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The Effects of Temperature on the Machining of Metals

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Abstract. The machining behaviors of metals at various workpiece temperatures are studied by the milling operation. Cutting power was recorded; tool life, chip size, surface finish and the microstructures of chips were examined.

INTRODUCTION

The machining of metals has been studied for over a century. The experience and knowledge on this subject are well documented into charts and tables in handbooks, which guide machinists in the determination of the optimal machining condition. The commonly considered machining variables are: tool material, tool geometry, cutting fluid, cutting speed, cutting depth, and feed rate. In general, machining at room temperature is assumed. It is well known that most of the work done in metal cutting is converted to heat, and that results in a temperature rise in the tool, workpiece, and chip. All the machining variables mentioned before affect the temperature distribution. Temperature is always of concern in machining. For example, higher cutting rates generate more heat; the cutting fluid cools workpieces and tools; and the tool selection is limited by temperature. The idea of raising or lowering the temperature of a material during cutting is not a new one. However, the technique has not been adopted by industry.

Three materials with very different mechanical responses will be studied by milling at various temperatures to determine if there is any advantage of machining at a workpiece temperature different than ambient.

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Machining Temperature

To lower the cutting temperature, cryogenics is usually applied to remove the heat. This technique is known as cryogenic machining. The coolant is applied locally at the cutting tool, at the workpiece, or at the chip. Hollis [1] used liquid CO_2 to remove heat from the cutting tool when machining titanium alloys. In the experiments of machining and grinding carbon steels, Jainbajranglal and Chattopadhyay [2] applied a liquid nitrogen jet to cool the region of the workpiece in the cutting area. The advantages of enhancing tool life, improving surface condition, and reducing cutting forces were reported. (For a more complete review of the work in cryogenic machining the reader is referred to Chattopadhyay et al. [3].) By impelling a jet liquid lubricant cooled by CO_2 at the chip, an effective chip breaker [4] was developed that produced good chips both in size and form.

Machining at elevated temperatures is referred to as hot machining. The idea is to soften the workpiece by increasing the temperature so the material is easier to remove. The early work was done by Tour and Fletcher [5], who investigated hot spot machining of carbon and alloy steels by using induction heating or gas to heat the workpiece just ahead of the point of cutting, and by Schmidt [6], who conducted hot milling tests of steels with the workpieces preheated in a furnace or heated by a torch on the milling machine. Reductions in power requirements, faster cutting speeds and feeds, excellent finish, and good tool life were reported. Recently, laser-assisted machining [7] was investigated. The results showed that the traditionally hard-to-machine materials, such as nickel base alloys and titanium alloys, became easier to cut.

With the development of very difficult-to-machine materials in the aerospace industry, the requirement of accuracy and integrity in many modern applications, and energy and economic considerations, the control of the workpiece temperature may become advantageous. This paper explores the benefits of considering the workpiece temperature as a machining variable. Its purpose is to study the temperature effects on the following characteristics of the cutting process: the cutting tool wear rate and life, the cutting force and power, the quality of the surface finish, and the chip size control for removal and handling. Since changing the workpiece temperature will change the mechanical behavior of the material and also the temperature distribution in the tool and the chip, this study will provide basic insights to the machining process.

The Milling Operation

The main objective of this project is to study the effects variation of the workpiece temperature has on the machining of metals. A CNC (computer numerical control) Bridgeport Series I vertical milling machine was selected for conducting the controlled experiments requiring the exact repeatability of the test cut. It was possible to design a suitable holding fixture for the workpiece on the milling machine that met requirements allowing the temperature of the workpiece to be varied.

The workpiece fixture is an insulated polystyrene aluminum box type structure that is capable of holding the specimen to be machined in a bath of liquid nitrogen. The higher temperatures were obtained by removing the insulating material and inserting a heating coil onto which the specimen was attached. Preheating the specimen in a furnace prior to mounting it in the fixture enhanced the heating process. The fixture was insulated from the milling machine preventing heat from dissipating into the machine. The fixture is shown in Figure 1.

In contrast to turning on a lathe, the milling operation produces chips of varying thickness and hence a varying cutting force is experienced on the tool. However, the milling operation is better for holding a steady temperature during the machining process.

