing typically requires process temperature of 973K to 1273K (Genel et al., 2003; Yapar, 2004; Dong et al., 2009). The thickness of boride layer formed is determined by the temperature and time of the treatment (Jain & Sundararajan, 2002). Boronizing surface treatment is a good choice for certain tooling and tribological applications due to its high hardness and wear resistance (Davis, 2002).

2.2.1 Superplastic boronizing (SPB)

The process that involves combination of both, superplastic deformation and boronizing is called superplastic boronizing. The basic principle of superplastic boronizing process is to conduct boronizing while the specimen in undergoing superplastic deformation (Xu et al., 1996). In 1996, Xu *et al.* had carried out superplastic boronizing on commercial high carbon steel and low carbon steel. It was found that the rate of SPB for both steels is about twice as fast as that of CB at the same temperature. During the SPB, the superplastic deformation created high densities of vacancies, dislocations and sub-grain boundaries. These defects were movable under the superplastic deformation processes, increasing the rate of atomic diffusion. It also produces equiaxed boride grains instead of acicular grains after conventional boronizing (Xu et al., 1996). The equiaxed boride structure has better mechanical properties than acicular grains (Xu et al., 1997). As compared with conventional boronizing, the borides grains produced by superplastic boronizing are smaller and non-acicular. When cracks develop along or through borides grains, they constantly meet new grains. Thus, cracks have to change their propagation directions, which consumes energy and slow down the propagation speed of the cracks. All these factors reduce brittleness and improve the mechanical properties of the boride layers produced by superplastic boronizing. The boride layer formed by the superplastic boronizing was more uniform than that produced by the conventional boronizing (Xu et al., 2001). It's also reported in Xu et al., 1996 that superplastic boronizing increased the fracture strength by 8%, toughness by 18%, and bending flexure by 15%, as compared to conventional boronizing.

2.2.2 Boronizing agent

The Ekabor TM boronizing agents supplied by BorTec Germany are listed in Table 2.1. The main constituents are the boron donor, the activator and the filler.

Table 2.1 EKABOR™ boronizing agents (Source: *Internet reference-1*)

Boronizing agent	Grain size	Comment
EKABOR™1	<150µm	Highest-quality surface layer; tends to bond
EKABOR™2	<850µm	Very good surface layer; the part is easy to unpack after treatment
EKABOR™3	<1400µm	Good surface layer; powder still has good flow properties after treatment
EKABOR™HM	<150µm	For hard metals, small bore sizes and thick boride layers; very good surface layers
EKABOR™ Paste	.	Universal application: immersion, brushing and spraying
EKABOR™ Ni	<150µm	For boronizing nickel-based materials.

2.3 Substrate Material

2.3.1 Duplex Stainless Steel

Duplex stainless steels are defined as a family of stainless steels consisting of a two-phase aggregated microstructure of α-ferrite and γ- austenite (Han and Hong, 2000). The balance 50% α-ferrite and 50% γ- austenite microstructure is obtained by controlled chemical analysis and heat treatment, to produce optimum properties (Charles and Vincent, 1997). Due to the two-phase microstructure, DSS combines the desirable properties of austenitic and ferritic stainless steels (Cabrera *et al.,* 2003). DSS has become established materials in many industrial applications such as in oil extraction, paper manufacturing and chemical industries (Cabrera*et al.,* 2003; Charles and Vincent, 1997).

2.3.2 Superplastic of Duplex Stainless Steel

Treated duplex stainless steel has finer grains as compared to the as-received, as shown in Figure 2.9. Duplex stainless steel with fine grain microstructure has the ability to show superplastic behavior since the grain growth is effectively suppressed at high temperature due to the two phase aggregated microstructure (Han and Hong, 1999). As reported by Reddy, 2012 an ultrafine grain size is the most important microstructural attribute of superplastic alloy. The finer the grain size, more are the grain boundaries.

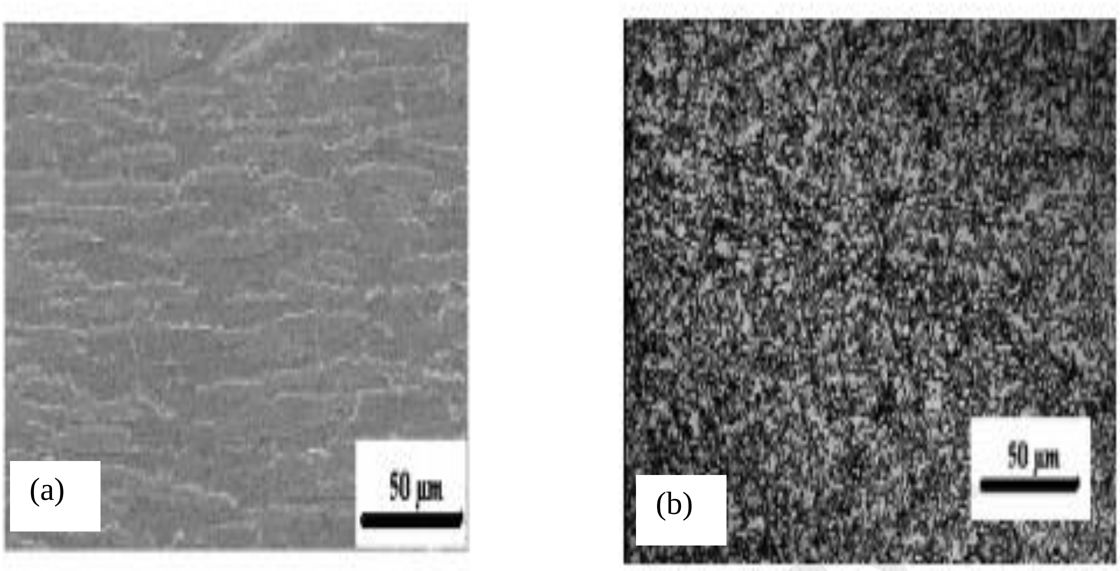


Figure 2.9: Microstructure of duplex stainless steel (a) Coarse DSS and (b) Fine microstructure DSS with average grain size of 3 µm (Jauhari et al., 2007)

It is known that a thermomechanical process consists of solution treatment followed by cold rolling is an essential stage in producing superplastic duplex stainless steel. The tensile elongation of superplastically deformed duplex stainless steel increased with increasing amount of reduction during cold rolling (Han & Hong, 1997). The fine grained duplex microstructure is obtained through the precipitation of the second phase particles when the thermomechanically treated duplex stainless steel is heated up at test temperature (Han & Hong, 1999). The microduplex structure consists of a subgrains and fine γ particles (Tsuzaki *et al.*, 1996). In order to obtain treated duplex stainless steel (fine grain microstructure of DSS), the as-received DSS was initially chemically treated at 1573K for 1hour and followed by water quenching. It was then cold rolled until 75% of reduction area. Schematic diagram of the thermo-mechanical treatment process is shown in the Figure 2.10.

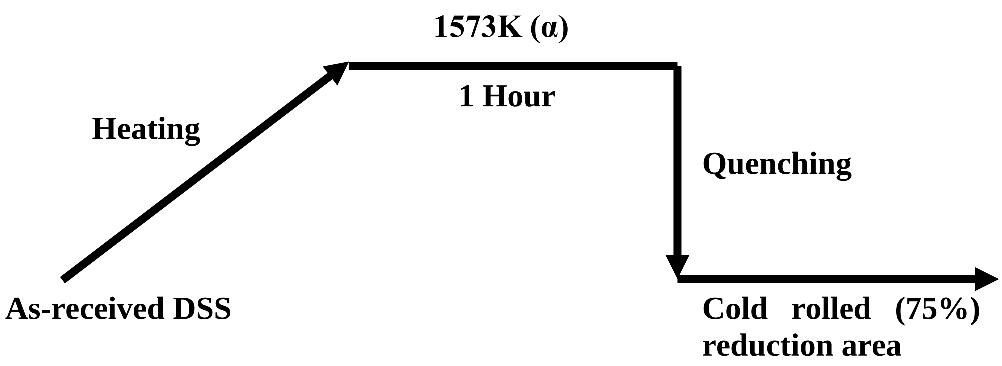


Figure 2.10: Schematic diagram of thermo-mechanical treatment process on DSS (Jauhari et al., 2007)

2.3.3 Superplastic Boronizing of Duplex Stainless Steel

It has been shown that through superplastic boronizing process, a very hard surface can be produced and the surface properties of duplex stainless steel can be improve significantly (Jauhari et al., 2007). In their work, good results were obtained from the aspect of the surface mechanical properties, with a surface hardness up to 4000 HV through combination of superplastic effect and usage of boron powder size less than 20 µm. The initial pressure that applied in the superplastic bronizing process has initiated deformation on fine grain of duplex stainless steel. Hence, promotes diffusions of boron atoms into the surface of the substrate. The surfaces asperities are superplastically deformed subject to the initial pressure applied, thus promote the acceleration of boron atoms and reduce the space between the boron powders (Jauhari et al., 2003). Improve in surface hardness and boride layer of the substrate. With the aid of load applied, surface asperities were the first area deformed during superplastic boronizing (Aziz et al., 2012).Initial pressure applied will also promote high density of dislocation at grain boundaries, thus will become a more active area compared to the inner side of the grain. Hence, promotes more diffusion of boron atoms.

From the previous work (Jauhari et al., 2007) the effect of powder particle sizes has been studied. Higher diffusion rate are obtained through fine powder particle size. The fine particle size encouraged better diffusion by increases the contact surface between boron atoms and substrate, consequently diffusion become easier and faster. As the conclusion of their work, the surface properties of the superplastically boronized sample are strongly influenced by boron atom powder particle size. Figure 2.11 shows superplastic boronizing clamp design.

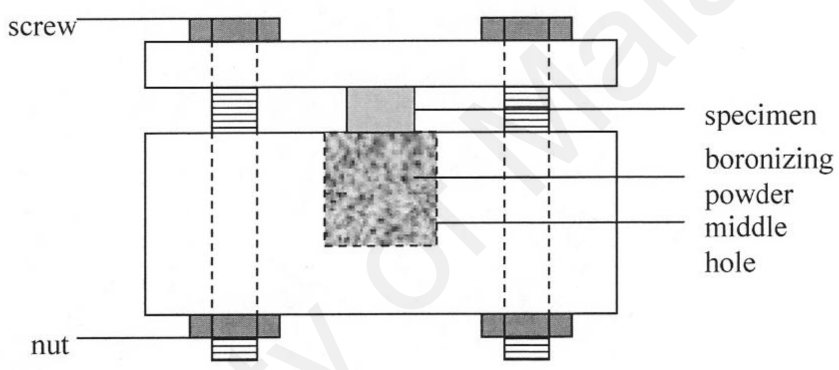


Figure 2.11: Superplastic boronizing clamp design. (Hasan, 2006)

2.4 Cutting Tool

Cutting tool is the tool that used to remove material from the workpiece by means of shear deformation. There are several ideal based on the characteristic of the cutter that should be considered for cutting material, before it can be chosen as a cutting material. Those characteristics are, the cutting material should be harder than the workpiece it is cutting, it should also has high temperature stability, resistance to wear and thermal shock, have high impact resistance and chemically inert to the work material and cutting fluid (Settineri and Faga, 2006). The cutting tools are subjected to high localized stresses, high temperatures, sliding of the chip along the tool rake face and sliding of the machined surface along the tool flank (Kumar et al., 2006). Thus, better properties of cutting tool are important to perform well as a cutting tool.

2.4.1 Cutting tool materials

Common cutting tool materials consist of high speed steels (HSSs), cast cobalt alloy, sintered carbides, ceramics based on alumina (Al_2O_3) or silicon nitride (SiN_4), and extra hard materials such as polycrystalline diamond (PCD) and polycrystalline cubic boron nitride (PCBN). Most of these materials are manufactured by powder metallurgy technique at high temperature and pressure.

2.4.1.1 High speed steel (HSS)

High-speed tool steels are so named mainly because of their ability to machine materials at high cutting speeds. HSS type has the mean hardness of about 75 HRC and widely use in machining due to its toughness and low cost. However, conventional HSS is not the first choice if the workpiece is hard and from the type of alloy due to its hardness. This tool is coating to improve the surface properties such as surface hardness and its resistance to wear. Most of HSS tool is coated with heat and wear resistive materials like TiC and TiN, by coating methods like chemical vapour deposition (CVD) and physical vapour deposition (PVD). Another ways to enhance its properties are by refinement of microstructure, addition large amount of cobalt and vanadium and manufactured by powder metallurgical process. However, prior to continuous development and high demands in machining industry, other tool like cemented carbides and ceramics which could machine much faster than the HSS tools has been taken place.

