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Research Article

AN INVESTIGATION INTO THE PERFORMANCE OF HSS DRILLS WHEN DRILLING COMMERCIALLY PURE MOLYBDENUM

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ABSTRACT

The use of commercially available molybdenum materials, which exhibit good mechanical and thermal properties, has been increasing day by day, and therefore their machinability has become important. Due to their good mechanical properties, shaping of these materials through machining methods causes some problems such as rapid tool wear, low surface quality and tool breakage. Besides, the determination of the machining conditions and methods of these materials which are quite expensive compared to other metals and alloys is very important in terms of improving the machined part quality and reduced costs. In this study, it is aimed to determine optimum cutting conditions in drilling of molybdenum of commercial purity using high speed steel (HSS) drill bits. For this purpose, experimental studies were carried out to reveal the effect of cutting parameters on surface roughness, drill bit wear, deviation on hole diameter, cylindricity error and drill bit temperature. It is seen from the experimental results that the drill bit failed quickly when drilling over 40 m/min. Significantly high surface roughness values are obtained nearly at all the conditions. As the cutting speed and feed rate increase, the drill bit temperature increases.
Keywords: Molybdenum, drilling, wear, dimensional and geometric tolerances, temperature.

1. INTRODUCTION

Commercially pure molybdenum contains > 99.97 % molybdenum. Its modulus of elasticity ranges from 320 to 350 GPa and Poisson’s ratio is 0.38. Yield strength and ultimate tensile strength values of this material are 450-550 MPa and 600-650 MPa, respectively. Hardness of pure molybdenum is about 225 BHN [1]. Molybdenum alloys have high hot hardness and high recrystallization temperature and they retain their properties significantly after thermal cycles [2].

More than two-third of molybdenum produced worldwide are used in alloying especially in cast and wrought alloy steel and heat resistant alloys. Molybdenum is also used in making various parts generally subjected to high temperatures [3]. Solid-propellant rockets, jet engines, electronic components, heating elements and dies for casting are some of the applications of molybdenum. Molybdenum is an increasingly used material due to the increasing demands of space, defence, nuclear and electronic industries [4]. It was seen that molybdenum has no harmful effect on human health [5].

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Machining characteristics of molybdenum is similar to those of other metals and alloys. Machining operations on molybdenum parts with the required dimensional accuracy can be carried out. Geometries of these parts can range from very simple to very intricate. The obtained surface quality depends on the used cutting conditions and the cutting tools. Generally high speed steel and carbide cutting tools are used to machine molybdenum. The machining of molybdenum results in higher cutting tool wear than that of steels of the similar hardness. High speed steel cutting tools are generally used for rough machining operations while carbide cutting tools are required for good surface quality and tight tolerances [6].

Limited work is available in the published literature regarding the machining of molybdenum and its alloys. One of these limited work is belong to Zlatin et al. [7]. Zilatin et al. carried out a wide range of machining tests on various refractory materials including TZM molybdenum alloy. Their machining tests included turning, facing, end milling, drilling, reaming, tapping and grinding. Siginificant reduction in tool life was seen when a cutting fluid was not used [7]. Sortino et al. subjected the sintered molybdenum to dry turning tests. They concluded that ceramics and cermet cutting tools were not suitable for machining of molybdenum due to their highly brittle natures. They also concluded that good surface quality and acceptable tool life could be obtained at relatively higher cutting speeds without using cutting fluid if very fine grained WC cutting tools with cobalt contents of intermediate amount. In addition, it was also reported that increasing the cutting speed significantly reduced the surface roughness and that similarly the cutting force also decreased with increasing the cutting speed [8]. In another work, Kuljanic et al. examined the machinability characteristics of various difficult to cut materials including hardened steel, titanium alloys, nickel based alloys and molybdenum alloys. They reported that grain structure of the commercially pure molybdenum had a significant influence on its machinability [9]. In a bulletin published by ED FAGAN Company, some guidelines are given regarding the machining of molybdenum and its alloys through a wide range of processes including sawing, turning, milling, drilling, reaming, tapping, grinding, polishing and honing. It was stated that high speed steel cutting tools are suitable for poor surface quality and rough machining operations while carbide cutting tools for good surface quality and tight tolerances [6]. It was stated in another bulletin published by International Molybdenum Association (IMAO) that molybdenum and its alloys can be shaped through common machining processes and that good surface quality and good dimensional accuracy can be obtained with a relatively sharp cutting edge provided that optimum machining conditions are selected [10]. Gökçe et al. carried out a work on milling of commercially pure molybdenum in order to examine the influences of cutting tool and cutting parameters on the surface roughness and cutting force. They reported that the feed rate was the most influential parameter for the cutting force while the cutting speed was for the surface roughness [11].

