JMEPEG (2006) 15:117-121
DOI: 10.1361/105994906X83510

1059-9495/$19.00

Machining Characteristics and Fracture Morphologies in a Copper-Beryllium (Cu-2Be) Alloy

K.V. Sudhakar, J.C. Cisneros, Hector Cervantes, and Cosme Gomez Pineda

(Submitted August 10, 2005)

The technology of materials removal is improved greatly by the introduction of advanced cutting tools like cubic boron nitride, ceramics, polycrystalline diamond and the more recent whisker-reinforced materials. In this paper, the influence of cutting temperature on machinability, mechanical properties, microstructure, and fracture morphology of Cu-2Be alloy using a polycrystalline diamond cutter is investigated. The information on machining, microstructure, and fracture morphology of Cu-2Be alloy are very useful to understand their fabrication characteristics and the basic mechanisms of its deformation and fracture. The machinability (in terms of surface finish) of Cu-2Be alloy is evaluated as a function of cutting temperature, resulting from wet and dry cutting. Machining is carried out on a Hardinge Cobra 42 CNC machine (Hardinge Inc., Elmira, NY), and the machining parameters used—cutting speed, depth of cut, and feed rate—are kept constant during both wet and dry cutting. The machined surface finish on Cu-2Be alloy is measured using a surface finish analyzer (Surftest 401, series 178) technique. The machined specimens are examined for their strength and hardness properties using a standard Universal Testing Machine and Rockwell hardness tester, respectively. Wet cutting (using coolants) produced a smooth surface finish when compared with dry cutting of the Cu-2Be alloy. The machined specimens are examined for their microstructural features using a Nikon optical microscope. The specimens are etched using a suitable etchant solution for revealing such microstructure constituents as grain size, phase proportions, and the possible overheated areas (especially in dry cutting). The fractured surfaces from the tensile and impact toughness tests are investigated for their fracture morphologies (dry and wet cutting) using a microprocessor-controlled scanning electron microscope (Jeol Model JSM 5910 LV). A detailed analysis is also made to understand and interpret the basic fracture mechanisms responsible for crack initiation and crack propagation. The Cu-2Be alloy showed relatively higher mechanical properties in wet cutting in comparison to dry cutting operations. Fracture studies demonstrated intergranular and ductile fractures as dominant modes of fracture mechanisms in Cu-2Be alloy.

Keywords Cu-2Be alloy, fracture morphology, machining, mechanical properties, microstructure, polycrystalline diamond cutter, wet and dry cutting

1. Introduction

The technology of metal cutting has been improved by contributions from all branches of industry with an interest in machining. Productivity has been increased through the introduction of such recent cutting tools as alumina-based ceramics and silicon nitride-base ceramics, the most recent being whisker-reinforced materials that allow cutting speeds to be increased by many times. To further increase efficiency and reduce costs, it is necessary to improve our understanding of the metal cutting process. The special properties required for cutting machine steel at high speed have led to the development of the most advanced tool materials. This development continues today with the use of ceramics with multiple coating technology and ultrahard tool materials. Machine tool manufacturers have developed machines capable of making full use of the new tool materials. Tool designers have optimized the tool shapes to provide a long tool life at high cutting speeds. New coolants and lubricants have been designed to improve surface finish and permit increased rates of metal removal (Ref 1). Metal cutting operation is an important manufacturing process in car industry, electrical engineering, railways, shipbuilding, aircraft manufacture, and the machine tool industry itself, and all of these have large machine shops with automated facilities. Therefore, to further increase efficiency and reduce costs, it is necessary to improve our understanding of the metal cutting process. Although the effect of temperature on stress-strain relationship and the flow and fracture properties is well known for a metallic work piece material, it is important to consider the type of cutter used for machining/cutting. In general, the strength of the material decreases and the ductility increases as the temperature is increased. Cutting fluids are widely used in machining operations.