2.4.1.2 Cast Cobalt alloys

Introduced in early 1900s, this alloy has maximum hardness values of 55 - 64 Rc (*Internet reference-2*).Cast cobalt alloys also known as stellite tool, commonly used due to its high hardness. Stellite tool have good wear resistance and can maintained their hardness at elevated temperatures. They perform well at higher surface speed than conventional high speed steel tool and are more resistant to chipping than standard carbide grades (Davis, J.R., 1995). Cobalt can be ground using a standard aluminium oxide grinding wheel. As compared to high speed steel tool, cobalt tool has longer working life and less re-sharpening or grinding required. After grinding during resharpened, the satellite tool need to be cool in air. By quenched in the water, it can cause cracking on the cutting edge. Thus by air cooling, cracking can be prevented from occurring. However, this will take a longer time and as a result less effective. Another drawbacks of this tool are, it more prone to the thermal shock and it is not as tough as high speed steel tool and sensitive to the impact force. Thus, cast cobalt alloy now only in the limited use.

2.4.1.3 Carbides

Carbide tool also known as cemented carbides or sintered carbides are the most common cutting tool used by machinist today. The tools are produced by powder metallurgy technique, where the powder of tungsten carbide and cobalt is mixed, pressed and sintered to desire tool shape. These tool materials are much harder, and chemically more stable, have better hot hardness, high stiffness, lower friction, and operate at higher cutting speeds than HSS. They are more brittle, expensive and use strategic metals such as tungsten, cobalt and tantalum more extensively. Tungsten carbide tools are commonly used for machining steels, cast irons and abrasive non-ferrous materials. Tungsten carbide is more recommended cutting tool since it is hard and very stable in term of thermal and chemical stability (Lacelle et al., 2011). Figure 2.12 shows different type of carbide tools.

Figure 2.12: Different shape of carbide tools

2.4.1.4 Ceramics

Ceramic material is fabricated by moulded the ceramics powder and compacted to form the desired shape and then to be sintered at high temperature. Ceramics are very hard and refractory materials, withstanding more than 1500°C without chemical decomposition (Lacelle *et al.*, 2011). As has been state by Xiao, 1992 ceramic tool materials can significantly increase the tool-life and hence reduce the production times and costs. They are hard, and can retain their hardness at high temperature, thus can be used at high cutting speed. However, the intensely low fracture toughness that caused brittleness has restricted their applications. The fracture toughness and flexural strength of the ceramic tool is still low and far from the requirements of practical application (Huang *et al.*, 2002). Hence, this type of cutting tool is fragile which caused limitation in their usage and tend to the tool failure. Therefore, new developments in ceramic tool materials have been develop namely pure oxide ceramic, mixed oxide plus carbide & nitride and silicon nitride based material.

2.4.2 Coating Method of Cutting tool

Most of cutting tools are coated with other materials to enhance their properties. The cutting tools are coated by other materials to improve wear resistance, surface hardness and the lifetime of the tool. The most popular coating methods used nowadays is physical vapour deposition (PVD), chemical vapour deposition (CVD).

2.4.2.1 Physical Vapour Deposition (PVD)

Physical vapor deposition (PVD) is referred to deposition processes of thin films and nanostructures through the evaporation of solid precursors into their vapor phase by physical approaches followed by the condensation of the vapor phase on substrates (Yap, 2012). Three types of PVD techniques included thermal evaporation, ion sputtering and arc discharge. The most common PVD coating materials are cubic boron nitride, polycrystalline nitride superlattices, carbon nitride, and aluminium oxide. The process was carried out in the range temperature of 150°C to 500°C.

Depending on PVD techniques, there are some disadvantages found on the processed. For example in evaporation technique, filament degradation in the electron gun results in a non-uniform evaporation rate. Hence very complicated geometries cannot be coated evenly. While for PVD sputtering technique, it involved of more complicated setup process and the film morphology may be rougher and damaged due to bombardment of energetic growth with clustering of the growth species due to high deposition pressure. Other PVD techniques are arc vapor deposition. The drawback of this type of PVD process is that it produces ‘macroparticles’, which are metal droplets, 1 to 15 pm in diameter, ejected from the target surface that become imbedded in the coating. For many tooling applications, these macroparticles are not harmful, but they can be detrimental when the surface finish of the tool is important (William, 1996). Figure 2.13 shows schematic of PVD process.

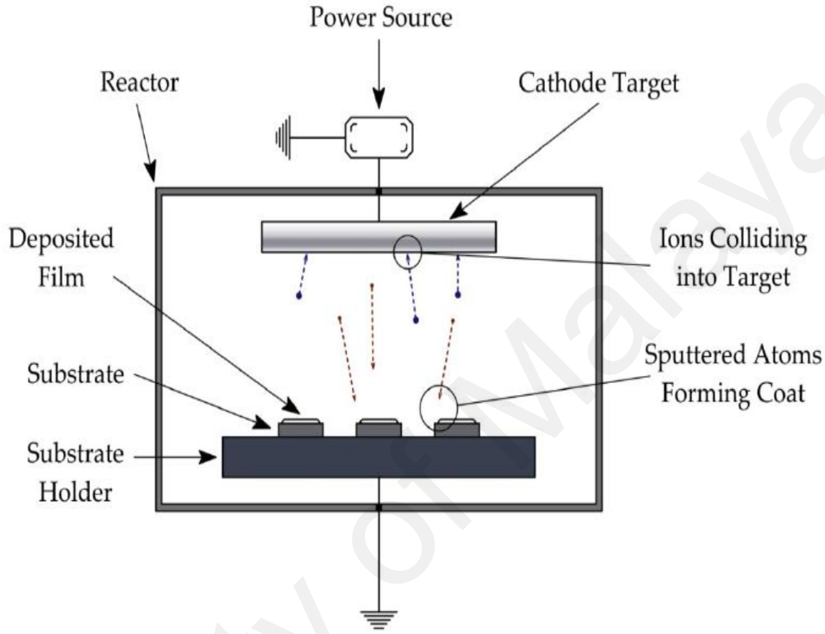


Figure 2.13: Schematic of PVD sputtering process: (Montgomery et al., 2010)

2.4.2.2 Chemical Vapour Deposition (CVD)

As reported by Choy, 2003 chemical vapour deposition (CVD) of films and coatings involved chemical reactions of gaseous reactants on or near the vicinity of a heated substrate surface. In the CVD process, substrate to be coated are placed in a hydrogen reducing atmosphere furnace – with the hydrogen typically at about 10% of atmospheric pressure. Gases containing the coating elements are added to the atmosphere and circulated through the furnace and over the inserts. The coatings are formed on the surfaces of the inserts, by chemical reactions between the gases, depending on the temperature of the surfaces (Davis, 1995). However, if the coating is too thick, it will lose the toughening reinforcement that it gains from its substrate (Davis, 1995). This atomistic deposition method also can provide highly pure materials with structural control at atomic or nano meter scale level. But some drawback has been found in this coating method, where it is involves complex chemical system and expensive in the term of cost. It also involved high level of toxic products, thus became the problems of this method (Kennedy et al., 2010). Figure 2.14 indicates the schematic diagram of CVD coating process.

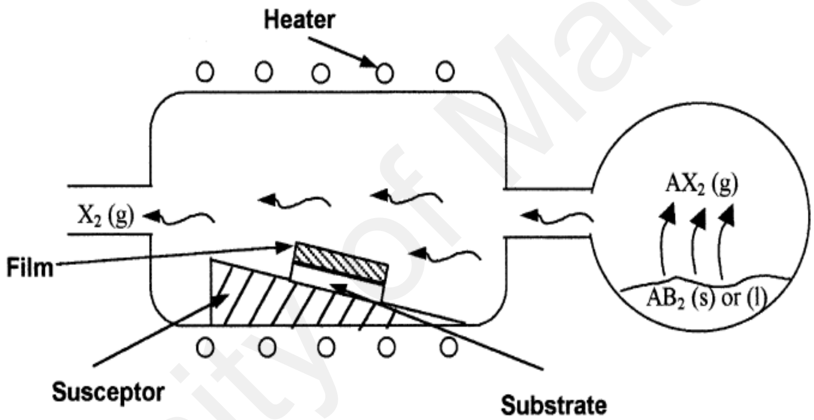


Figure 2.14: Schematic diagram of the CVD coating (Choy, 2003)

2.5 Machining

There are several types of machining operations. Turning, Drilling and milling are the examples of the types of machining operation process. Generally machining involved two cutting process, which are roughing cuts and finishing cuts. Roughing cuts involving large material removal from the as received material to the nearly shape or part. Whereas finishing cuts usually used to complete and finished the final finishing surface. In finishing operations, surface integrity and dimensional accuracy are of primary concerned, while in roughening operations the excessive cutting force and chatter are limiting factor (Astakhov et al., 2008). Table 2.2 shows general guidelines for feasible roughness for different processing methods in machining.

Table 2.2: General guidelines for feasible roughness, Ra for different processing methods (Source: *Internet reference-3*)

Material removing or separating operations	roughness R_a in um												
	0.012	0.025	0.05	0.1	0.2	0.4	0.8	1.6	3.2	6.3	13	25	50
flame cutting											□	○	◇
sawing								□	○	○	○	◇	
planing							□	○	○	○	◇		
punching						□	○	◇					
chemical treatment							□	○	○	◇			
spark erosion machining							□	○	○	◇			
drilling							□	○	○	◇			
boring							□	○	○	◇			
milling						□	○	○	○	◇	◇		
turning						□	○	○	○	◇			
broaching						□	○	○	◇				
reaming						□	○	○	◇				
filing						□	○	○	◇				
grinding					○	○	○	○	◇				
barreling			□	□	○	○	◇	◇					
brushing				□	○	◇							
electrolytic grinding				□	○	◇							
honing			○	○	○	◇							
polishing				○	○	◇							
lapping			○	○	○	◇							
superfinishing			○	○	◇	◇							

○ AVERAGE ACHIEVABLE ROUGHNESS □ FINER ◇ COARSER

2.6 Chips

The metal that removed by the action of cutting tool is known as chips. The chip is considered to be formed by a process of shear that is confined approximately to a single plane expanding from the cutting edge to the workpiece surface ahead of the tool (Merchant, 1945). There are various type of chips produced depends on the condition of cutting. The classification of chips type is generally divided into three groups that are discontinuous chips, continuous chips and chips with built-up-edges. The chip type in machining is determined depending on the combined effects of workpiece material properties, cutting speed, and tool geometry (Guo and Yen, 2004). The types of chips formed usually affected the surface finish of workpiece. As stated by Astakov, et al., 1997, lack of chip control often leads to rough surface finish, poor machining accuracy, and problems with chip removal from the machining zone. The chip morphology is also an important aspect which is commonly considered to evaluate the performance of the cutting operations.

2.6.2 Type of chips

The three types of chips produce during cutting are discontinuous chips, continuous chips and chips with built-up-edges. Continuous chips usually produced when machining ductile material. While discontinuous chips produced when cutting more brittle materials like gray cost iron, bronze and hard brass (Singh et al., 2014). A continuous chip is preferred since it has good surface finish. However the usage of chip breaker is required since chips tend to entangle to the tool holder during machining. In term of chips disposal, the process is demanding. Discontinuous chips are often most desirable to avoid entanglement with tooling and to aid with mechanized removal systems (Dornfeld and Pan, 1985). These types of chips are easier in term of chips disposal and also provide better surface finish of workpiece.

Chip with a built-up-edge (BUE) consist of layers of material from the workpiece that are gradually deposited on the tool (additional molten material sticking to it) and may form at the tip of the tool during cutting. These sticking materials usually stick to both the chip and the workpiece, hence producing a poor surface finish. The BUE that form is one of the most important factors affecting surface finishing in metal cutting. However, the BUE can be regarded as desirable in metal cutting if it is small in size and stable, since it protects the rake face as well as the tool tip (Chern, 2005). Thus, result in the increasing tool life of cutting tool. Figure 2.15 shows types of chips in machining.