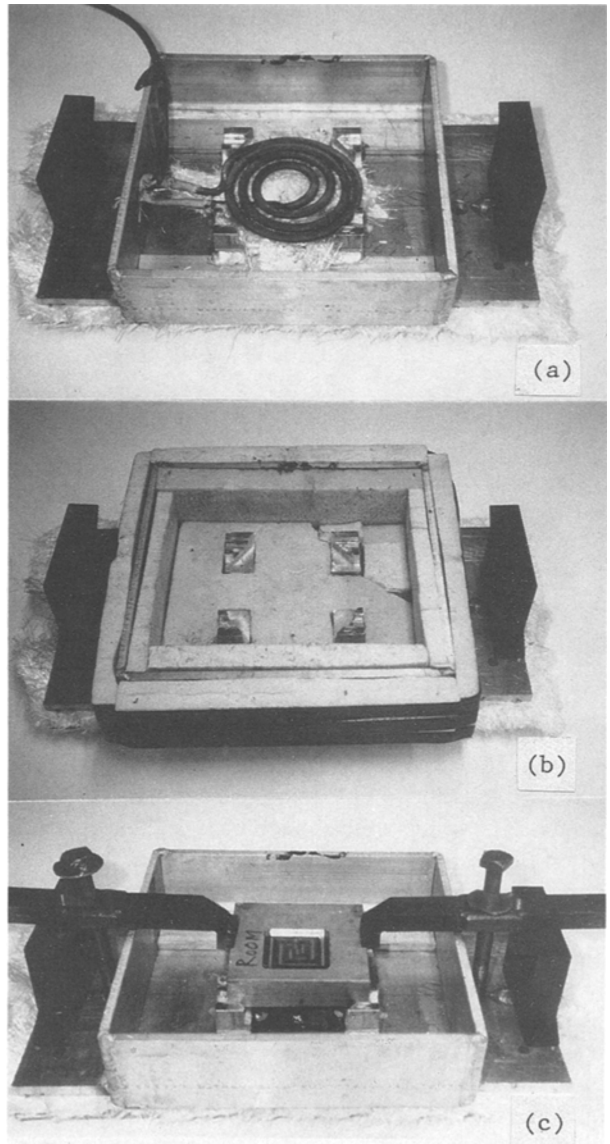

Fig. 1. Workpiece fixture for milling at (a) high temperature (280° C), (b) low temperature (−190° C), and (c) room temperature. A test sample in place is shown in (c).

MATERIALS AND PROCEDURES

Materials

Polycrystalline specimens of OHFC copper, 304 stainless steel, and titanium alloy containing 8% Al, 1% Mo, 1% V (Ti-8-1-1) were the materials selected for this investigation. Copper is face centered cubic in structure and plastically deforms in a well behaved fashion. Stainless steel is also face centered cubic in structure, however it is a material which work hardens extensively and is difficult to shape by machining operations. Ti-8-1-1 is an hexagonal closed packed alloy containing a small fraction of a body centered cubic phase.

Titanium and alloys of titanium are difficult to machine under normal conditions [8,9] and have been shown [10] to deform extensively by twinning at low temperatures and high strain rates. The different mechanical response of these three materials as a function of temperature and strain rate should lead to different responses to temperature changes during machining by milling.

Test Machining Device

The experiments were performed on a Bridgeport Series I CNC vertical milling machine. The mill was controlled by Bridgeport's R2E4 control using BOSS 9 (Bridgeport operating system software) software.

A workpiece fixture was designed and fabricated whose primary functions were as follows:

1. To hold the workpiece in the desired position. This was done with standard strap clamps that were incorporated into the fixture.
2. To hold sufficient quantity of liquid nitrogen so as to maintain the specimen at a steady liquid nitrogen boiling temperature.
3. To maintain the specimen at a high temperature.

Tool Selection

The cutting tools chosen were $\frac{3}{8}$ in., two-flute end mills. Standard high speed steel (HSS) end mills were used on copper. Initially HSS was used on the stainless steel; however, it was necessary to change to Cobalt based alloy end mills for the stainless steel because of tool failure at low temperatures. Cobalt based alloy tools were also used for cutting titanium.

The Test Cut

The cutter path chosen for these experiments created a square pocket with dimensions 5.1 × 5.1 cm. A mechanical pocket in titanium is shown in Figure 2.

The depth of cut in machining of the pocket was different for each material. This was done to insure the completion of the cut without tool failure. The same depth of cut was used for a given material at all three temperatures.