As there is no research work on drilling of molybdenum ant its alloys, this study is considered to be of significance. In this current study, drilling operations were performed on commercially pure molybdenum workpieces at four different cutting speeds and five different feed rates using HSS drill bits. The influence of the cutting speed and feed rate on surface roughness, drill bit wear, deviation on hole diameter, cylindricity error, drill bit wear and drill bit temperature was aimed to be investigated.

2. MATERIALS AND METHOD

Workpieces for the drilling tests were cut off from cylindrical part of commercially pure molybdenum in 60 mm diameter. They were machined to 15 mm height so that the hole depth was three times the drill bit diameter. Various properties of the workpiece are given in Table 1.

Table 1. Some properties of commercially pure molybdenum [11]

Property	Unit	Pure molybdenum
Chemical composition	%	>99,97 Mo
Density (20 ºC)	g/cm^3	10,22
Melting point	ºC	2617
Brinell hardness	BH	205
Yield strength	MPa	600
Tensile strength	MPa	800
Modulus of elasticity	GPa	330
Poisson's ratio		0,38
Coefficient of thermal conductivity (20 ºC)	[W/(mK)]	138

Through holes were drilled on the commercially pure molybdenum using high speed steel (HSS) drill bits. The holes were drilled at 4 different cutting speeds and 5 different feed rates without using coolant. Initially, five different cutting speeds were selected. However, the pilot drilling tests showed that at the highest cutting speed of 50 m/min, the drill failed quickly. Therefore, the number of cutting speed was reduced to four. A total of 20 holes were drilled at these conditions. The cutting speed and feed rate were selected based on the drill bit manufacturer's suggestion and previous studies. The used cutting parameters and their levels are given in Table 2.

Table 2. Cutting parameters and levels

Cutting parameters	Unit	Levels				
		1	2	3	4	5
Cutting speed (Vc)	m/min	10	20	30	40	-
Feed rate (f)	mm/rev	0.04	0.08	0.12	0.16	0.20

The twist fluted high speed steel (HSS) drill bits were 5 mm in diameter and produced by MTE. Their drill point and helix angles were 118° and 30°, respectively, Figure 1. These drill bits were suitable for drilling alloyed steels and cast iron with great accuracy.

Figure 1. HSS drill bit

The drilling tests were carried out on an Arion IMM-600 CNC vertical machining centre. As the molybdenum workpieces were cylindrical, a three-jaw precision chuck was used to clamp the workpieces. Through holes were drilled on the workpiece. The drill bits were clamped to the spindle of the machining centre using a suitable collet. Tool overhang was kept constant for all the tests. Before the drilling tests, a thin surface layer of the workpiece was face milled to remove irregularities.

Temperature measurement was carried out using a Fluke Ti200 infrared camera. Each drilling cycle was started from the point 2 mm above the workpiece in Z direction and the cycle was also completed at this point. The temperature was recorded as the video file during the whole cycle and the temperature value just before the end of each cycle was taken into account.

Drill bit wear was examined using a digital Dinolite digital microscope. Surface roughness values of the drilled holes were measured using a Mitutoyo SJ-410 unit.

Generally high precision is required for the parts used in defence and aerospace industries. Therefore, geometric and dimensional tolerances of the holes on these parts are of quite importance. Deviation on hole diameter is the difference between the nominal diameter and measured diameter of the drilled hole while, cylindricity is defined as the combination of parallelism, circularity and straightness of a cylinder surface. The cylindricity error is the variation between measured cylindrical surface and its ideal cylindrical surface. Deviation on hole diameter and cylindricity error were measured using a Hexagon Global Advantage CMM by taking two measurements from each hole. In each measurement, the probe touched four points along the periphery. The measurements were taken 3 mm below and above the top and bottom surfaces of the workpiece, respectively. The experimental setup is shown in Figure 2.