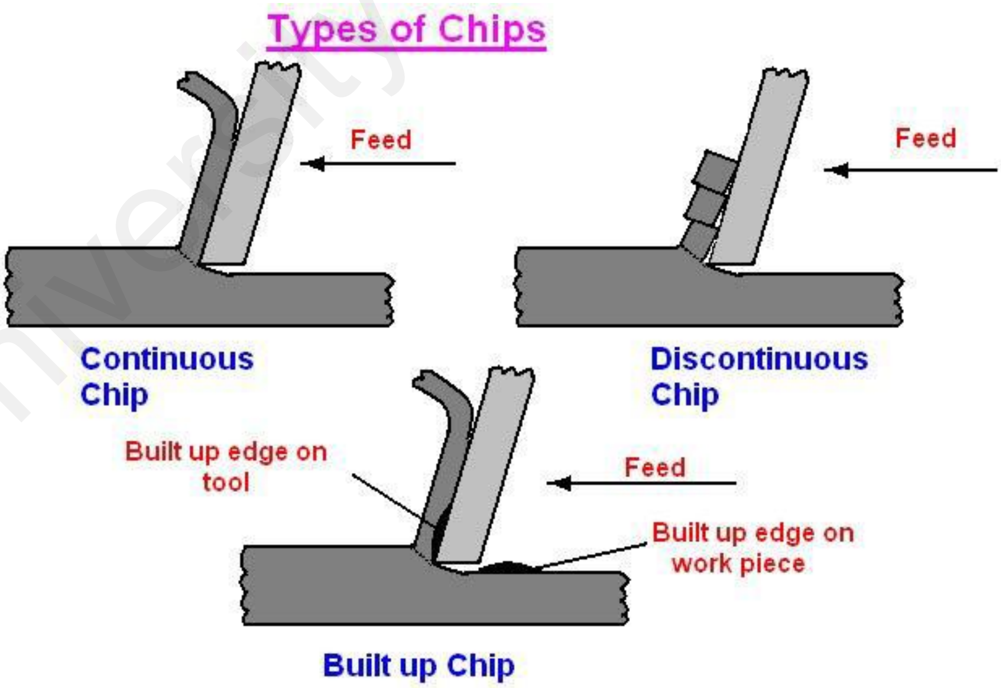


Figure 2.15: Types of chips (Singh et al., 2014)

CHAPTER 3: MATERIALS AND METHODOLOGY

Methods in this work involved of six main stages which were jig and die fabrication, powder preparation, sample preparation, superplastic boronizing process, superplastically boronized sample evaluation and cutting test with evaluation. The flow of the works can be depicted in the Figure 3.1.

3.1 Substrate Material

Treated duplex stainless steel (DSS) with fine grain and proportion of 50% α-ferrite and 50% γ-austenite were used as a substrate material in this work. Table 3.1 shows the constituents as confirmed by Shimadzu OES-5500II.

Table 3.1: Chemical composition of treated duplex stainless steel (JIS SUS329J1) in wt%

Material	C	Si	Mn	P	S	Ni	Cr	Mo	Fe
JIS SUS329J1	0.06	0.42	0.30	0.03	0.06	4.18	24.5	0.49	Bal

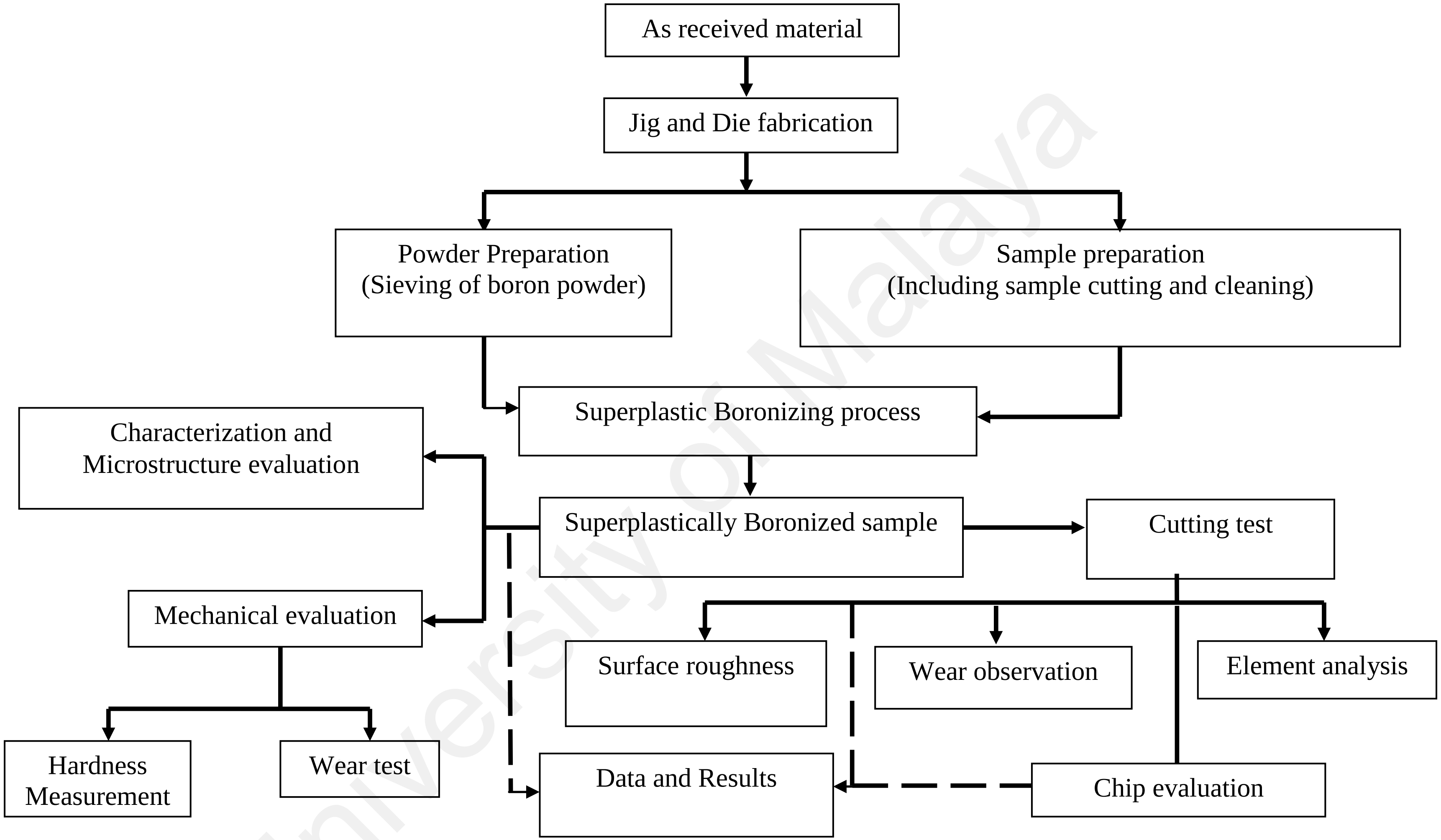


Figure 3.1: Flowchart of experimental work

3.2 Fabrication of Superplastic Boronizing Clamp

A clamp consisting of die and jigs was specially designed and fabricated to perform superplastic boronizing, as shown in Figure 3.2. The material used in fabrication of boronizing clamp is high temperature resistant stainless steel. The high temperature resistant stainless steel is well known of its corrosion resistance, high ductility, strength and hardness. It has melting point in range of 1673K to 1723K. Thus, these properties are suitable for fabrication of clamp for superplastic boronizing process.

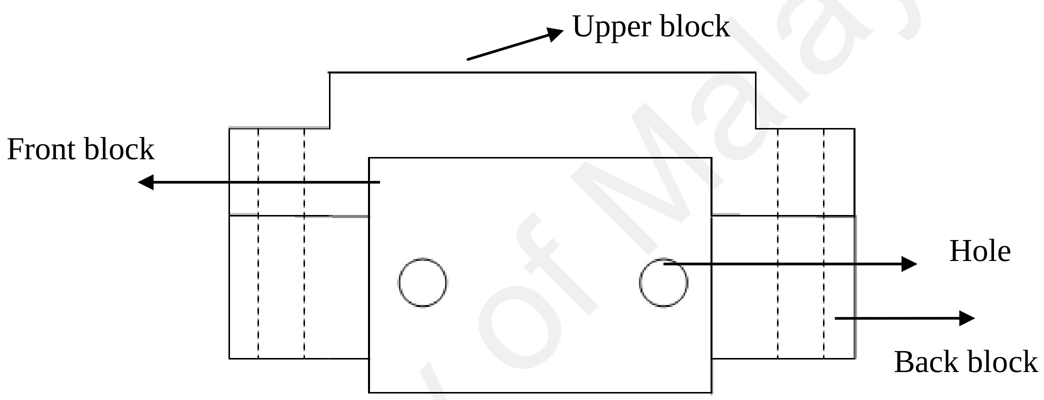
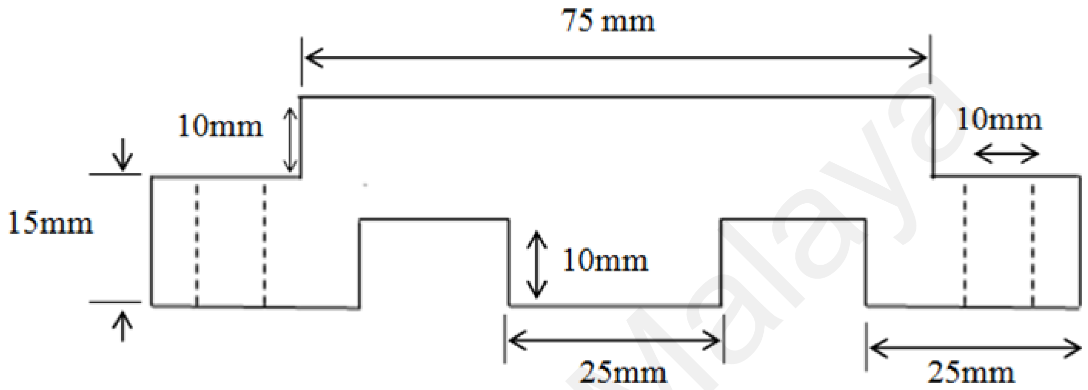


Figure 3.2: Schematic diagram of superplastic boronizing clamp

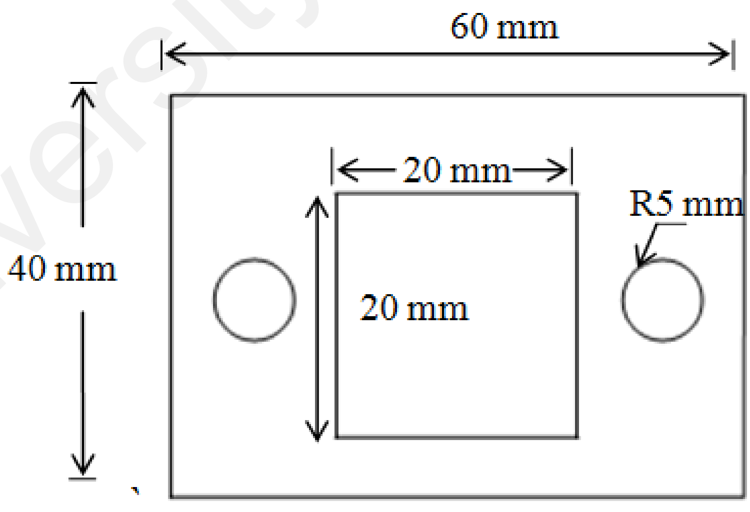
The purpose of designing the clamp is to hold the sample that surrounded by boronizing powder in the middle hole of clamp, while initial load applied. The designed clamp can be divided into 3 parts which were upper, front and back block. The function of the parts is as follow:

i. The upper block was designed to cover the upper clamp.
ii. The front block will covered the front part of clamp.
iii. The back block was designed to place the sample.

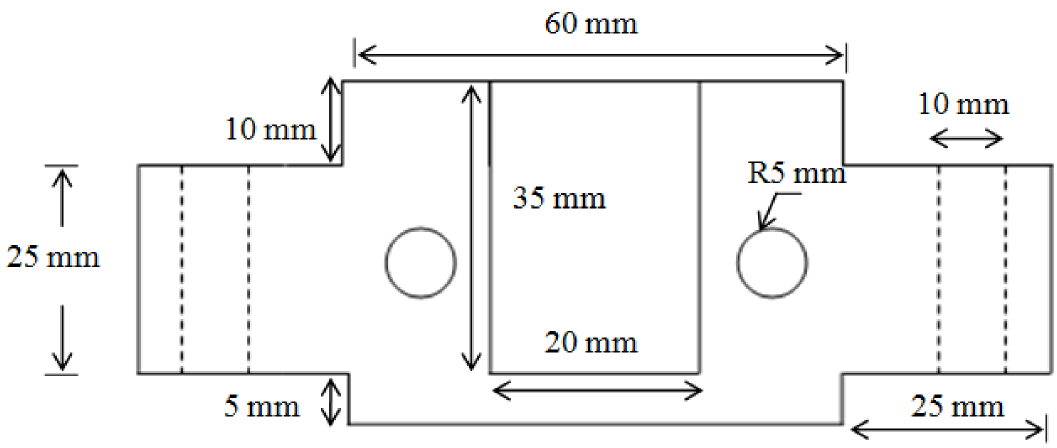
Hole with radius 5 mm on the all parts of clamp were drilled in order to slot in the bolts and nuts. Therefore, all parts attached and initial load can be applied. Initial load is applied by tightening the bolts and nuts of the clamp with certain values of torque using a torque wrench. The dimension and schematic diagram for all parts are shown in the Figure 3.3. The thickness selected for the clamp design is appropriate to resist pressure and temperature applied during the superplastic boronizing process.