The copper beryllium alloys are commonly supplied in wrought product form. Wrought products are those in which final shape is achieved by mechanical working (by forging, rolling, extrusion, drawing etc.) rather than by casting. Copper beryllium alloys are often chosen due to their inherent resistance to stress relaxation. Miniaturization in computer hardware, automotive interconnections, and aerospace systems has accented the importance of high thermal stability. Today, many electronic contacts and other spring elements must remain stable longer while operating at higher temperatures than ever before. Wire (typical size varying from 0.50 to 0.050 in.) is one

---

K.V. Sudhakar, J.C. Cisneros, Hector Cervantes, and **Cosme Gomez Pineda,** Department of Mechanical Engineering, Universidad de las Américas-Puebla, Santa Catarina, Mártir, Puebla 72820, México. Contact e-mail: sudhakara.katapadi@mail.udlap.mx.

Table 1 Chemical composition of Cu-2Be alloy

Element	Be	Co	Ni	Pb	Cu
Weight, %	2.0	0.1	0.1	0.01	Bal

of the most versatile copper beryllium product forms with no other product having applications based on as many diverse attributes. Applications of round wire include miniature machined electronic sockets; long travel coil springs; cold headed fasteners; spring-loaded test probes; lightweight, fatigue-resistant stranded cable; connector contacts; shielding cloth; corrosion- and biofouling-resistant marine wire and wire mesh structures; and eyeglass frames. The ease with which copper beryllium can be worked allows fabrication of large, near-net shape components by forging and extrusion. Typical forging processes include rotary forging, ring rolling, roll forging, swaging, cold heading, and various open and closed die techniques. Forgings include disc-shaped resistance seam welding electrodes (open die forging), generator rings (ring forged), aerospace and hydrospace components, and gears and power transmission couplings. Extrusions find application in continuous long lengths, where economy is achieved by near-net shape techniques, in short lengths, where near-net shape processing is combined with high production rate, and in back-extruded parts, where relatively large diameter hollows can be produced economically. Extrusions include wear-resistant guide rails for computer peripheral equipment, heat- and fatigue-resistant mold segments for continuous casting equipment, abrasion- and galling-resistant dies, and die inserts for resistance flash welding.

The thermal expansion coefficient of copper beryllium is independent of alloy content over the temperature range in which these alloys are used. The thermal expansion of copper beryllium closely matches that of steels including the stainless steel grades. This ensures that copper beryllium and steel are compatible in the same assembly. Copper beryllium also has an elastic modulus 10-20% higher than other specialty copper alloys. Strength, resilience, and elastic properties are the specific properties that make copper beryllium the alloy of choice.

Specific technical literature (Ref 2-5) was consulted for Cu-Be alloys for review of their machining and mechanical properties. However, the technical information on their fracture behavior is very limited. The basic objective of the present investigation is to focus on fracture morphologies apart from studying the machining characteristics, mechanical properties, microstructure, and fracture morphology as a function of cutting tool and cutting temperature, with and without the use of coolant.

2. Materials and Methods

2.1 Material

The material used in the present investigation is a copper-beryllium (Cu-2Be) alloy in a rod form (wrought product), the chemical composition of which is given in Table 1. This is basically a high-strength Cu-Be alloy having relatively higher beryllium content.

2.2 Machining

The surface finish as a measure of the machinability of Cu-2Be alloy was evaluated as a function of cutting temperature, resulting from wet and dry cutting. Machining was carried out using a CNC machine (Hardinge Cobra 42, Hardinge Inc., Elmira, NY), and the machining parameters, namely, cutting speed, depth of cut, and feed rate, were kept constant during both wet and dry cutting. The machined surface finish on the Cu-2Be alloy was measured using a surface finish analyzer (Surftest 401, series 178, Mitutoyo Mfg. Co. Ltd., Kawasaki, Japan).

2.3 Tensile Testing of Cu-2Be Alloy

Mechanical properties of Cu-Be alloys are most frequently measured by the simple uniaxial tensile test. The test provides information that can be used in component design and applications. Tensile test information is also used in materials acceptance and in the process control of operations such as stamping, bending, rolling, machining, drawing, and slitting. Copper beryllium's properties are moderately strain-rate sensitive for test speeds in the strain rate range of 0.005-0.2 min^{-1}. The test was conducted at a constant speed or strain rate, outside this range.

The tensile tests for Cu-2Be alloys were performed as per the ASTM standard E8 (Ref 6). Specimens with gauge diameter 12.5 mm and gauge length 50 mm were tested on a universal testing machine (UTM) of capacity 300 kN. At least three specimens were tested for each of the average values of tensile properties reported in Table 3.