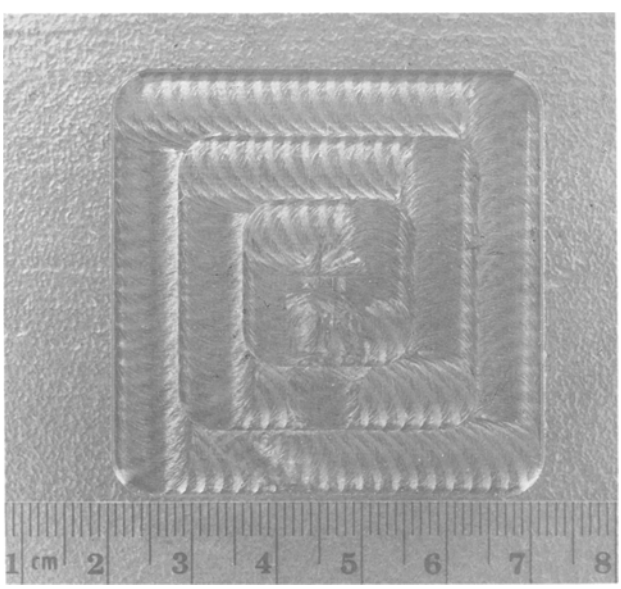

Fig. 2. A pocket machined in titanium at −190° C.

For the copper a total depth of 1.27 cm (0.5 in.) was used with a maximum depth of cut of 0.318 cm (0.125 in.). The total depth of the pocket in the stainless steel was 0.635 cm (0.25 in.), with a maximum depth of cut set at 0.254 cm (0.1 in.). Note that the total depth and the depth of cut were decreased for the stainless steel in comparison to the copper. Previous trial cuts in the stainless steel with larger depths resulted in tool failure for the low temperature cut, thus it was necessary to decrease the depth.

The total depth and the depth of cut for the titanium were decreased even further to 0.19 cm (0.075 in.) for the total depth of the pocket and 0.159 cm (0.0625 in.) for the depth of cut. Many trial cuts were performed to find a depth of cut that the tool would survive. No satisfactory depth of cut was found that successfully cut titanium; at high temperature, every trial resulted in tool failure.

Cutting Speed Parameters

The initial parameters used were standard recommended speeds and feeds for the material being cut and the material of the cutting tool. However, since these parameters are for cutting at room temperature in the presence of cutting fluid or coolant, it was necessary to make some modifications. The main goal in deciding on the final cutting speed and feed rate was to complete the cut in each material at all three temperatures; low, ambient, and high. Several trial cuts were made to arrive at an acceptable parameter. Since it was important that the parameters be the same for all the machining involving the same workpiece material, it was necessary to do trial cuts for the various materials for all three temperature ranges to see if the cut could be completed without tool failure. On one occasion, after successfully completing the low temperature cut for titanium, the tool failed during the ambient temperature experiment. This required the low temperature experiment to be repeated at a new parameter setting. The cutting of titanium at high temperature was not achievable with the stock and cutting tools available.

The parameters that were finally chosen for the various materials are listed in Table 1. Since it was necessary for the cutter to make a plunge cut into the material, a plunge feed of one half of the mill feed was chosen. The Bridgeport plunges in such that the cutter "ramps" down into the part rather than plunging straight down.

Measurements Made

The temperature of the workpiece was monitored using a platinum RTD (resistance thermal detector) purchased from Lakeshore Cryotronics Inc., model PT-102. The RTD used for the experiment could record

Table 1. Cutting Speed Parameters

	Copper	Stainless Steel	Titanium
Spindle speed (rpm)	1700	700	450
Feed rate, cm/sec (in./min)	0.64 (15)	0.12 (2.9)	0.15 (3.6)
Cutting tool used	HSS	Cobalt	Cobalt

temperatures ranging from −260 to 600° C. The fluctuation in load was continuously monitored by a three-phase wattmeter connected to the Bridgeport main motor input.

Evaluation of The Machined Surface

The roughness of the machined surfaces was determined using a profilometer. From the traces of the surface profile the largest peak to valley distances were determined and these are reported in Table 2. The smoothest surface (3 μm roughness) was that of the Ti-8-1-1 alloy milled at −190° C. Both the 304 SS and copper showed improvement in surface roughness as the temperature of the workpiece decreased.