(a) Upper block



(b) Front block



(c) Back block

Figure 3.3: Schematic diagram of superplastic boronizing clamp (a) upper block (b) front block and (c) back block

3.3 Powder Preparation

Commercial Ekabor-1 powder by Bortec Germany is used as a boronizing agent. Initially the as received particle size of the boron powder is less than 150 µm. However, powder with particle size less than 20 µm is used in this experiment since ultra hard boride surface can be obtained through usage of this powder. To obtain powder with particle size less than 20 µm, sieving process is done using analytical sieve shaker. The sieving process is started from the largest to the smallest screen sieve opening. The top sieve has the largest screen openings is poured by the largest particle size of boron powder with size less than 150 µm, followed by size less than 90 µm, less than 45 µm and last with size less than 20 µm. The column (consist of sieve screen opening that have been compiled accordingly) is typically placed in a mechanical shaker and fixed with the time. The process is repeatedly, in order to obtain an amount of smaller particle size of boron powder. Figure 3.4 show an illustration of the sieving process. Previous study shows that the surface properties of sample strongly influenced by size of powder particle. The finer the powder particle, the higher layer thickness and surface hardness obtained (Jauhari et al., 2007).

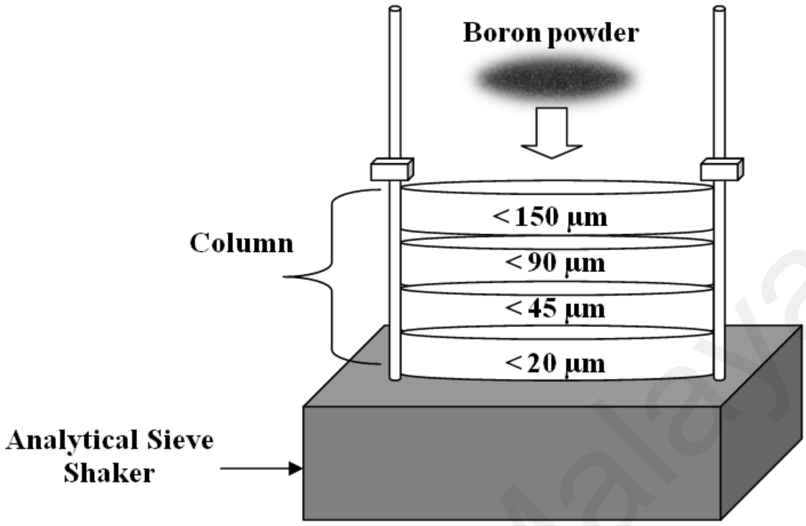


Figure 3.4: Illustration of sieving process using Analytical sieve shaker

3.4 Sample Preparation

Based on the size of commercial cutting tool, the treated duplex stainless steel is cut to the dimension of 12 mm x 12 mm x 5 mm with edges and hole radius of 1 mm and 2.5 mm respectively, using electrical discharge machine (EDM) as depicted in the Figure 3.5(a) and (b). EDM was selected because it can give relatively high degree smoothness and flatness to sample surfaces as compared to other cutting machine. Then, the sample was cleaned to remove grease and any contaminant by immersing it in the alcohol solution.

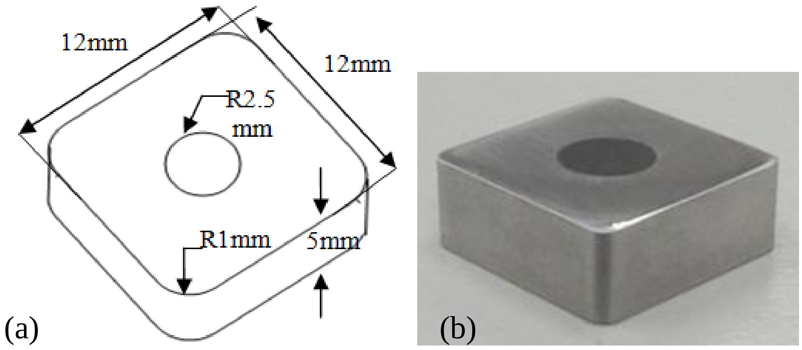


Figure 3.5: (a) Schematic diagram of sample and (b) Actual sample

3.5 Superplastic boronizing process

A boronizing agent, commercial Ekabor-1 powder with grain size less than 20 μm, was pack-filled into the die using a pack tool. Then, the sample was secured in the middle of the back block and surrounded by the powder. The upper and the front block sides of the clamp were put in place. Then the nuts are tightened together by using a torque wrench to the value of 6 kgf. m as an initial load is shown in Figure 3.6. The cross section schematic diagram set up for the superplastic boronizing clamp is shown in Figure 3.7. The superplastic boronizing process is conducted in a Carbolite tube furnace type CTF 17/75/300 at 1223 K (950 °C) for 6 hours holding time under argon gas atmosphere condition. Figure 3.8 shows the process diagram of superplastic boronizing process. The presence of argon gas is to prevents oxidation at high temperature and will be constantly supplied until the end of the process, where the sample cool down at about temperature of 470K.

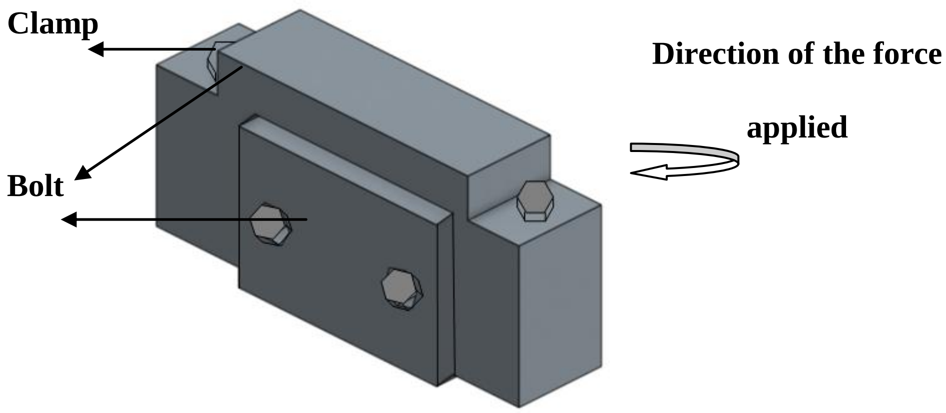


Figure 3.6 : Schematic diagram of clamp and direction force applied to the bolts and nuts

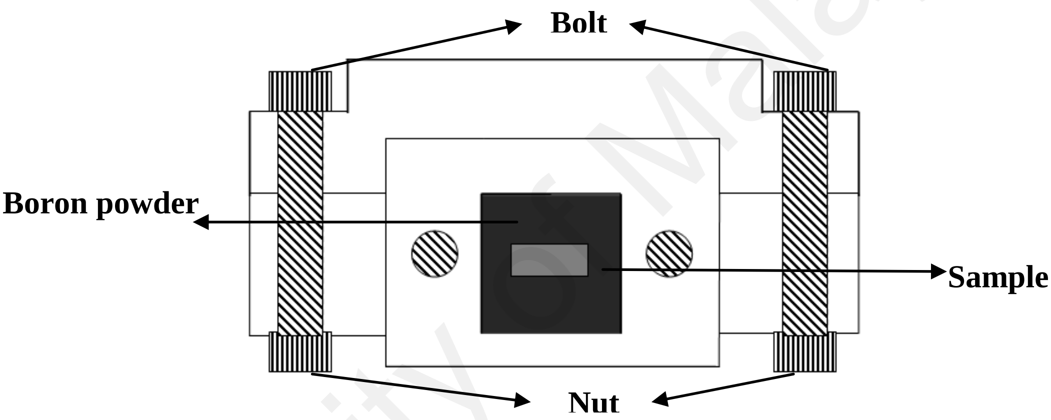


Figure 3.7 : Cross section schematic diagram of superplastic boronizing clamp

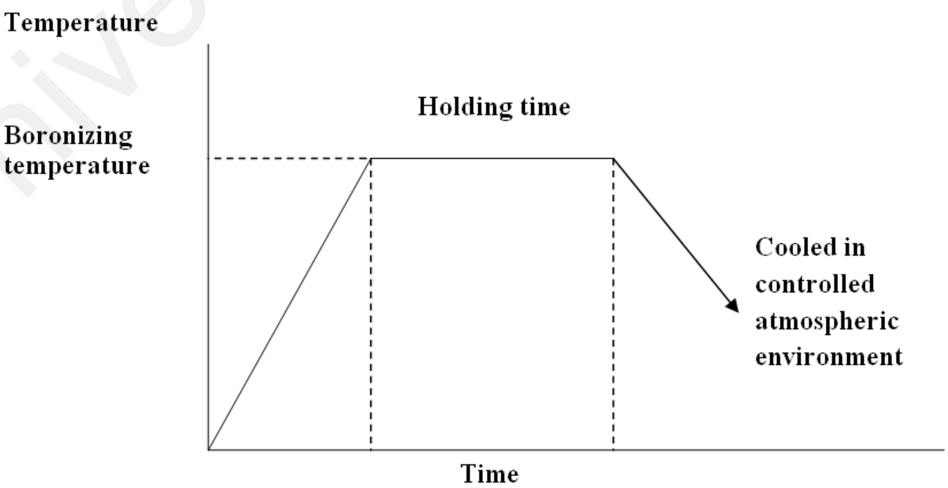


Figure 3.8 : Process diagram of superplastic boronizing process

3.6 Characterization and Microstructure Evaluation

The superplastically boronized (SPB) sample is evaluated in terms of its microstructure and the boronized layer thickness. The presence of boride phases were confirms by using a Philips X'Pert MPD PW3040 (XRD) analysis. As for microscopic study, optical microscope and Field Emission Scanning Electron Microscopy (Zeiss FESEM) were executed to observe microstructure and boronized layer. Prior to the study, sample was cut using Stuers diamond saw machine coupled with coolants as the cutting took place. It is then mounted to facilitate the application of grinding and polishing. The specimen was then ground with several grades of emery papers and followed by polishing, using alumina powder. After that, the specimen is etched by using etching solution. For microscopic study, special etchant for duplex stainless steel is prepared from hydrochloric acid (HCl) saturated with ferric chloride (FeCl3) and activated with small amount of nitric acid (HNO3).

3.7 Mechanical evaluation

For mechanical evaluation, hardness of the sample is evaluated by using Mitutoyo microhardness tester model MVK-H2. While coefficient of friction (cof) value is obtained by conducting wear test using Ducom pin on disc tester model TR20LE.

3.7.1 Surface hardness

Surface hardness of the boronized layers was measured with a Vickers diamond indenter under a load of 2N. The value of surface hardness is obtained by taking an average of three consistent readings.

3.7.2 Wear Test

Wear test is conducted to obtain coefficient of friction value. The measurement of cof value are done using pin on disc tester in which stationary pin (sample) was in contact with rotating disc aluminium 6061 plate. The pin is held stationary on top of rotating disc, while the load is applied through the pin. In this test, the sample is mounted into cylindrical pin shape on the pin holder during wear test. In order to obtained cof value of sample against aluminum 6061, the disc plate from aluminum 6061 has been specially fabricated, resembles to the original disc plate. As for comparison, cof for commercial carbide tool grade SNMG 120408-23 and high speed steel (HSS) tool has also been measured. During the test, the sample is held pressed against a surface of rotating disc through applied load. There is an electronic force sensor for measuring the friction force during the test and a computer for displaying the parameters and data of the test. The wear tests were performed under dry sliding conditions where the track diameter adopt as 80 mm, with a constant load (20 N), rotational speed recorded (477 rpm) and sliding speed (2 m/s). The value of cof directly obtained from the data. Figure 3.9 shows wear test set up using pin on disc tester.