2.4 Hardness Testing of Cu-2Be Alloy

The surface of the samples was cleaned and polished to facilitate accurate hardness measurement. The hardness measurements were performed using a Rockwell hardness tester (Wilson Instrument Div., Model 3JR, NY). Although hardness testing does provide an indication of material strength, it is not a substitute for tensile testing. When tensile and hardness test data are both listed, tensile data is precedent and hardness data is from reference materials.

2.5 Optical Microscopy

The optical microscopy of the sample was carried out using a Nikon Epiphot 200 (Tokyo, Japan). The metallographic samples were subjected to standard polishing stages to obtain a scratch-free mirror finish. Cu-2Be alloy was etched using an etchant having composition 100 ml water, 1 ml NH_4OH, and 3 g ammonium persulfate. This etchant is specifically recommended for Cu-Be alloys.

2.6 Scanning Electron Microscopy

The fracture features of copper-beryllium alloy were studied using a microprocessor-controlled scanning electron microscope (SEM; Jeol Model 5910 LV, Tokyo, Japan). The fractured surfaces were cleaned thoroughly using acetone liquid in an ultrasonic stirrer before examination.

3. Results and Discussion

3.1 Influence of Dry Cutting on Machining Characteristics

Machinability is usually measured in terms of tool life, surface finish, power consumed, or productivity (Ref 7). In the present case, the surface finish of the copper beryllium alloy was evaluated for machining characteristics. The results of the

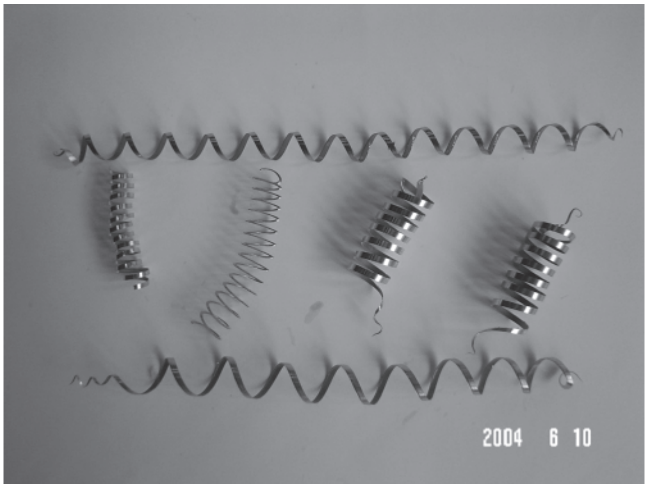

Fig. 1 Cu-2Be alloy chips from dry cutting

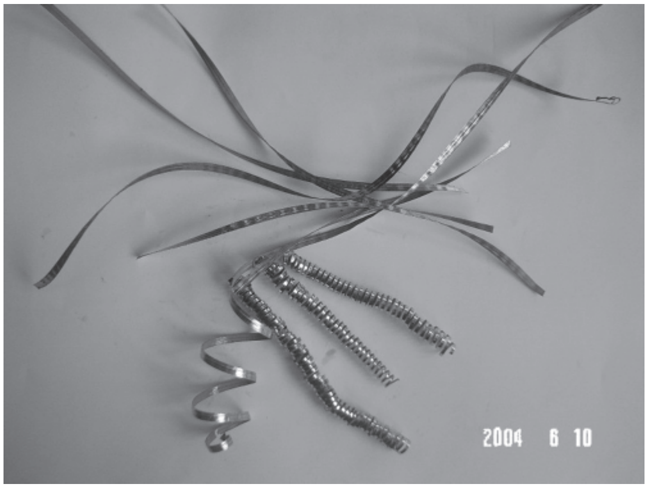

Fig. 2 Cu-2Be alloy chips from wet cutting

Table 2 Machining characteristics

Type of machining	Surface finish
Dry machining	1.035 μm
Wet machining	0.77 μm

Table 3 Mechanical properties

Type of machining	0.2% proof strength, MPa	Tensile strength, MPa	Elongation, %	Area reduction, %	Hardness, HRC
Dry machining	1118	1312	6.25	7.8	36.5
Wet machining	1184	1405	7.42	9.4	32.8

surface finish are given in Table 2. The type/nature of Cu-2Be alloy chips produced from dry cutting is demonstrated in Fig. 1.