Optical Metallography

Specimen preparation. Specimens of the materials as received and samples of the chips that were produced from the materials during milling at room temperature, −190° C, and 280° C were prepared for optical observation. The preparation of the specimens consisted of cold mounting, rough polishing on a belt sander, hand polishing through 600 grit paper, and finish polishing on alumina dressed cloth wheels. The microstructures of etched specimens were recorded using an inverted stage optical metallograph. The etchants employed on the metallic materials are listed in Table 3.

RESULTS

Power Consumed in Milling

Copper. It is quite obvious from the data reported in Table 4 that copper machined best at high temperatures. The plunge load is maximum when copper was machined at low temperature and minimum when machined at high temperature. It is interesting to note that the net change in temperature when copper is machined at room and high temperature is almost the same. But at low temperature, liquid nitrogen is cold enough to maintain the workpiece at more or less a steady temperature.

Stainless Steel. Stainless steel did pose problems in the beginning. The experiment to machine stainless steel at liquid nitrogen temperature using a HSS tool was attempted first. However this run was unsuccessful due to chip build-up problems. The chip would weld itself to the tool and prevent further machining. The tool was changed three times in the same run and ultimately the run had to be abandoned. However, this problem was overcome with a change of tool. It was decided to use a cobalt based alloy tool with a reduction in feed rate. The results listed in Table 5 show that the plunge load is the lowest at high temperature. These observations indicate that stainless steel is easier to machine at high workpiece temperature.

Titanium. There was no appreciable change in load at all at low temperature while there was some change in load during a plunge cut at room temperature as shown in Table 6. However, high temperature definitely posed problems with titanium. During the first run, the tool failed after it had completed nearly two-thirds of the run as there was a lot of heat generated at the cutting edges which was evident from the orange glow at the tool interface. A second run

Table 2. Surface Roughness of The Machined Surfaces, μm

	Copper	Stainless Steel	Titanium 8-1-1
−190° C	8	7	3
RT	6	10	7
280° C	7	18	16

Table 3. Metallographic Etchants

Stainless steels	
As received	62 ml perchloric acid (70%)
Electropolishing	700 ml ethanol
reagent	100 ml buthyl cellusolve
	137 ml distilled water
Machined chips	3 parts distilled water
Chemical etchant	2 parts hydrochloric acid
	1 part peroxide
Copper	10 g ferric chloride
	30 ml hydrochloric acid
	130 ml distilled water
Titanium 8-1-1	10% hydrofloric acid
	5% nitric acid
	70% distilled water

Table 4. Test Data—Copper

	Liquid N_2 Temp.	Room Temp.	High Temp.
Starting temperature[1], °C	−191.64	23.02	280.34
Max. temperature[2], °C	−193.24	52.35	308.39
Change in temperature[3], °C	1.6	29.33	28.05
Plunge load[4], Watt	600	400	200
Cutting load[5], Watt	200–600	200–400	200–400

[1]The temperature of the workpiece before the commencement of machining.
[2]The maximum temperature attained by the workpiece during machining.
[3]The absolute difference of the starting and the maximum temperature.
[4]The deviation from idle load during a plunge. Idle load refers to the load on the machine when the spindle is rotating but is not machining.
[5]The deviation from idle load during cutting.

Table 5. Test Data—Stainless Steel

	Liquid N_2 Temp.	Room Temp.	High Temp.
Starting temperature, °C	−194.18	25.08	291.54
Max. temperature, °C	−190.70	57.04	299.94
Change in temperature, °C	3.48	31.96	8.4
Plunge load, Watt	200	100	NAC*
Cutting load, Watt	NAC	NAC	NAC

*NAC—no appreciable change. Since the meter would pick up changes in load of magnitude 100 W or more, NAC indicates that the change in load on the machine was less than 100 W.

Table 6. Test Data—Titanium

	Liquid N_2 Temp.	Room Temp.	High Temp.
Starting temperature, °C	−194.18	24.56	277.54
Max. temperature, °C	−194.18	40.15	NA[1]
Change in temperature, °C	0	15.59	NA
Plunge load, W	NAC[2]	100	NAC
Cutting load, W	NAC	NAC	NAC

[1]Not applicable, because the tool failed.
[2]No appreciable change. (see Table 5.)

was carried out in order to confirm the result of the previous run and the results of the second run were in agreement with those of the first. Thus the machinability of titanium is improved at low workpiece temperature.