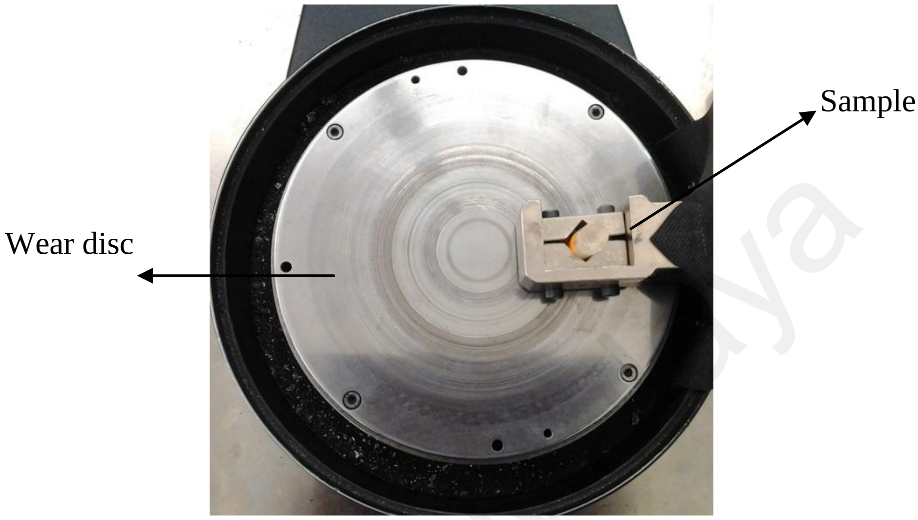


Figure 3.9: Wear test set up using Pin on disc tester

3.8 Cutting test

Assessment of cutting performance of sample is done by finishing operation turning test using Okuma computer numerical control (CNC) lathe machine type LB15. Finishing cut is selected prior to the thickness of the boronized layer obtained in this work. Most common method used for cutting process is turning operation, especially for finishing machined parts.

Aluminum alloy rod grade Al 6061 was used in this work as a workpiece material during the cutting test since it is widely used in engineering application and one of the most extensively used of the 6000 series aluminium alloys (Ramesh *et.,* al 2015). Figure 3.10 shows schematic diagram of workpiece used during cutting test. The workpiece was divided into several portions with 60 mm length for every portion, in order to make an evaluation at different length. While to evaluate cutting tools performances and as comparison, carbide tool grade SNMG 120408-23 and high speed steel (HSS) tool were used during the cutting test.

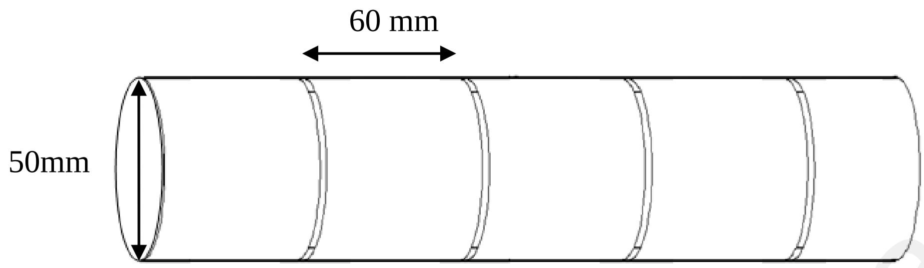


Figure 3.10: Schematic diagram of workpiece used during cutting test

Sample and workpiece setup for cutting test are shown in Figure 3.11. The cutting conditions were as follow:

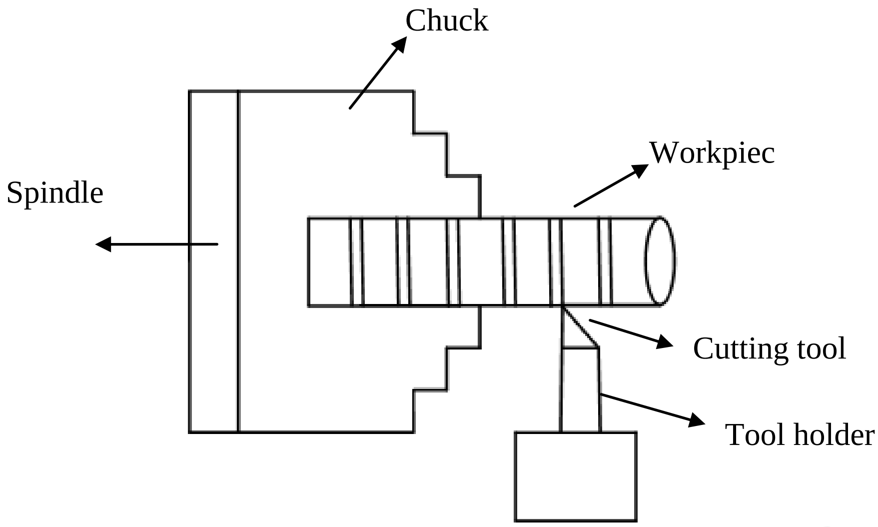
Feed rate : 0.05 mm/rev

Cutting speed : 250 m/min

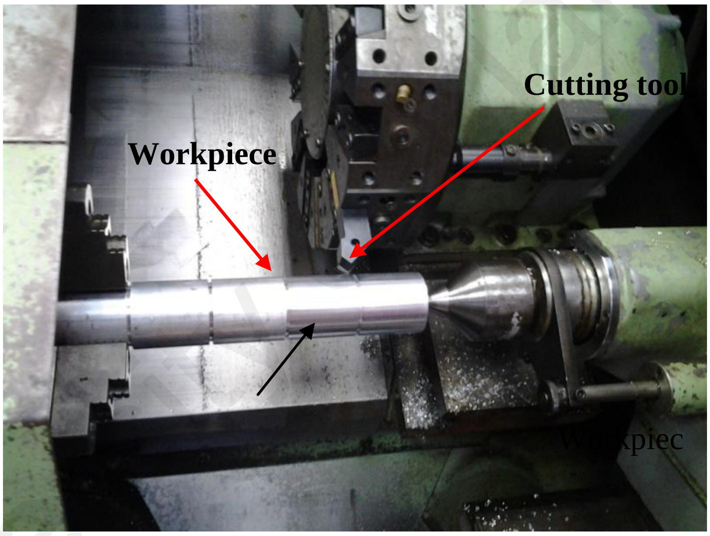
Depth of cut : 0.5mm

The cutting conditions are selected based on type of material to be machined (aluminum 6061) and machining operation (finishing operation turning test). As reported by Jaharah *et* al. (2009), the average surface roughness (Ra) produced is significantly affected by feed rate, followed by the cutting speed and depth of cut where the contribution of feed rate, cutting speed, and depth of cut were 45%, 32%, and 23%, respectively. Faster cutting speed applied results in better surface roughness (Abdallah et., al 2014). The tests are done in dry a dry machining, where no usage of coolant or lubricant.

Note: Dry machining or a green machining can help on saving the environment by reducing the use of cutting fluid.



(a) Schematic diagram of workpiece and cutting tool setup



(b) Cutting tool and workpiece set up for cutting test using CNC lathe machine

Figure 3.11: (a) and (b) cutting tool and workpiece set up for cutting test

3.9 Cutting test evaluation

Evaluation is done based on the surface roughness of the workpiece, condition of the tool after machining, and type of chip produced. The aluminium 6061 workpiece surface quality after machining is evaluated using Mitutoyo surface roughness measurement machine type S-3000, by measuring the average roughness of the surface involved. Prior to the measurement, the workpiece should be clean of any contaminants in order to get accurate data. The measurement is done by moving a stylus at a constant speed across a length of the workpiece surface. The roughness reading was automatically given after the stylus detected the surface of the workpiece in a few second. Roughness average (Ra) obtained, is the arithmetic average of the absolute values of the roughness profile ordinates. The result of surface roughness is obtained by taking an average of three readings.

Wear of cutting tool after machining and elemental analyses are observed by using scanning electron microscopy XL-40 (SEM) and energy-dispersive x-ray spectroscopy (EDX). By using of SEM, it is able to produce images with higher resolution and higher magnification. Elemental analysis is done to determine whether occurrence of element transferred between sample and workpiece material during the machining process through considering the percentage of existing element on cutting tool after machining process. Whereas type of chip produced is determined by using SEM.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 X-Ray Diffraction

Figure4.1 demonstrates the XRD patterns of treated DSS before and after superplastic boronizing process at 950°C. From the relative peak intensity in the XRD pattern, the existence of boride phases, FeB and Fe_2B were detected. These prove that occurrence of superplastic boronizing through diffusion of boron atoms into the substrate.

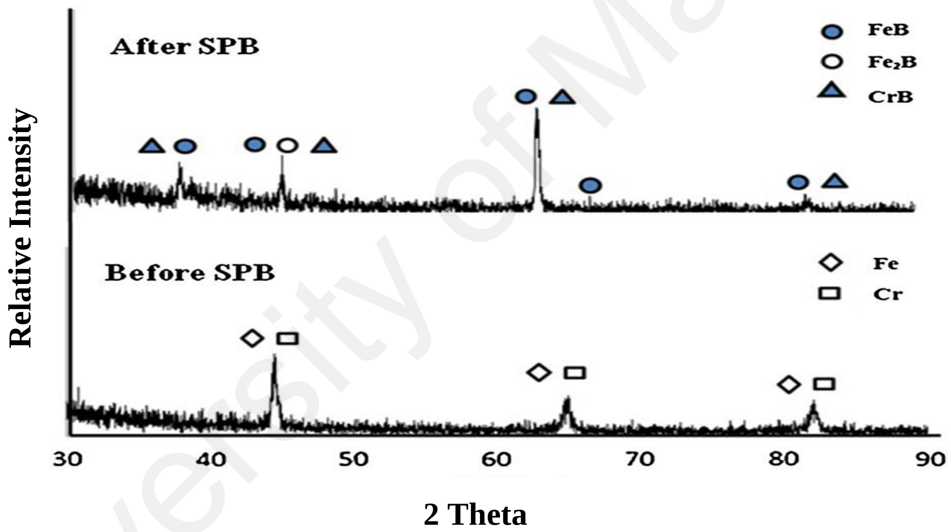


Figure 4.1: XRD pattern of DSS before and after superplastic boronizing

4.2 Microstructure of Superplastically Boronized Cutting Tool

4.2.1 Boronized layer

Figure 4.2(a) and (b) showed the morphology of superplastically boronized (SPB) samples. The figures shows smooth and compact boronized layer having boronized layer thickness of 50.5 µm in average. The boronized layer thickness obtained is comparable to the previous work done (Jauhari *et* al., 2007). Suggesting that superplastic boronizing has occurred as expected.

During the superplastic boronizing process, the surface asperities of the substrate has superplastically deformed through the initial pressure applied, creating a high density of vacancies, dislocations, and sub-grain boundaries. These defects are movable under the superplastic deformation, thus boron atoms diffused into the vacancies in the grain and at the grain boundary side (Xu et al., 1997). Therefore, increasing the rate of atoms diffusion leads to a formation of thick boronized layer.

The used of powder particle with size less than 20 µm also contributed higher diffusion rate in this work. As stated by Jauhari *et* al (2007), the finer the powder particle size, the bigger the contact surface between boron atoms and the substrate which finally leads to higher diffusion rate. Consequently, thick boronized layer obtained in this work.

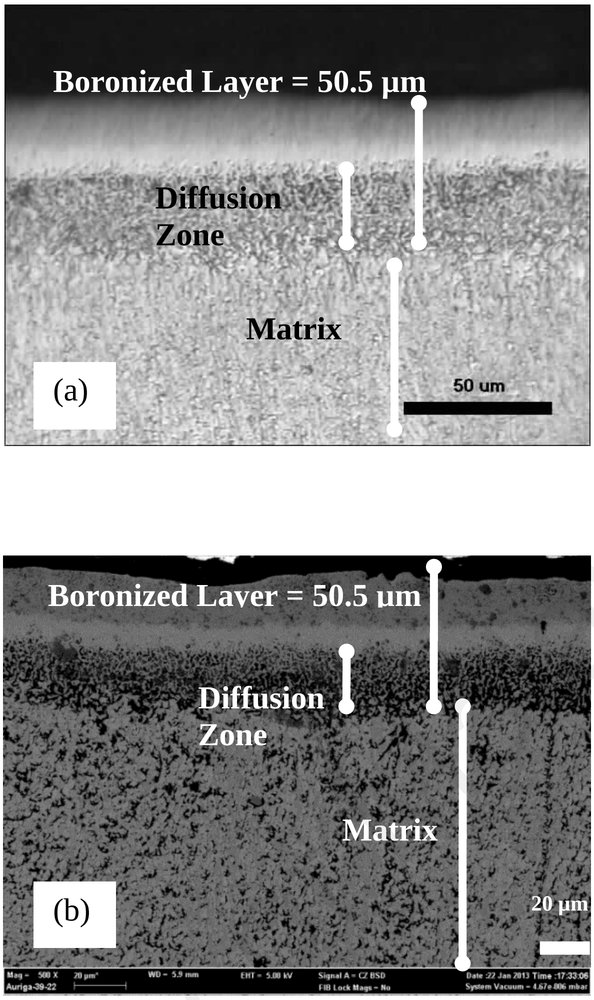


Figure 4.2: Boronized layer thickness of duplex stainless steel at temperature of 1223K with initial pressure applied 6 kgf under (a) Optical microscope and (b) FESEM

4.3 Mechanical properties of superplastic boronized cutting tool

4.3.1 Hardness

The initial hardness value for treated DSS with fine grain was 320 HV on average and conversely, after undergoing SPB processes, the surface hardness significantly increased to 3956 HV on average as showed in the Table 4.1. While, for commercial carbide and HSS, the average surface hardness values were 2500 HV and 1216 HV, respectively. This shows that SPB possess the highest value of hardness.

