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Dry turning of sintered molybdenum

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ABSTRACT

Molybdenum is a refractory metal which is recommended for advanced engineering applications requiring high mechanical strength and corrosion resistance at extremely high temperatures. However, Molybdenum-based alloys are generally difficult to machine, due to their superior physical and mechanical properties, usually requiring effective refrigeration. In this work, the feasibility of dry machining of sintered Molybdenum using commercial tools in finish longitudinal turning was investigated. A list of suitable tools was selected and cutting tests were performed in order to evaluate their performance and assess the machinability of sintered Molybdenum. Specifically, chip formation and chip control, surface roughness and cutting forces were considered. It turned out that most of the tools were inadequate for this application, therefore tool life tests were carried out on the remaining tools. Nevertheless, the analysis of experimental data confirmed that good surface quality and satisfactory tool life can be achieved in dry conditions at relatively high cutting speeds by using commercial tools.

1. Introduction

Efficient machining of advanced engineering materials has become a key issue for modern manufacturing industries producing parts for automotive, aerospace and biomedical applications, as well as for steel and process industry (König et al., 1990). The superior mechanical and physical properties of these materials assure good performances in severe operating conditions, on the other hand they are expensive and difficult to machine. Among the new materials, machinability of Titanium alloys has been extensively studied, as shown by the comprehensive review presented by Ezugwu and Wang (1997). Similarly, Nickel based superalloys have been deeply investigated, due to their increasing use. Recent achievements are discussed by the same author (Ezugwu et al., 2003), including the effect of different cutting tool materials, cutting parameters, innovative lubrication systems and machining techniques.

When high strength and corrosion resistance at extremely high temperatures are required, the application of refractory metals such as Niobium, Tantalum, Tungsten and Molybdenum is recommended (ASM, 1990; El-Genk and Tournier, 2005). However, refractory metals are difficult to machine and scarce information concerning their machinability can be found in literature. For example, machinability of Tantalum and other difficult to cut materials was investigated by Wang and Rajurkar (2000) and by Wang et al. (2002); sintered Tungsten–Copper was recently studied by Davim et al. (2009) and by Gaitonde et al. (2010).

Molybdenum is a refractory metal with body-centered cubic crystal structure, with relatively high atomic number and density, see technical information reported by Plansee (http://www.plansee.com/en/Materials-Molybdenum-402.htm).

Molybdenum based alloys are mainly fabricated by powder metallurgy and arc-casting methods. In both cases, the obtained billets or ingots are generally hot-worked by applying bulk deformation processes such as forging, rolling, extrusion and drawing. Eventually, they undergo specific thermo-mechanical treatments in order to achieve a semifinished product, which can be further processed through machining operations.

Physical and mechanical properties of (almost pure) sintered Molybdenum are summarized in Table 1. Except the considerably higher Young modulus, its mechanical properties are comparable to those of conventional carbon steels. However, key features of Molybdenum are its higher mechanical strength and hardness at higher temperatures, especially when considering sintered Molybdenum alloys with dispersed particles, see Takida et al. (2004). This is due to the very high melting point (2620 °C) and recrystallization temperatures of sintered Molybdenum, which are comparable to those of Inconel 718 (http://www.specialmetals.com/documents/Inconel%20alloy%20718.pdf). Of course, mechanical properties of sintered Molybdenum are also influenced by grain dimension and structure, as well as by the adopted sintering procedure, as shown by Srivatsan et al. (2001). Also, Molybdenum exhibits low thermal expansion, high thermal conductivity, and low heat capacity in comparison with most ferrous materials. Besides, it has high corrosion resistance

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Table 1
Physical and mechanical properties of sintered Molybdenum and other reference materials.

Property	AISI 1045 (Ck45)	Inconel 718	Sintered Mo
Chemical composition (% in weight)	C0.42–0.50; Si ≤ 0.40; Mn 0.65; Cr ≤ 0.40; Ni ≤ 0.40; Mo ≤ 0.10; Cr + Mo + Ni ≤ 0.63	C ≤ 0.08; Mn ≤ 0.35; Si ≤ 0.35; Cr 17–21; Ni 50–55; Mo 2.8–3.3; Nb + Ta 4.75–5.50; Ti 0.65–1.15; Al 0.2–0.8; Co ≤ 1; Fe(balance)	Mo 99.97
Density at 20 °C (g/cm^3)	7.85	8.20	10.28
Melting point (°C)	1350	1336	2620
Recrystallization temperature (°C)	540–675 °C	>850 °C	800–1200
Young Modulus E (GPa)	210	205	340
Yield strength Y (MPa)	300–450	550–1000	350–700
Tensile strength R (MPa)	570–800	800–1450	450–850
Brinell Hardness (HB)	170–230	250–400	200–230
Elongation A (%)	16	5–20	<30
Coefficient of linear thermal expansion at 20 °C, [μm/(m K)]	11.5	13.0	5.2
Thermal conductivity at 20 °C [W/(m K)]	46–52	11.2	140
Specific heat capacity at 20 °C [J/(kg K)]	480	435	254
Cutting pressure k_s (MPa)	2000–2600	2500–5000	2500–4500
Recommended cutting speed v_c (m/min) in finish turning	350–500 (cemented carbides); 400–650 (cermets)	40–90 (cemented carbides); 150–220 (ceramics or cBN)	<140 (cemented carbides)
Approximate relative cost ()	1	≈25	≈65