3.2 Influence of Wet Cutting on Machining Characteristics

Surface finish was evaluated to determine the influence of wet cutting on machining characteristics of Cu-Be alloy (Ref 6). The experimental results are given in Table 2. Surface finish of the wet machined samples was found superior when compared with dry machined samples due to the presence of coolant. During wet machining, the surface has lower frictional forces, resulting in lower coefficient of friction. This considerably reduces the impact forces on the surface resulting in relatively a smooth surface. The type/nature of Cu-2Be alloy chips produced from wet cutting is demonstrated in Fig. 2.

3.3 Variation of Tensile Properties as a Function of Cutting Temperature

Tensile properties of Cu-2Be alloy after dry and wet machining are given in Table 3. The proof strength, tensile strength, % elongation, and % reduction in area were determined as higher in wet-machined samples. As can be seen in Table 3, an increase in hardness due to excessive work hardening effects resulted in a reduction in tensile strength values. It is important to note that the ductility characteristics (in terms of % elongation and % reduction in area) of wet-machined samples were also higher.

3.4 Hardness as Influenced by the Temperature of Cutting

Hardness values for dry and wet machining are given in Table 3. In comparison, dry-machined samples showed relatively higher Rockwell hardness value as opposed to wet-machined samples. This difference in hardness is attributed to the absence of excessive plastic deformation (due to work hardening effects) in wet-machined samples. The application of coolant during wet machining prevents the work hardening effect.

3.5 Heat Treatment and Microstructure Characterization in Cu-2Be Alloy (Ref 8-12)

Heat treating is an important process that makes copper beryllium alloy system very versatile. Unlike other copper base alloys that acquire their strength through cold work alone, wrought copper beryllium obtains its high strength, conductivity, and hardness through a combination of cold work and a thermal process called "age hardening." Age hardening is often referred to as precipitation hardening. The ability of these alloys to respond to this heat treatment results in forming and mechanical property advantages not available in other alloys. For example, intricate shapes can be fabricated when the material is in its ductile, as-rolled state and is subsequently age hardened to the highest strength and hardness levels of any other copper-based alloys.

Precipitation hardening of copper beryllium alloys involves a two-step process that consists of solution annealing and age hardening. Age hardening response depends on time, temperature, and amount of cold work because strengthening is governed by precipitate size and distribution. For each alloy, there is an optimum temperature-time combination that is designated as standard practice because it produces maximum strength. A temperature higher than standard causes more rapid precipitation but leads to grain coarsening and lower strength, while a lower temperature results in a slower strengthening rate and