As explained in the previous section, affects from initial applied load has increasing the rate of atoms diffusion which leads to a formation of thick boronized layer. The same element has also increasing the hardness value of SPB. By applying initial pressure, high density of dislocation at grain boundaries of substrate will become more active area as compared to the inner side of the grain. This will promote more diffusion of boron atoms into substrate, consequently increasing hardness value of SPB. The initial load was also reduced the spaces among the powders, hence increased the interaction area between boron powder and sample. As has been stated by Jauhari *et* al (2007), the initial pressure applied not only superplastically deformed the surface asperities of substrate but also compacting the boron powder so that less void or space exist between them. Thus, this phenomenon contributed higher surface hardness value of SPB.

It is also known that superplastic deformation occurs mainly from the grain boundary sliding and slipping of the fine grains. The fine grains consisted of more grain boundaries on its structure, thus it is expected that these fine grains had transported the boron atoms from the surface to the inner part of the substrate through the said grain boundary sliding and slipping. Other than that, the particle size of the boron powder used in boronizing process also seems to be significant. The smaller the particle size of boron powder, the larger contact surface, thus producing better diffusion rate which resulting high surface hardness. This showed that the boron atoms with small particle size have an ability to diffuse deeper into substrate.

Figure 4.3 shows the variation of hardness value from surface layer to the core. It shows that the highest hardness was obtained at the surface. The high hardness of SPB was obtained by a combination of these elements; superplastic deformation of substrate's surface asperities (initial pressure), fine grain of duplex stainless steel and smaller particle size of boron powder (Jauhari et al., 2007).

Table 4.1: Hardness value for SPB, carbide, and HSS

Samples	Surface Hardness (HV)
SPB	3956
Carbide	2500
HSS	1216

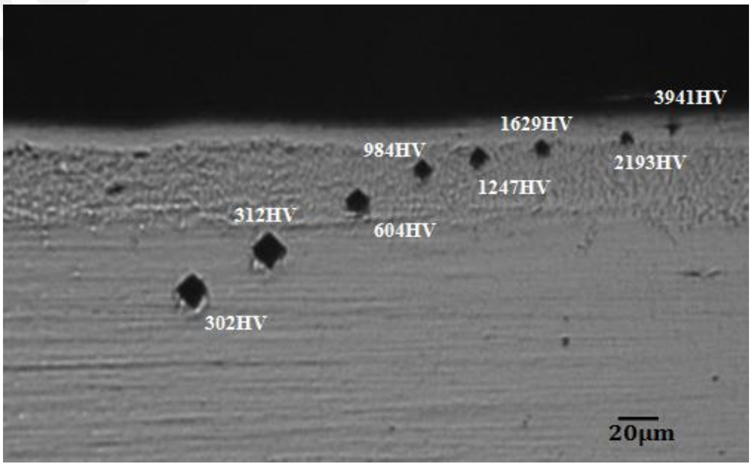


Figure 4.3: Optical micrograph showing the variation in hardness indentation from top layer to the interior of superplastic boronized DSS

4.3.2 Coefficient of Friction (COF)

One of the important parameter that should be determined is frictional coefficient value, since cutting process involved surfaces countering each other that will influence machining performances. The exposing surfaces will be directly affected by the surface friction through an energy that is transformed into motion and heat. Thus, it is necessary to determine the value of frictional coefficient for the superplastically boronized (SPB) cutting tool.

From the results obtained as described in Table 4.2, the frictional coefficient value for SPB sample with Al 6061 disc was 0.62 which was the lowest as compared to carbide and HSS. Whereas for carbide and HSS, the frictional coefficient value were 1.02 and 0.80, respectively. From Figure 4.4, SPB sample shows less frictional force involved during the wear test as compared to HSS and carbide, resulting in low value of cof obtained. SPB sample, consist of a smooth boride layer on the top surface that reduced friction to give a lower cof value. Low cof value gives an impression of less friction involved between the surfaces of SPB and the workpiece, which shows an improved machinability. Additionally, low coefficient of friction between two contact surfaces will lessen the amount of energy that is transformed into heat or noise - instead of motion - where it can disrupt machining process by formation of built-up edge (BUE) with unpleasant noise. With low coefficient of friction, the motion becomes smoother and more efficient contributing towards better performance of cutting tools.

Table 4.2: Coefficient of friction value for SPB, carbide and HSS tool

Samples	Coefficient of Friction (Al 6061)
SPB	0.62
Carbide	1.02
HSS	0.80

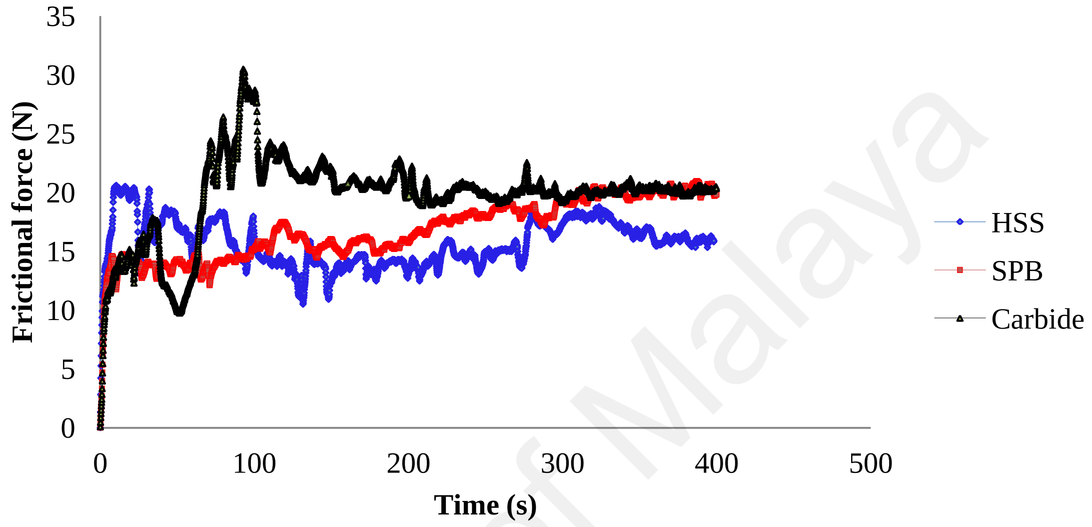


Figure 4.4: Frictional force vs time graph for sample of SPB, HSS and carbide cutting tools

4.4 Cutting test: Performances and Evaluations

Cutting tests were carried out to test the reliability of SPB cutting tool and to ensure that it can be served as a cutting tool.

4.4.1 Surface roughness of Aluminum 6061 workpiece

Mainly, two types of machining operation are roughing and finishing cuts. In this work, the thickness of boronized layer was accomplished at 50.5 µm. Therefore, the study is particularly emphasizes in finishing cut, adapting the said thickness of boronized layer. According to the surface roughness produced by the common production methods (ANSI B46.1-1962, R1971), surface roughness value for turning finishing is 0.4 µm, whereas for superfinishing is 0.025 µm.

Table 4.3 shows the average surface roughness (Ra) value of workpiece surface after certain amount of cutting. Results shows that for SPB and carbide sample, the measured values of Ra were much favourable, ranging between 0.16 µm to 0.31 µm and 0.16 µm to 0.26 µm respectively. Still in the preferred range of finishing. However for HSS, the average surface roughness value was distinct from SPB and carbide. From the initial machining until 1087.56 m of total tool travel distances, Ra value for HSS ranging between 11.75 µm to 15.35 µm, which is is out of the desired finishing range. Therefore, the cutting test for HSS is finished at total tool travel distances of 1087.56 m. However the cutting test for SPB and carbide are continued until total tool travel distances of 3054.83 m.

Table 4.3: Average surface roughness with increasing of total tool travel distances

No.	Total Tool Travel Distances (m)	Average Surface Roughness (Ra)		
		SPB	Carbide	HSS
1	182.96	0.17	0.21	14.57
2	364.45	0.19	0.16	14.24
3	545.94	0.26	0.26	15.35
4	727.43	0.24	0.20	14.49
5	907.66	0.24	0.21	11.75
6	1087.56	0.21	0.17	12.38
7	1267.79	0.18	0.18	
8	1448.01	0.16	0.19	
9	1988.69	0.25	0.22	
10	2521.76	0.19	0.21	
11	3054.83	0.31	0.19	

The data of Ra value is plotted into graph. Similar pattern of Ra value is observed in the graph for both SPB and carbide cutting tools as shown in Figure 4.5. The graph shows the variation of average surface roughness as a function of total tool travel distances, for both samples of SPB and carbide until 3054.83 m total tool travel distances. As can be seen, the Ra value for both tools are comparable from initial machining until 2521.76 m total tool travel distances. However at 3054.83 m total tool travel distances, the Ra value slightly higher for SPB tool but still in the preferred range. This may suggest that initial tool wear or existing of adhered layer (built up edge) on cutting edge of tool may interrupt the machining processed, since instantaneous change in roughness profile of SPB is observed. As stated by Mathew *et* al (2010), the built-up-edge (BUE) which changes the instantaneous cutting tool profile has the greatest influence on surface roughness than most other factors. Thus, this factor may consider in instantaneous change of Ra value for SPB sample at 3054.83 m total tool travel distances.

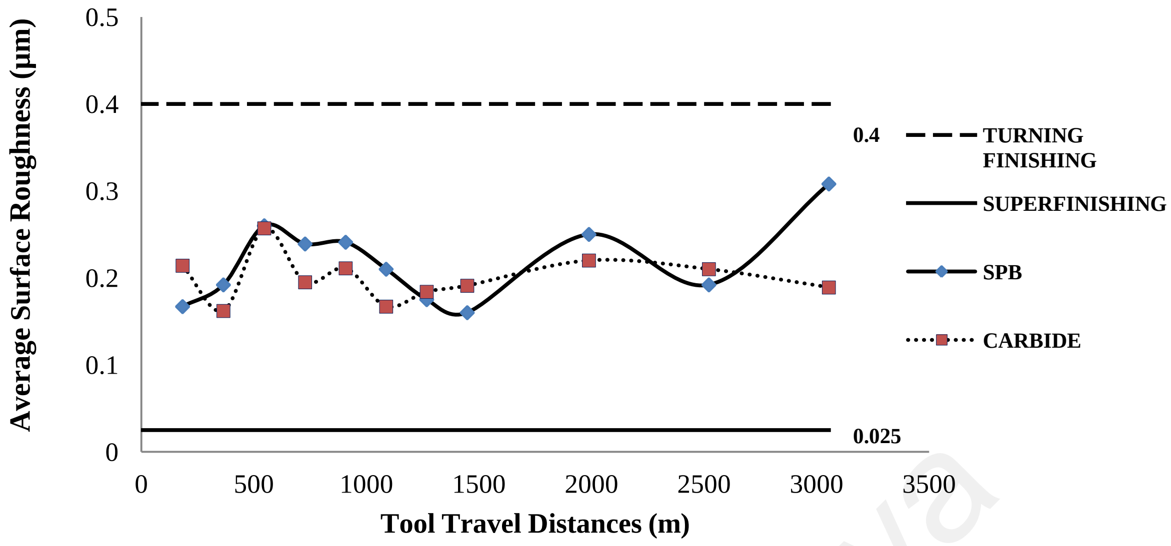


Figure 4.5: Average surface roughness (Ra) as a function of tool travel distances on Aluminum 6061 workpiece

Since the Ra value for HSS was out of the desired finishing range, data for HSS has finished at 1087.56 total tool travel distance and does not included in the graph . As stated by Siddanil et al (2016), soft and ductile material like cemented carbide, ceramics and HSS will cut at higher cutting speed than alloy or carbon steel tools. This shows that HSS required higher cutting speed during machining and may suitable in roughing cut, instead of finishing cut. Thus, from these result, it can be deduced that surface roughness value is tool material type dependent (Lawal et al., 2016).