to molten glass and metals, which are desirable characteristics for several engineering applications. It is also worth noting the extremely high cost of sintered Molybdenum, that is more than twice the cost of Inconel and about 65 times the cost of steel.

In comparison to sintered Molybdenum, which is the focus of this research, arc-casted Molybdenum alloys exhibit slightly higher tensile strength (about 800 MPa at room temperature), smaller tensile ductility (total elongation of about 18%) and slightly higher Brinell Hardness (about 260 HB), as illustrated by Cockeram et al. (2004) and Cockeram et al. (2011).

Sintered Molybdenum alloys are generally difficult to machine, since Molybdenum has the tendency to stick to the tool while being machined, causing build up edge formation and short tool life. Moreover, rather poor surface quality is usually obtained, and the machined surface is affected by undesired work hardening.

A few decades ago the Institute of Advanced Manufacturing Sciences (Machinability Data Center, 1980) and later Davis (1989) proposed some guidelines – cutting tool geometries, tool materials, cutting parameters and process conditions – for machining refractory metals, including sintered Molybdenum. Analogous guidelines are also available on the website of the material supplier (http://www.plansee.com/en/Materials-Molybdenum-402.htm).

The key recommendations are as follows:

- relatively sharp tool geometries are preferable;
- the workpiece should be firmly chucked, tools rigidly supported, and machining system should be sufficiently powerful and free from chatter or backlash;
- low cutting speeds (less than 140 m/min) should be applied in order to avoid excessive tool wear rate;
- copious supply of coolant (oil emulsion, kerosene or sulphur based cutting oils, chlorinated oils or solvents) must be provided.

Concerning the coolant, it has to be pointed out that toxic coolants may be absorbed into the porosities of sintered Molybdenum, thus representing a danger for the health of the operators involved in the manufacturing process and handling of the machined parts.

A core issue for companies which produce components made of sintered Molybdenum is to reduce production costs, especially due to the high cost of the workpiece material, and dry machining is a very interesting opportunity both from economical and environmental viewpoints.

In this work, which was financed by industry and by public institution, the feasibility of dry machining of sintered Molybdenum using commercial tools in finish longitudinal turning was investigated. For this purpose, a list of suitable tools was selected and cutting tests were performed in order to evaluate their performance and assess the machinability properties of sintered Molybdenum.

2. Characterization of workpiece material, tool selection and experimental setup

Workpiece material was sintered Molybdenum alloy (99.97% pure), with an average Brinell Hardness of 201 HB. Workpiece initial diameter D was 80 mm and workpiece total length L was 150 mm. In order to characterize the microstructure of the workpiece material, cross and longitudinal sections of a workpiece sample were obtained and analyzed, see Fig. 1(a) and (b) respectively. In order to highlight grain borders, the polished specimen surface was etched by using Murakami reagent. The analysis of cross section evidenced irregular grains of characteristic size ranging from 2 to 15 μm approximately, whereas the longitudinal section evidenced long and narrow grains of about 50 μm length, which were aligned with main direction of the bulk deformation process applied after the sintering phase. Material porosity observed in the cross section was about 5%.

Turning tests were performed on a turning and milling machining centre Okuma Multus B300. A surface Roughness tester (Mitutoyo Surftest SJ-201) was used for surface quality measurements. Other non-compliances of the machined surface such as chatter marks or microchips were assessed by direct visual inspection. A special turning dynamometer developed by Totis and Sortino (2011) was applied for triaxial cutting force measurements, whereas cutting process vibrations were measured by means of a piezoelectric uniaxial accelerometer Kistler 8704B50 installed at the machine tool head along the longitudinal feed direction A_Z. For automatic tool inspection during tool wear tests, a digital microscope mounted on a special fixture attached to the opposing spindle of the CN lathe was applied, see Fig. 2. A Leica M165C stereomicroscope was also used for direct visual inspection of worn tools, as well as a Scanning Electron Microscope – SEM – was used for the final in-depth investigations.

Regarding data acquisition, all sensor signals were sampled at 20 kHz by using a National Instruments device (cDAQ-9178 with NI9215 modules) connected via USB to a PC. Data were elaborated in MathWorks MATLAB environment.