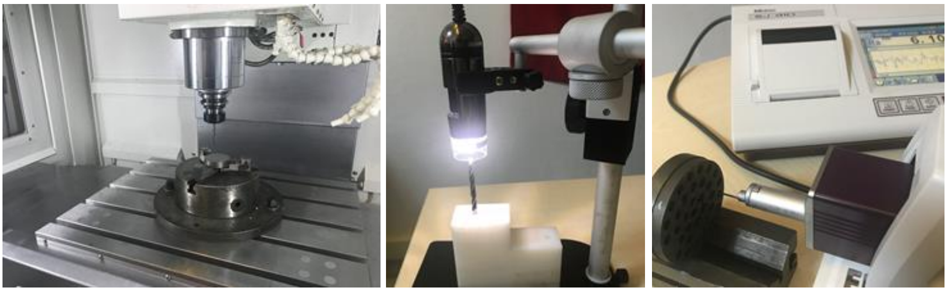


Figure 2. The experimental setup

3. RESULTS AND DISCUSSION

Table 3 gives the average surface roughness (Ra), deviation on hole diameter, cylindricity error and drill bit temperature values in dry through hole drilling on a commercially pure molybdenum workpiece at four different cutting speeds and five different feed rates.

Table 3. Average surface roughness, deviation on hole diameter, cylindricity error and drill bit temperature values

Run	Cutting speed (m/min)	Feed rate (mm/rev)	Surface Roughness (µm)	Deviation on hole diameter (mm)	Cylindricity error (mm)	Drill bit temperature (°C)
1	10	0.04	3.208	0.144	0.019	43
2	10	0.08	4.898	0.112	0.018	78
3	10	0.12	6.724	0.070	0.013	78
4	10	0.16	7.851	0.027	0.014	111
5	10	0.2	6.370	0.148	0.022	120
6	20	0.04	8.673	0.160	0.020	54
7	20	0.08	9.483	0.070	0.014	112
8	20	0.12	3.900	0.094	0.006	127
9	20	0.16	8.856	0.119	0.007	176
10	20	0.2	5.070	0.036	0.020	148
11	30	0.04	9.169	0.005	0.009	73
12	30	0.08	8.538	0.024	0.011	43
13	30	0.12	5.900	0.003	0.012	90
14	30	0.16	10.572	0.010	0.009	168
15	30	0.2	7.820	0.071	0,023	230
16	40	0.04	4.394	0.043	0.010	90
17	40	0.08	6.837	0.024	0.014	90
18	40	0.12	6.196	0.065	0.032	226
19	40	0.16	7.745	0.027	0.031	237
20	40	0.2	6.672	0.062	0.003	246

3.1. Surface roughness

Figure 3 shows the measured surface roughness values of the drilled holes. As can be seen from Figure 3, the surface roughness values vary significantly depending on the drilling conditions. The lowest surface roughness value is seen to be 3.208 µm at the lowest cutting speed and feed rate of 10 m/min and 0.04 mm/rev, respectively. On the other hand, the highest surface roughness value is seen to be 10.572 µm at 30 m/min cutting speed and 0.16 mm/rev feed rate. These surface roughness values are quite high and equivalent to N9-N10 roughness grade numbers. Therefore, they can be acceptable for rough machining operations.