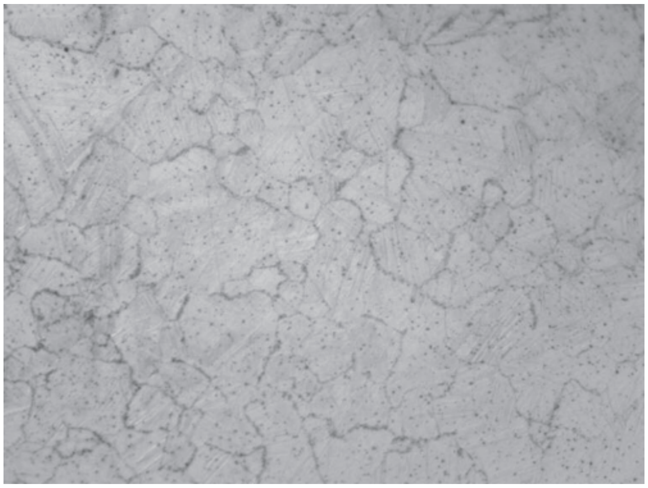

Fig. 3 Typical microstructure of a Cu-2Be alloy

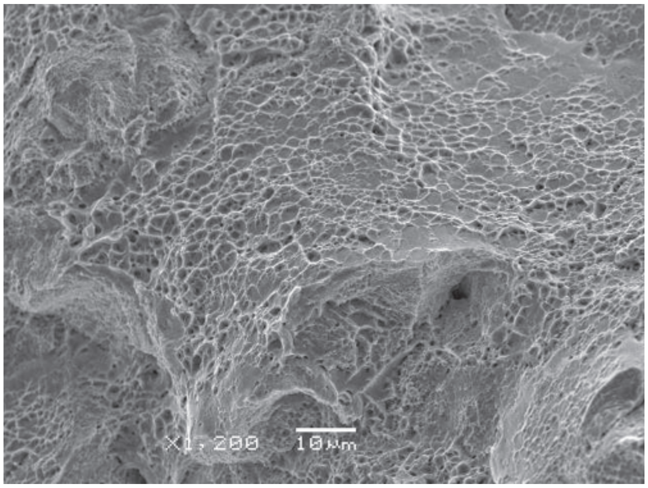

Fig. 4 Fracture surface dominated by dimples

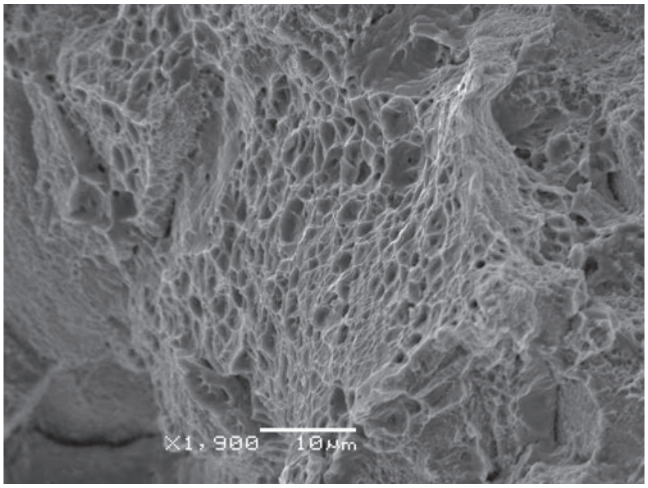

Fig. 5 Ductile fracture surface showing dimples and ridges

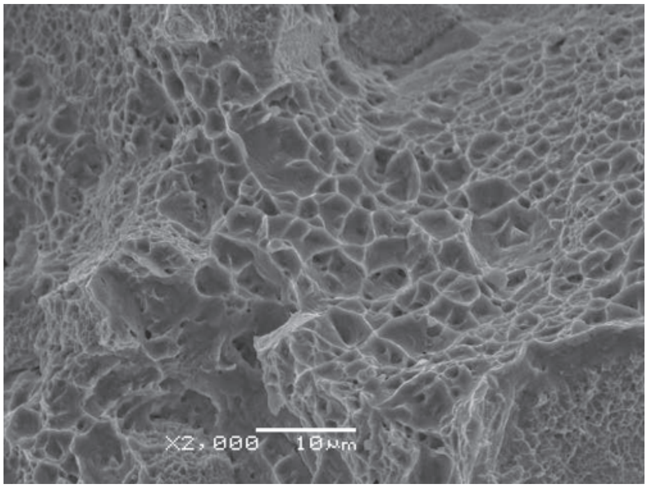

Fig. 6 Fractograph showing gross ductile fracture

decrease in strength. During the age hardening process, microscopic, beryllium-rich particles are formed in the copper base matrix. This is a diffusion-controlled reaction, and its strength varies with aging time and temperature. Standard age hardening time and temperature combinations have been determined for each copper beryllium alloy and are available in ASM/ASTM metal references/handbooks. These standard times and temperatures allow parts to reach peak strength in about 2-3 h, without the risk of strength decrease due to extended temperature exposure. The process of age hardening increases the density of the high-strength alloys slightly as a result of the precipitation reaction. This density change is accompanied by a decrease in linear dimensions of approximately 0.2%. The dimensional change in high conductivity alloys is negligible for most applications. These distortions are usually prevented by using appropriate fixtures during heat treatment.