Microstructure Results

As-received material. The as-received microstructures of copper and stainless steel, respectively, were annealed single-phase structures shown in Figure 3(a) and (b). The stainless steel was fully annealed; however the copper was partially hardened, as can be seen by comparing the hardness of the as-received material at room temperature and the hardness values give in Table 7 obtained from chips formed from the high temperature workpiece. The Ti-8-1-1 alloy microstructure consisted mostly of a fine grained hexagonal close packed alpha (light etching phase) mixed with a very small amount of body centered cubic beta phase (dark etching phase), Figure 3(c).

Machined chips. One of the most important considerations in the fully automatic machining of materials is chip control and handling. An important consideration is that the chips should not be large or they may stop the operation of the machine. Very small chips are desirable because they are easily removed from the machine. The smallest chips produced in this study came from the machining of titanium at a workpiece temperature of −190° C. The largest size chips of titanium were formed when the workpiece was at ambient temperature. The limited ductility and extensive fracturing necessary to produce the very small chips of the Ti-8-1-1 alloy at −190° C could be due to the crack nucleation at twin intersections as first suggested by Cahn [11] and further developed by Meakin and Petch [12].

The microstructures of the chips formed from workpieces at room temperature and −190° C were typical of heavily cold worked structures. The structures of the chips formed from workpieces at −190° C contained a large number of crystallographic deformation markings which could be slip bands or mechanical twins. The appearance of many of the markings indicate that they are all twins. These twins are very visible in the optical micrographs of the copper and stainless steel specimens shown in Figure 3(d) and (e), respectively. Mechanical twinning in copper was first reported by Blewitt et al. [13] at −196° C and by De Angelis and Cohen [14] under shock wave deformation conditions at room temperature. In the milling operation, twinning of the face centered cubic materials is observed only at the −190° C workpiece temperature conditions. The temperature of the chips