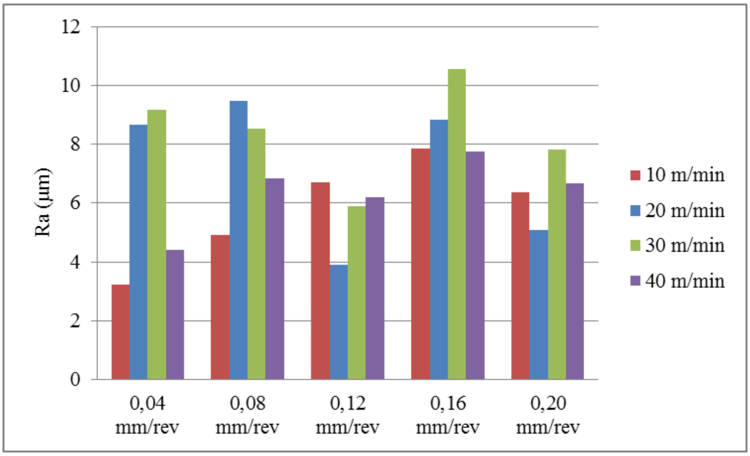
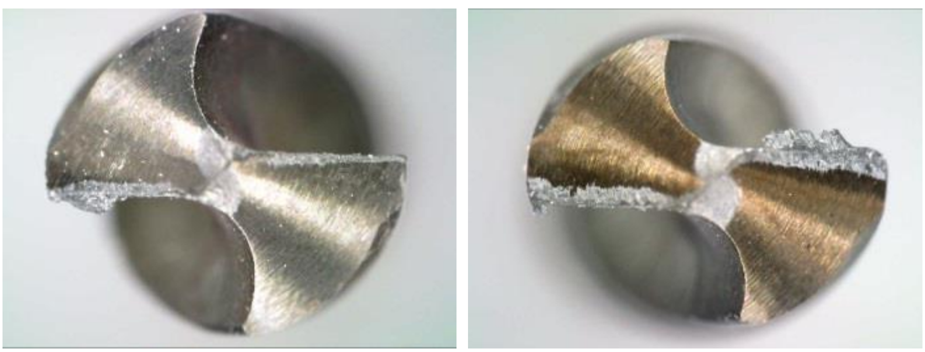


Figure 3. Average surface roughness values

These quite high surface roughness values can be explained by the relatively high ductility of commercially pure molybdenum. Higher surface roughness values are usually seen in machining of commercially pure metals like aluminium, copper and nickel at lower cutting speeds [12]. As the used drill bits are made of HSS, the cutting speeds used in this study are quite low. Therefore, the higher surface roughness values can also be attributed to these quite lower cutting speeds.

As can be seen from Figure 3, the lowest surface roughness value is seen when drilling at the lowest cutting speed and feed rate. In addition, the obtained surface roughness values do not show a prominent trend depending on the cutting parameters. Normally, increasing cutting speed and decreasing feed rate generally decrease the surface roughness values in all machining operations. However, this is not the case in this study.

In addition, these higher surface roughness values can be attributed to the unstable adhered workpiece material to the drill bits. Especially the adhered workpiece to the drill bit's margins leads to higher surface roughness values. The used drill bits are shown in Figure 4. Significantly adhered and detached workpiece material is seen from Figure 4. It can be inferred that the adhered and detached workpiece material during drilling is the other reason for the higher surface roughness values.



(a) (b)

Figure 4. The drill bits used at 20 m/min cutting speed and a) 0.12 mm/rev and b) 0.16 mm/rev feed rates.

3.2. Drill bit wear

The images in Figure 5 show the wear on the drill bits. It is seen from the images that wear is mainly seen at the chisel edges of the drill bits at all the drilling conditions. The wear mode is chipping at the chisel edges. Normally, chipping is usually seen when cutting is interrupted as in milling or in turning a slotted bar. In these cases, the cutting edge is subjected to impact stresses as well as mechanical or thermal fatigue stresses [13]. In addition, chipping usually occurs when using brittle tool materials. In this current study, although the tool material is HSS which has the highest toughness among the all tool materials, significant chipping is seen. This indicates a very strong adhesion between the drill bit and the commercially pure molybdenum during drilling.