Figure 4.6 shows theworkpiece aluminum 6061 conditions after machining at tool travel distances of 1087.56 m for HSS, SPB and carbide. From observation, HSS show rough surface finished while SPB and carbide shows fine (shiny look) surface finished. These figure indicated the value of Ra obtained at total tool travel distances of 1087.56 m. Rough surfaces usually wear more quickly and have higher friction coefficients than smooth surfaces(Siddani et al., 2016). The finest roughness profile obtained for sample of SPB was at tool travel distance of 1448.01 m as shows in Figure 4.7. Whereas for carbide and HSS tools were at 364.45 m and 907.66 m respectively. .

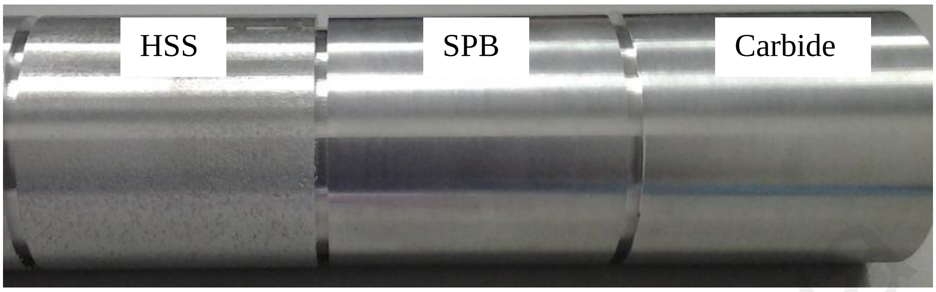
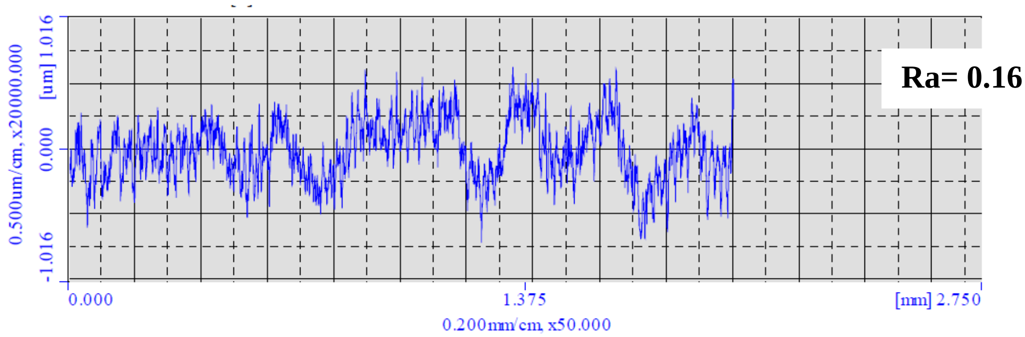
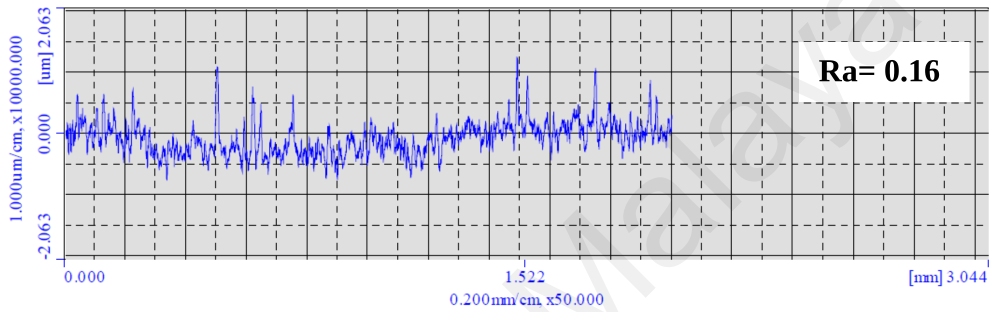


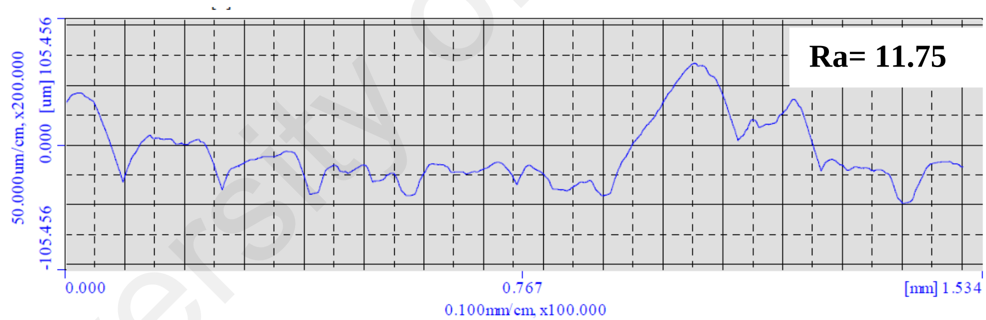
Figure 4.6 : Workpiece aluminum 6061 condition after tool travel distances of 1087.56m for sample of HSS, SPB and carbide



(a) SPB



(b) Carbide



(c) HSS

Figure 4.7:The finest roughness profile obtained for samples of SPB at tool travel distances of (a) SPB (1448.01 m), (b) carbide (364.45 m) and (c) HSS (907.66 m)

During machining aluminum alloys, the use of lubricant is important since aluminum alloys likely to stick to the workpiece and cutting tool due to the heat generated. These continuous action will form built-up edge (BUE) on the tool at which this BUE will influence the surface finish of the workpiece. As stated by Sreejith and Ngoi (2000), in dry machining, there will be more friction and adhesion between the tool and the workpiece, since they are subjected to high temperatures.From results in Figure 4.5, although the test was performed in the dry or green machining, SPB still can achieved finishing range up to 3054.83 m total tool travel distances.

The use of lubricant can reduce the temperature during machining process since machining involved of heat generated between cutting tool and workpiece. However in term of ecology, dry machining were more desirable. The use of coolant is known to cause pollution with regard to waste disposal. Apart from that, dry machining would be more cost effective for manufacturing process in the aspects of procurement, maintenance and waste management. The coolants and lubricants used for machining represents 16% - 20% of the manufacturing costs, hence the extravagant use of these fluids should be restricted (Sreejith and Ngoi, 2000).

From these outcomes, it is proved that the workpiece shall remain workable yet distinctively yielded better surface finishing without the use of lubricant in machining aluminum alloy. Thus, shows that machining with SPB sample can be qualifying as eco-friendly. Besides, SPB sample can also be recycled since it is categorized as metal base cutting tool.

4.4.2 Wear Analysis

All samples of SPB, carbide and HSS being characterized by FESEM showed the formation of adhered layer in form of built-up edge (BUE) material on the rake face and tool flank as shows in Figure 4.8 and Figure 4.9. However, prior to the poor results of HSS in the previous section, comparison are done only between SPB and carbide tool in this section.

The formation of BUE fluctuated with the increasing of machining distances as shown in Figure 4.9. Since BUE is an unstable material, its formation will be seen developing and diminishing during the machining process. From the observation under FESEM, the existing of BUE on the rake face and tool flank of the both samples of SPB and carbide were unstable. The position of BUE has changed at machining distances 1988.69m from left side (Figure 4.8(a)) to the right side (Figure 4.8(b)). Whereas at machining distances 3054.83m, most of BUE materials had vanished and only little BUE were found on both samples.

These were results from the cutting action, where it involved of high pressure and high frictional force between two contact surfaces. The contact surfaces during machining involving of two types, that are between – workpiece and cutting tool-cutting tool and chip- surfaces. As has been state by Nedic (2005), the cutting process was carried out with high pressure between contact surfaces; large amount of heat generated in the cutting zone and intensifies tool wear. The formation of high friction force leads to develop adhered layer in the form of BUE. Since it is unstable material, BUE may vanish. The existence of the adhered layer (in form of BUE) on the rake face of SPB and carbide tools suggested high friction forces involved between the chip and the tool. Hence, machining zone involved of high pressure and high frictional force, it is significantly influenced the machining quality of SPB and carbide tool. Whereas, a smaller amount of energy (heat) entering the machining zone results in an increase of the tool life and machining quality (Astakov et al., 1997).

BUE that formed in the rake face and tool flank of the SPB and carbide can be divided into two zones namely the sticking and the sliding zones as shown in Figure 4.8. Sticking zone was formed by tool and chips interface reaction during cutting process. Whereas, sliding zone was formed due to excessive BUE material that spread through chips side during the cutting process. Adhesion between the chip and the tool was higher than the adhesion between the layers of the chip itself (Xiao et., al 2009). However it can be seen that most of these regions disappear at machining distances of 3054.83 m since BUE was unstable material. From results, the condition of cutting tool for both SPB and carbide most comparable from the earlier of machining until 3054.83m of total tool travel distances. Showed that better cutting tool from metal base can be produced through superplastic boronizing process.

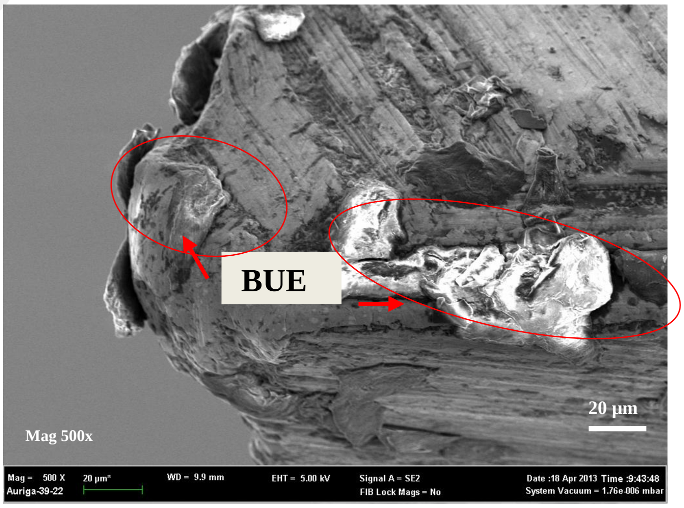


Figure 4.8: Formation of BUE on cutting edge of HSS

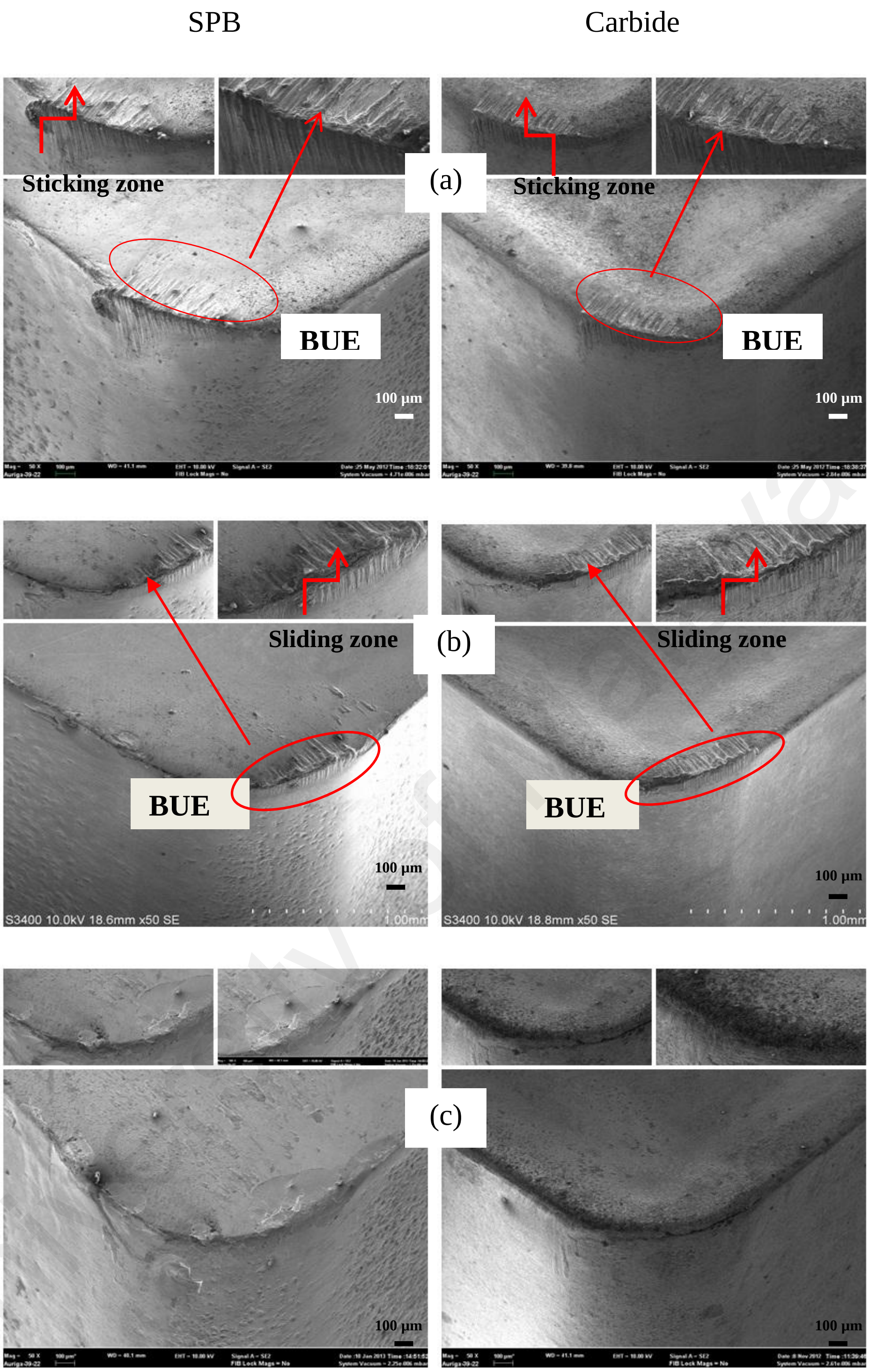
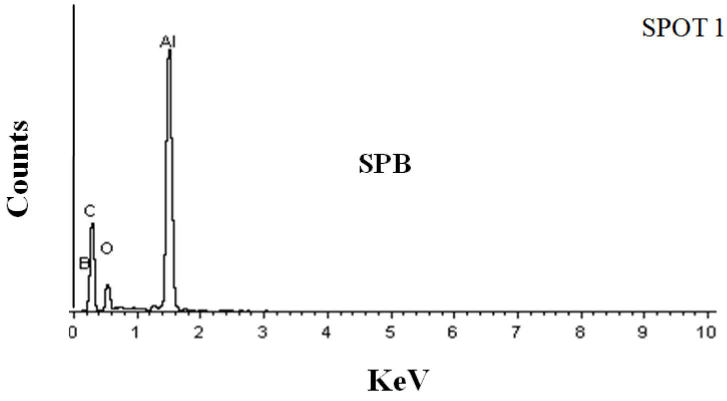