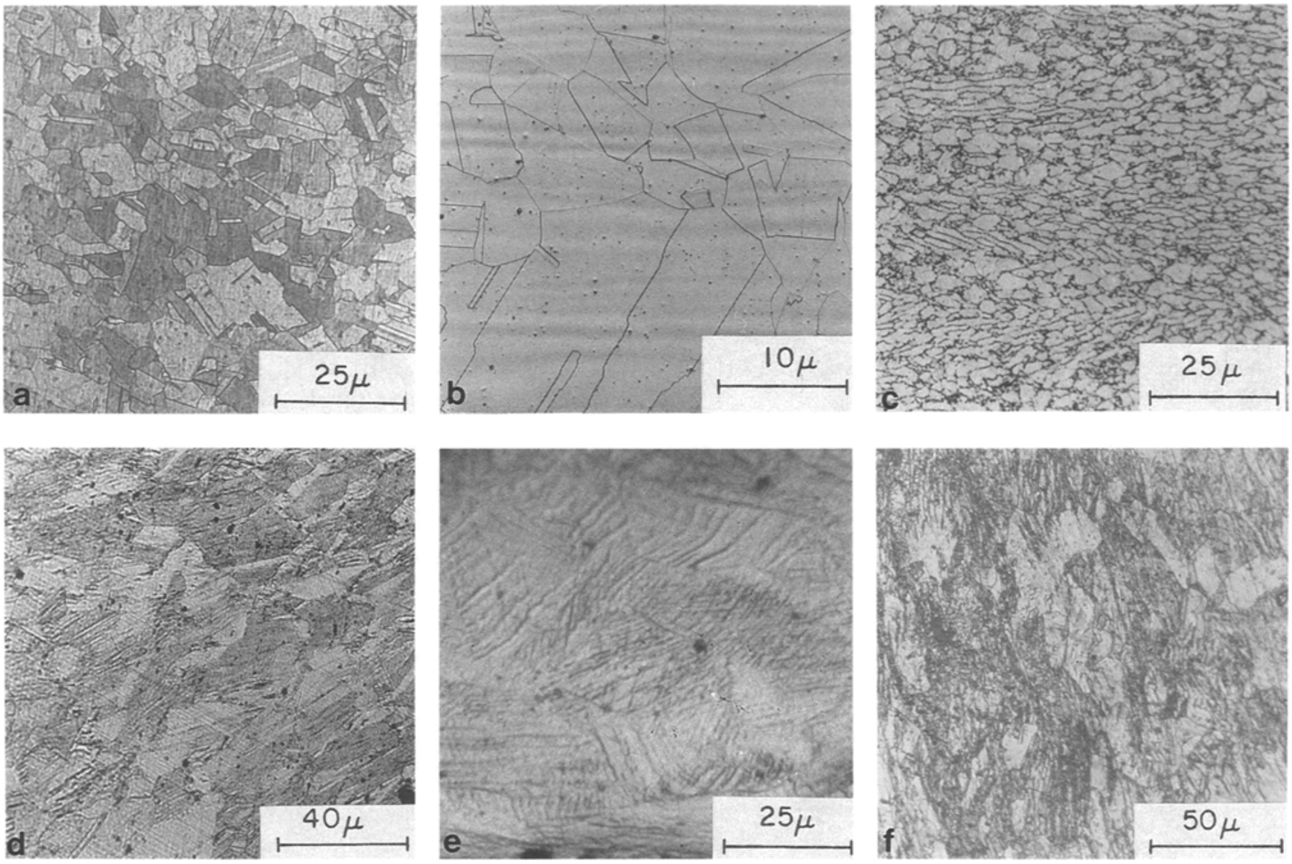

Fig. 3. Optical micrographs of the as-received (a) copper, (b) stainless steel, (c) Ti-8-1-1, and chips formed at −190°C for (d) copper, (e) stainless steel, (f) Ti-8-1-1.

formed from the room temperature workpiece condition are estimated from the microstructure to be about 200°C which is apparently above the temperature at which the twinning mode of deformation is operative.

The hardness of the chips formed from the 304 SS and copper at the workpiece temperature of 280°C was lower than that of the chips of the same materials formed at room temperature (see Table 7). The copper chips were fully annealed while the 304 SS chips were partially annealed. The microstructure of the 304 SS chips formed from a 280°C workpiece contained regions of recrystallized grains, an indication that the temperature of these regions of the chip was above 600°C. The hardness data of the stainless steel and titanium alloy at ambient workpiece temperatures compare very favorably with similar data reported by Child and Dalton [15].

Table 7. Hardness (VHN) of the Metals and Machined Chips

	Titanium 8-1-1	Stainless Steel	Copper
As received			
−190°C	393	NA	NA
RT	371	166	95
280°C	394	NA	59
Machined chips			
−190°C	389	432	118
RT	417	437	150
280°C	426	331	58

Twins that formed in the Ti-8-1-1 alloy were much finer than the twins that formed in the other two materials. The microstructures of the titanium alloy chips formed at the workpiece temperature of −190°C are shown in Figure 3(f). The enhanced twinning during the plastic deformation of titanium and its alloys at low temperatures was well established by Garde et al. [10]. In commercially pure titanium deformed in compression in the temperature range of 25 to 300°C, Paton and Backofen [16] observed that more than 80% of the total strain in titanium specimens was due to ⟨11-22⟩ twinning.

DISCUSSION

Concerning the association of fracture and twinning, Tuer and Kaufmann [17] stated that "twinning and fracture are both essentially cataclysmic processes of elastic stress (or strain) relief, and the conditions which are ideal for the development of one will generally be satisfactory for the development of the other." This competitive role of twinning against cracking depends closely on the mechanical and thermal properties of the material and the experimental conditions. In the case of Ti-8-1-1, as the workpiece temperature decreases the work required to remove metal decreases, the finish roughness decreases, and the length of the chips becomes shorter. These three desirable characteristics were connected with the increase in deformation by mechanical twinning and cracking. Another possible explanation of the improved machining behavior of titanium at −190°C is that suggested by Shaw [18]. He indicated that titanium machined at ambient temperatures forms chips which may be long but they are extremely heterogeneous in strain. This is due to the low thermal conductivity and specific heat of the material. As a shear band forms on a specific plane the material in the region is heated rapidly due to the low thermal conductivity [19]. The mechanical properties of titanium decrease rapidly with temperature which causes further deformation to localize in the heated region and produce further temperature increases. Finally cracking may occur. Due to greater strain localization, the potential for cracking would be much higher at the lower workpiece temperatures, as observed in this investigation.