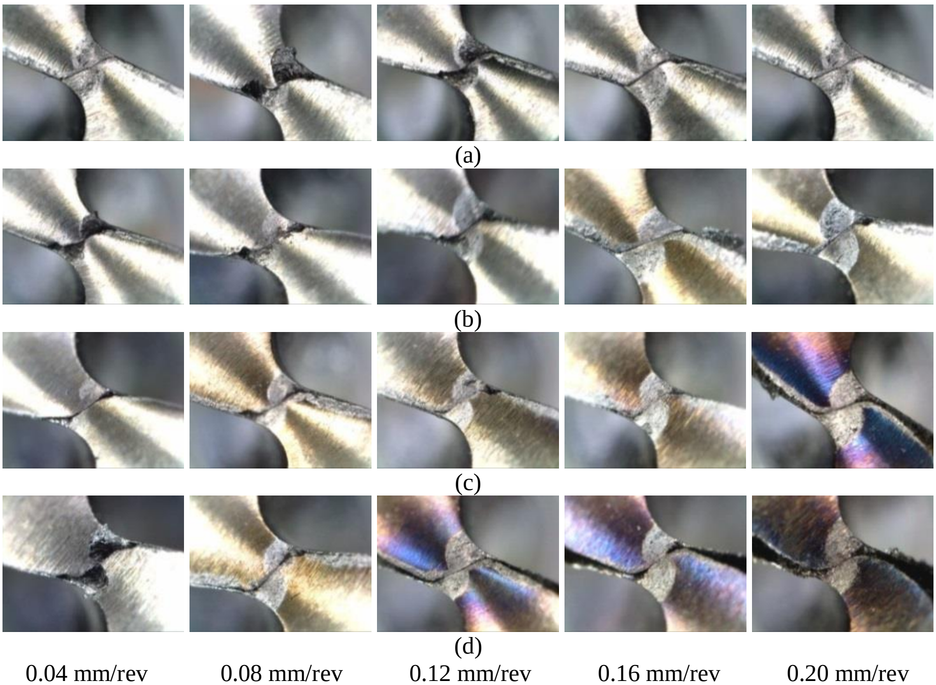


Figure 5. Worn drill bit images at various cutting speeds a) 10 m/min b) 20 m/min c) 30 m/min and d) 40 m/min

At the lowest cutting speed of 10 m/min employed in this study, the amount of chisel edge wear is seen to be independent of the feed rate, Figure 5a. In addition, the amounts of wear of the drill bits used at 10 m/min cutting speed are almost equal to the amounts of wear of the drill bits used at higher cutting speeds. These high amounts of wear can be explained by the very strong adhesion at the lowest cutting speed. Increasing the cutting speed increases temperature at the drill bit cutting edges and this, in turn, reduces the adhesion forces.

With the increasing the cutting speed, increasing the feed rate leads to increased wear as expected. The lowest wear is seen for the drill bit used at 30 m/min cutting speed and 0.04 mm/rev feed rate. At the higher cutting speeds and feed rates, the influence of heat on the drill bits becomes dominant. Especially, this is the case at the highest speed of 40 m/min. In addition to the chisel edge wear, some flank wear is also seen at cutting edges.

3.3. Deviation on hole diameter and cylindricity error

Figures 6 and 7 show the deviation on hole diameter and cylindricity error values of the drilled holes against the drilling conditions. The lowest deviation on hole diameter value is seen to be 0.003 mm at 12 mm/rev feed rate and 30 m/min cutting speed while, the highest one is seen to be 0.16 mm at 0.04 mm/rev feed rate and 20 m/min cutting speed. Similarly, the lowest cylindricity error value is seen to be 0.003 mm at 0.20 mm/rev feed rate and 40 m/min cutting speed while, the highest one is seen to be 0.032 mm at 0.12 mm/rev feed rate and 40 m/min cutting speed. Although there are some exceptions, it can be seen that increasing the cutting speed generally decreases the deviation on hole diameter and cylindricity error values. These decreases can be attributed to the decreasing cutting forces with increasing the cutting speed. In all machining operations, increasing the cutting speed generally leads to low cutting forces. These low cutting forces, in turn, lead to less deviation of the drill bits. Influence of the feed rate on the deviation on hole diameter and cylindricity error are not clear. This also might be due to the adhered and detached workpiece material to the drill bits as in the case of the surface roughness.