A typical microstructure of a Cu-2Be alloy is shown in Fig. 3. The microstructure revealed beryllium-rich precipitates (dark constituents mostly present at the grain boundaries) in a copper base matrix. These precipitates are responsible for strengthening. They form initially as Guinier-Preston (GP) zones; pass through several stages of increasing tetragonality, finally transforming to equilibrium γ phase. Two forms of surface oxides are present in Cu-Be alloys: beryllium oxide, present on surfaces exposed to the high temperatures needed for solution annealing, and combinations of beryllium and copper oxides, present on parts after precipitation hardening. Dry-machined samples showed relatively a coarse grain structure that comparable with wet-machined samples. This was due to the rise in the temperature of the dry surface during cutting.

3.6 Fracture Morphology

Secondary electron image (SEI) and back-scattered image (BSI) techniques were used to study the fracture morphologies in Cu-2Be alloys. In wet-machined samples, the mode of fracture was typically ductile dominated by dimples and ductile ridges at the grain and grain boundaries. These are demonstrated in Fig. 4 to 6. Ductile fracture characteristics are resulting from the absence of heating during machining due to the use of coolant. In contrast, intergranular fracture (fracture along/through the grain boundaries) was dominant in dry-machined samples as depicted in Fig. 7 to 9. During dry machining, work hardening (as a result of plastic deformation) and materials softening processes compete with each other. Because no is coolant used in dry machining, the work hardening

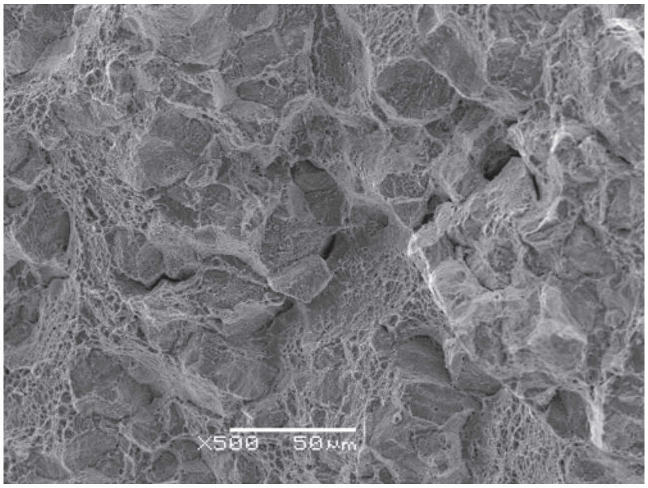

Fig. 7 Fractograph showing a typical intergranular fracture

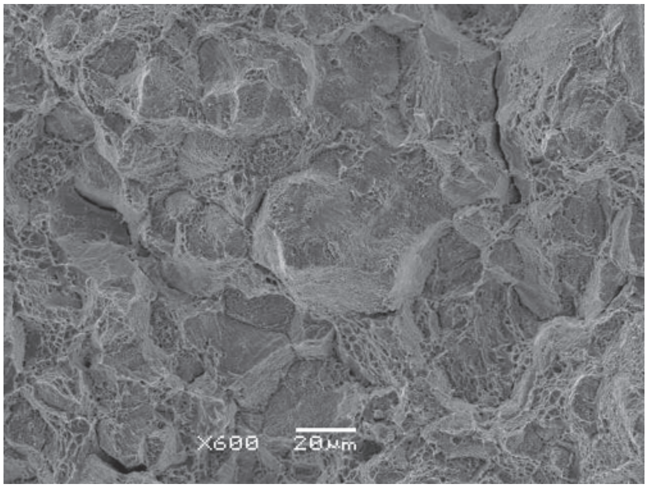

Fig. 8 Intergranular fracture surface in another location of the sample

process eventually dominates. Fractures occur along the grain boundaries (intergranular cracking) as the material tends to be relatively brittle (higher hardness) due to the work hardening effect.

4. Conclusions

- Machinablility of Cu-2Be alloy measured in terms of surface finish was determined superior for wet machining in comparison to dry machining.
- The quality of the machined chips in wet cutting was better in terms of geometry and material removal rate.
- Cu-2Be alloy (in both wet- and dry-machined conditions) demonstrated tensile strength properties typical of high-strength (greater than 1100 MPa) Cu-Be alloys. This is primarily due to the presence of beryllium-rich precipitates.
- Wet-machined samples exhibited higher tensile properties as opposed to dry-machined samples.
- Dry-machined samples showed relatively higher hardness values resulting from excessive work hardening effects during the machining process.