Figure 4.9: Formation of BUE on cutting edge of SPB and carbide tool at different magnification and tool travel distances (a) 182.96 m, (b) 1988.69 m and (c) 3054.83 m

4.4.3 Elemental Analysis

Elemental analysis is done using EDX, to prove the occurrence of transferring elements during the machining process. The EDX spectra of spot area on the cutting edge surfaces of SPB and carbide are showed in Figure 4.10 respectively. From results, the EDX spectrum peak of aluminum is seen to be the highest. Aluminum is the main element in aluminum 6061 alloy with proportion of 95.8 wt% - 98.6 wt% (Kumar et., al 2016). Thus, by considering the main element of the workpiece, its proved that there are existence of aluminum element on the cutting edges surfaces of SPB and carbide samples, in the form of BUE.

Both samples of SPB and carbide showed the presence of aluminum with proportion of 24.59 wt % and 55.11 wt % respectively, at the spot area of cutting edge as shown in Figure 4.11. Since BUE is unstable material, this element increases, decreases and sometimes disappear during the machining process as has been discussed in the previous section. As has been stated by Carrilero *et* al., 2002, these fragments are mechanically unstable and, thus, it can be removed from the tool surface by the action of the high strength cutting forces that are produced. However, the drawback – existing of this transferring element - leads to produce poor surface finishing in machining. BUE may result in higher surface roughness and less precision. While on the other hand, BUE layer prevents the rake face from wear and is probably a reason why no wear of the rake face is ever observed in machining of aluminum (Xiao et., al 2009).



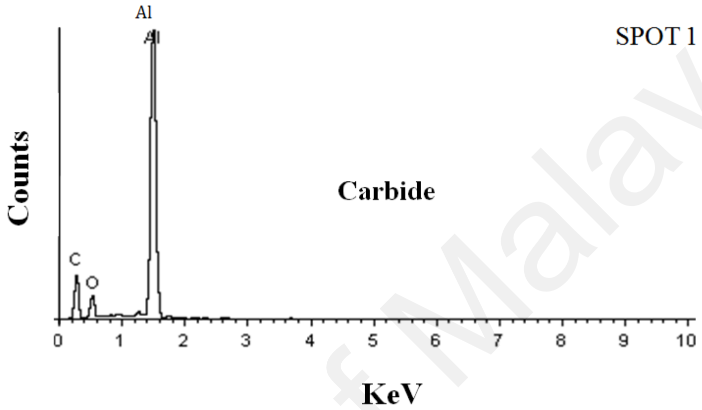


Figure 4.10: EDX spectraon cutting edgesurfaces for sample of SPB and carbide

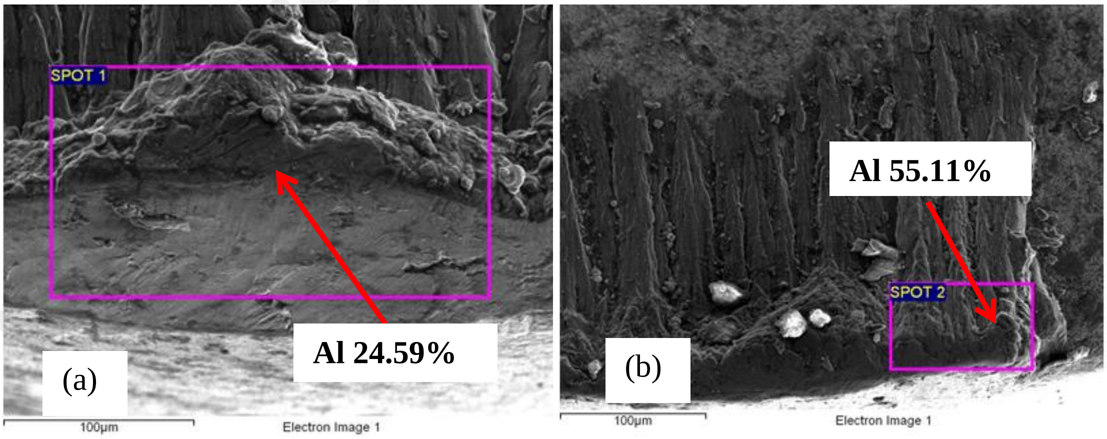


Figure 4.11 : Aluminum 6061 elements on the surface of the tools in wt% (a) SPB and (b) Carbide

4.4.4 Chip Evaluation

In machining, the types of chip formed greatly influenced the surface finished of the workpiece, cutting forces and cutting operation. Chips produced by an action of shear between workpiece and cutting edge. Through observation under FESEM, the chips that formed in the earlier machining for SPB and carbide were almost similar. The chips that formed can be depicted in the serrated types with saw tooth appearance as shown in the Figure 4.12(a) and (b). Whereas at 3054.83m of tool travel distances, the chips that formed for SPB were in the saw tooth but with lamellae like wrinkles. However carbide tool remained in the saw tooth shape as shown in the Figure 4.12(c). The serrated chip is the frequent chip morphology during high-speed machining of ductile materials (Bing and Zhanqiang, 2013). The formation of saw tooth with lamellae like wrinkles for SPB sample may suggests that tool wear has taken place. This can be related with the previous section, where the average surface roughness of the aluminium 6061 workpiece increased quite significantly at this point, but yet still in the preferred turning finishing range.

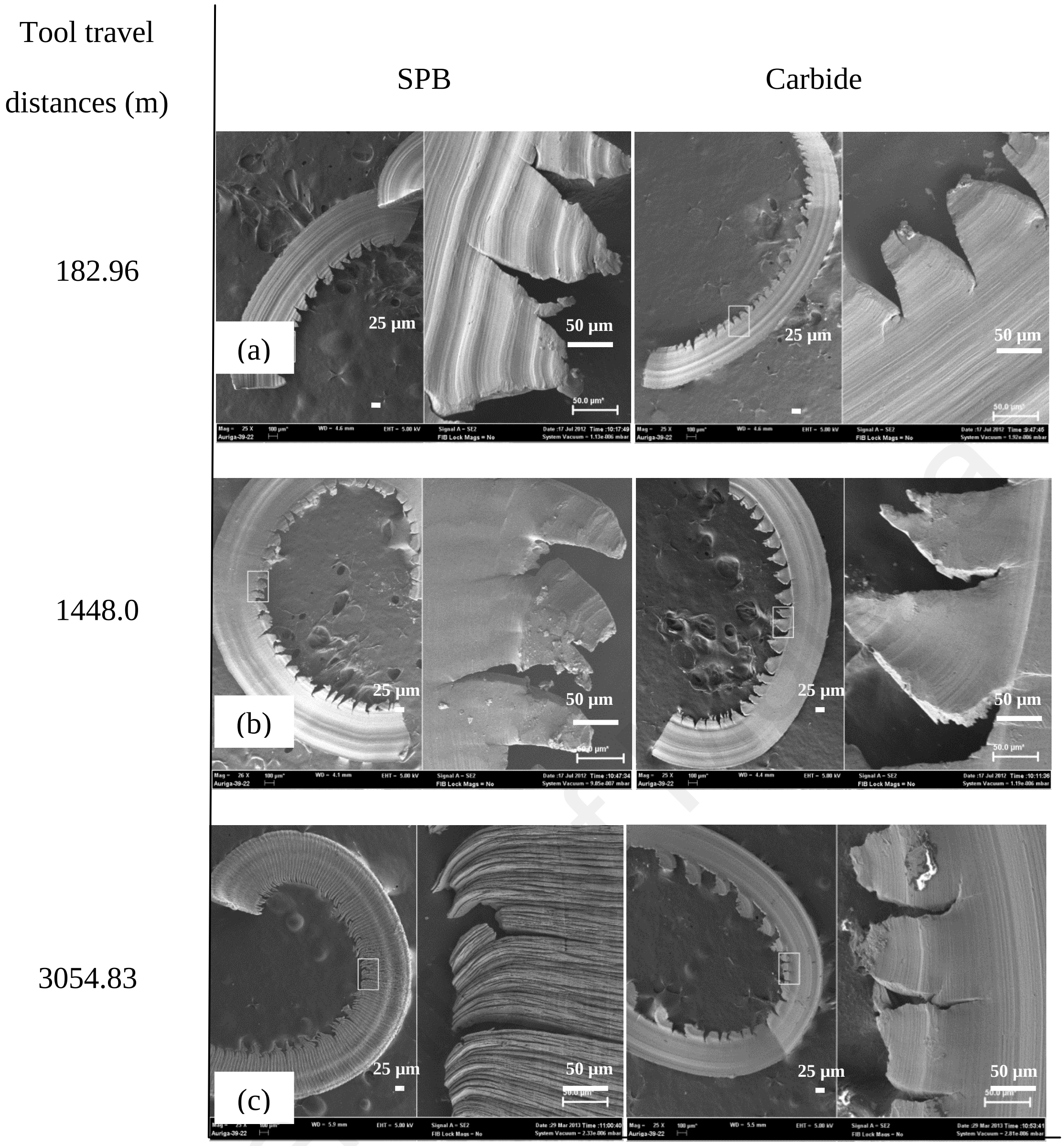


Figure 4.12: The shape of chips after (a) 182.96 m (b) 1448.01 m (c) 3054.83 m total tool travel distances

CHAPTER 5: CONCLUSIONS

In this study, development of cutting tool by exploitation of superplastic boronizing process and duplex stainless steel has been carried out successfully. The results were compared with the commercial carbide and HSS tools. From the results obtained, this study can be concluded as follows:

1. Through superplastically boronizing of DSS, a high quality metal base cutting tool that is comparable to the conventional carbide tool is possible to be produced.

2. The superplastically boronized DSS tool produced boronized layer of 50.5µm with surface hardness of 3956HV and coefficient of friction value of 0.62, that is lower than those of carbide (1.02) and HSS (0.80) tools.

3. The aluminium 6061 workpiece machined by the superplastically boronized DSS tool under dry condition machining produced turning finishing below 0.4µm, beyond travel distances of 3000m that is comparable to carbide tool but far better than HSS tool.

RECOMMENDATIONS

1. Since SPB tool is comparable to the conventional carbide tool and has its own potential as a cutting tool, further study on improvement thickness of boronized layer can be done, thus the machining process will not only limited on finishing cuts only.

2. In order to measure performance of the superplastically boronized cutting tool, additional testing such as impact test can be done to determine the overall toughness of the tool.

3. Optimum cutting condition for SPB tool should be determined by test the tool at different cutting conditions. The optimum cutting conditions can lead to the minimization production costs and enhancement surface finish of the workpiece.

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