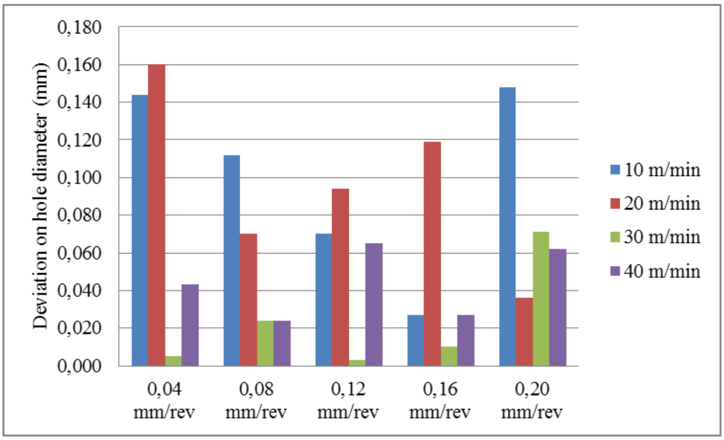


Figure 6. Deviations on hole diameter

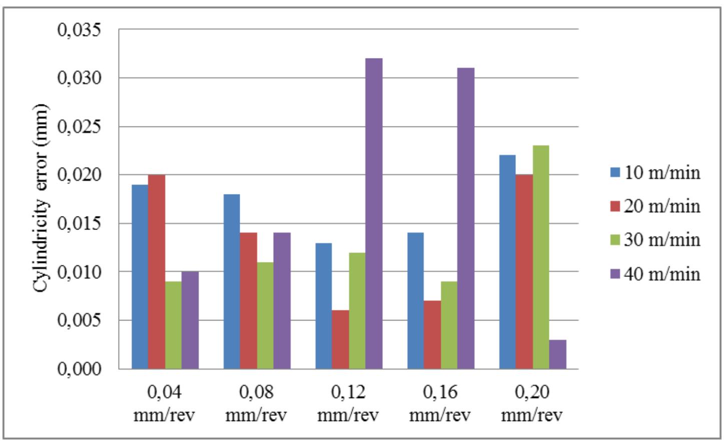


Figure 7. Cylindricity errors

3.4. Temperature

When Figure 8 is examined, it is seen that increasing the cutting speed and feed rate generally increase the drill bit temperature. The highest temperature is seen to be 246 °C at the highest cutting speed of 40 m/min and the highest feed rate of 0.2 mm/rev. The increase in the drill bit temperature with increasing the cutting speed and feed rate can be explained by examining the images of the used drill bits, Figure 5. Temperatures of over 200 °C are seen for the drill bits used at 40 m/min cutting speed and 0.12, 0.16 and 0.20 mm/rev feed rates and seen for the drill bit used at 30 m/min cutting speed and 0.20 mm/rev feed rate. Significant colour change at the cutting edges of these drill bits in Figure 5 is also another indication of the high temperature.

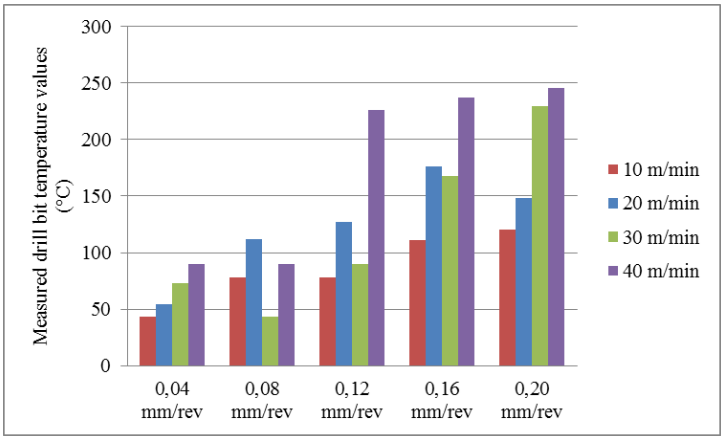


Figure 8. Measured drill bit temperature values

It is well known that increasing amount of wear usually increases the temperature in all machining operations. This is due to the increasing amount of wear at the contact area between the workpiece and the cutting edges. The increasing temperature with the increasing feed rate can also be explained by an increase in length of the contact area between the chip and drill bit rake face. The increased contact length results in increased amount of deformation and rubbing which also increase the temperature.

4. CONCLUSIONS

The following conclusions can be drawn from the present study:

- Preliminary tests showed that cutting speeds over 40 m/min are not suitable when dry drilling commercially pure molybdenum using HSS drill bits.
- The obtained surface roughness values were found to be quite high. In addition, a prominent trend in the surface roughness values was not seen depending on the drilling parameters.
- Significant chisel edge wear was seen for all the drill bits.
- Increasing the cutting speed generally decreased the deviation on hole diameter and cylindricity error values of the drilled holes.
- Drill bit temperature values were generally found to increase with increasing the cutting speed and feed rate.

NOMENCLATURE

f Feed rate (mm/tooth)
Ra Average surface roughness (µm)
Vc Cutting speed (m/min)
Mo Molybdenum
BH Brinell hardness
HSS High Speed Steel
TZM Titanium Zirconium Molybdenum
IMOA International Molybdenum Association

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