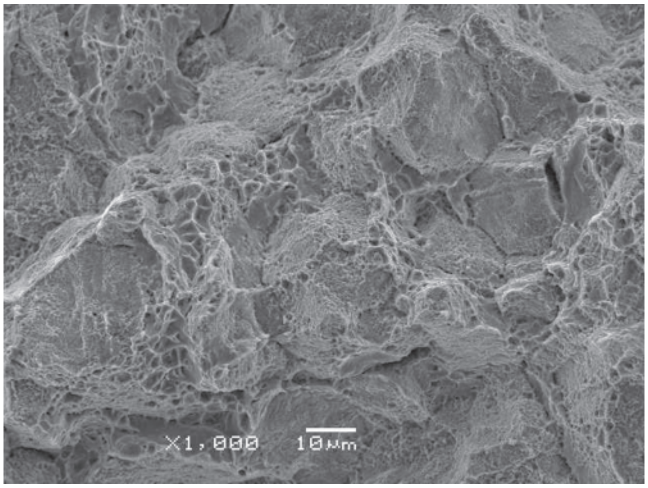

Fig. 9 Fractograph dominated by intergranular fracture but with some ductile ridges

- Wet-machined samples demonstrated relatively finer microstructure, although the basic microstructure features were the same, due to the absence of overheating.
- Intergranular and ductile modes of fracture were the dominant mechanisms characterizing the fracture in dry-machined and wet-machined samples, respectively.

Acknowledgments

The authors thank Dr. Robert Linnemann, General Manager, Mr. Delgado, Mr. Peralta, and Mr. Oscar of Volkswagen Company (Puebla Division, Mexico) for their co-operation and support for the scanning electron microscopy (SEM) work.

References

1. V. Kalhori, “Modeling and Simulation of Metal Cutting,” Ph.D. dissertation, 2001, Luleå University of Technology, Luleå, Sweden, p 28 (ISSN: 1402-1544)
2. W.R. Cribb and J.O. Ratka, Copper Spinodal Alloys, *Adv. Mater. Process.,* November 2002, p 27-30
3. J.C. Turn, Jr., “The Chloride Stress Corrosion Cracking Behavior of Beryllium Copper and Other Nonmagnetic Drill Collar Alloys,” Paper 303, presented at Corrosion ’87 (San Francisco, CA), National Association of Corrosion Engineers, March 1987
4. J.C. Turn and R.O. Ratka, “The Mechanical Behavior of Hydrogen Charged Beryllium Copper,” Paper 171, presented at Corrosion ’86 (Houston, TX), March 1986
5. J. Booker, W.C. Cribb, and J.C. Turn, Jr., “Corrosion Behavior of Beryllium Copper and Other Nonmagnetic Alloys in Simulated Drilling Environments,” Paper 220, presented at Corrosion ’84 (New Orleans, LA), April 1984
6. Standard Test Method for Tension Testing of Metallic Materials, ASTM-E8, 2002, p 60-81
7. N.P. Hung, Machining Aged Beryllium Copper, *Am. Machin. U.S.A.,* June 1986
8. R. Kuzel, C.R. Houska, H. Baoping, and C.H. Wu, XRD Characterization of Severe Matrix Distortions in Cu-Be Alloys, *Mater. Struct.,* 1995, 2 (1), p 52
9. B. Cheong, K. Hono, and D.E. Laughlin, *Twinning in Advanced Materials, Proc. of TMS Symposium* (October 1993), TMS Special Publication, 1994
10. N.P. Hung, Predict Anisotropic Shrinkage of Cu-Be Alloys for Precision Parts, *Procedings, National Symposium on Manufacturing Technology,* (Singapore), September 1993, pp. 9-16
11. N.P. Hung and I. Clinton, “Stress Relieving of Copper Beryllium by an Aging Process,” presented at the Second International Conference on Residual Stress (Nancy, France), November 1988
12. A.G. Khachaturyan and D.E. Laughlin, Structural Transformations During Decomposition in Cu-Be Alloys, *Acta Metall. Mater.,* 1990, 38 (10), 1990, p 1823-1835