In the case of copper the effects of temperature on machining were very slight. This behavior can be explained by the excellent thermal conductivity of copper combined with the lack of temperature dependence of the toughness. Stainless steel, on the other hand, shows an increase in toughness with decreasing temperature, the area under the stress–strain curves for temperatures of 204°C, room temperature, and −196°C are in the ratios of 1:2:3 [20]. This could easily account for the increased difficulty experienced in machining 304 SS at the reduced temperatures.

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REFERENCES

1. W.S. Hollis, "The Application and Effect of Controlled Atmospheres in the Machining of Metals," *Int. J. Mach. Tool Des. Res.*, vol. 1 (1961) pp. 59–78.
2. J.R. Jainbajranglal and A.B. Chattopadhyay, "Role of Cryogenics in Metal Cutting Industry," *Indian J. Cryog.*, vol. 9 (1984) pp. 42–46.
3. A.B. Chattopadhyay, A. Bose, and A.X. Chattopadhyay, "Improvements in Grinding Steels by Cryogenic Cooling," *Precision Engineering*, vol. 7 (1985) pp. 93–98.
4. J.D. Christopher, Metal Cutting Res. Ass., private communication.
5. S. Tour and L.S. Fletcher, "Hot Spot Machining," *The Iron Age*, vol. 164 (1949) pp. 78–89.
6. A.O. Schmidt, "Hot Milling," *The Iron Age*, vol. 163 (1949) pp. 66–70.
7. M.G. Jones, "Pulse Laser-Assisted Machining of Inconel 718 and Titanium 6A1-4V," Advanced Machining Research Program (AMRP), AFWAL-TR-84-4059, vol. 4—Laser-Assisted Machining (May 1984) pp. 61–69.
8. N. Zlatin and M. Field, "Procedures and Precautions in Machining Titanium Alloys," *Proc. of Technology*, Eds: R.I. Jaffee and H.M. Burte, vol. 1 (1973) p. 489.
9. E.M. Trent, *Metal Cutting*, Butterworths, London, (1984) p. 215.
10. A.M. Garde, E. Aigeltinger, and R.E. Reed-Hill, "Relationship Between Deformation Twinning and the Stress–Strain Behavior of Polycrystalline Titanium and Zirconium at 77 K," *Met. Trans.*, vol. 4 (1973) pp. 2461–2468.
11. R.W.J. Cahn, *J. Inst. Metals, 83* (1955) p. 493.
12. J.D. Meakin and N.J. Petch, *Fracture of Solids*, John Wiley and Sons, New York, Eds: D.C. Drucker and J.J. Gilman (1963) p. 393.
13. T.H. Blewitt, R.R. Coltman, and J.K. Redman, "Low-Temperature Deformation of Copper Single Crystals," *Dislocations and Mechanical Properties of Crystals*, John Wiley and Sons, New York, (1957) pp. 179–214.
14. R.J. De Angelis and J.B. Cohen, "Some Crystallographic Techniques for the Study of Mechanical Twinning and Their Application to Shock-Induced Twinning of Copper," *Deformation Twinning*, Gordon and Breach, New York, (1965) p. 430.
15. H.C. Child and A.L. Dalton, "Machining Titanium Alloys, Part 1—Metallurgical Factors Affecting Machinability," *Machinability*, Institute of Metals Special Report 94, Iron and Steel Institute, London, (1967) pp. 139–142.
16. N.E. Paton and W.A. Backofen, "Plastic Deformation of Titanium at Elevated Temperatures," *Met. Trans.*, vol. 1 (1970) pp. 2839–2847.
17. G.L. Tuer and A.R. Kaufmann, "The Metal Beryllium," ASM, Cleveland, Ohio, (1955) pp. 372–424.
18. M.C. Shaw, "Assessment of Machinability," *Machinability*, Institute of Metals Special Report 94, Iron and Steel Institute, London (1967) p. 1.
19. R. Komanduri and B.F. von Turkovich, "New Observations on the Mechanism of Chip Formation When Machining Titanium Alloys," Advanced Machining Research Program (AMRP), AFWAL-TR-84-4059, vol. 6—High-Speed Machining (May 1984) pp. 99–107.
20. *Atlas of Stress–Strain Curves*, Howard E. Boyer Ed., ASM International, Metals Park, Ohio (1987) p. 294.