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THE MANUFACTURING APPLICATIONS OF MOLYBDENUM METAL AND ITS ALLOYS

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ABSTRACT: This paper presents the several applications of molybdenum and its alloys and requirements in machining process for this metal. Molybdenum metal and its alloys are used in a variety of fields including electrical and electronic devices, materials processing, glass manufacturing, high temperature furnaces and equipment, and aerospace and defense applications.

1. INTRODUCTION

Molybdenum metal is available as ingot, foil, rod, plate and sputtering target and in numerous other forms and custom shapes. Ultra high purity and high purity forms include metal powder, submicron powder and nanoscale, single crystal or polycrystalline forms.

Molybdenum [1,5] has formula Mo, molecular weight is 95.94, and in all its appearance with silver. Moly (its short name) can be found as: molybdenite (MoS_2); wulfenite ($PbMoO_4$), and molydite (MoO_3). Molybdenite is concentrated mechanically and then roasted to convert it to the trioxide:

$$2\,MoS_2 + 7\,O_2 \implies 2\,MoO_3 + 4\,SO_2 \qquad (1)$$

Molybdenum metal is then made by firing the oxide with aluminum:

$$2\,MoO_3 + 4\,Al \implies 2\,Al_2O_3 + 2\,Mo \qquad (2)$$

Molybdenum is a refractory metal typically used in high temperature applications. Key properties include:

- Low co-efficient of thermal expansion -$5.1\text{x}10^{-6}$ m/m/°C, which is about half that of most steels;
- Good thermal conductivity
- Good electrical conductivity;
- Good stiffness, greater then that of steel -Young's Modulus 317MPa;
- High melting point -2615°C;
- Good hot strength, good strength and ductility at room temperature;
- High density -10.2 g/cm^3.

Molybdenum metal and its alloys are used in a variety of markets including electrical and electronic devices, materials processing, glass manufacturing, high temperature furnaces and equipment, and aerospace and defense applications. Moly and its alloys are used in manufacturing of many parts such as: lamp filaments, support structures for lighting and electronic tube, powders for circuit inks and the tooling used to apply them to multi-layer circuit boards, internal components for microwave devices, high-performance electronic packaging, electrical and electronic equipment from medical industry, internal components of X-ray tubes, electrodes for melting of glass, in construction of high temperature furnace and fixers and tooling associated them, in rockets and reactive gas valves, in munitions, components for fixtures and sintering boats, etc.

2. MANUFACTURING PROCESS OF MOLYBDENUM METAL AND ITS ALLOYS

Molybdenum has the third highest melting point of any element, exceeded only by tungsten and tantalum. Moly is a catalyst in the oil refining. It has many other applications, including in catalysts, pigments, corrosion inhibitors and lubricants. Moly [3] is available as metal and compounds with purities from 99% (Mo-M-01) to 99.999% (Mo-M-05), metals in the form of foil, sputtering target, and rod, and compounds as submicron and nanopowder submicron and nanopowder. It is used in steel alloys to had hardness and raise melting points. Moly is used in nuclear reactors and aerospace components. Moly is valuable as a catalyst in the refining of petroleum.

Molybdenum metal and its alloys could be cutting by all the common metal removal processes. The materials are capable of being machined in a wide variety of parts in a range of size with excellent surface finishes and to exacting tolerances. When preparing to machine Mo and its alloys is required to see some aspects. While Mo retains its strength to high temperatures, it's not particularly strong at ambient temperatures. Neither is its ductility as great as carbon steel or brass.

The machines must be rigid and free from backlash, and work should be securely clamped. A high attention is taken in choosing the tools. A wrong tool can tear the material instead of cutting it cleanly, and create microcracks that reduce the life of the workpiece. High speed tools are generally adequate, as long as they are kept sharp. Carbide grades perform well, particularly where problems arise due to the abrasiveness of chips and dust. The tendency for Mo to form discontinuous chips and abrasive dust is one reason why inexperienced shops sometimes are over-optimistic about their ability to machine these materials economically. Carbide tools also prove their economic worth in jobs where long uninterrupted cuts are required, due to their better life between regrinds.

Tabel 1. Parameters for some common machining operations with Mo.

<table>
<tr><th>Operation</th><th>Tool Material</th><th>Tool Geometry</th><th>Tool Used</th><th>Depth of Cut, in.</th><th>Width of Cut, in.</th><th>Feed</th><th>Cutting Speed, ft/min</th></tr>
<tr><td>Turning</td><td rowspan="2">C-2 Carbide</td><td rowspan="2">BR: 0° SCEA 15° SR: 20° ECEA: 15° relief: 5° NR 1/32"</td><td rowspan="2">5/8 in. Sq brazed tool</td><td>0.030</td><td>—</td><td rowspan="2">0.009 in./rev</td><td>450</td></tr>
<tr><td>Turning</td><td>0.060</td><td>—</td><td>350</td></tr>
<tr><td>Face Milling</td><td>T-15 HSS</td><td rowspan="2">AR: 0° ECEA: 10° RR: 20° CA: 45° Clearance: 10°</td><td rowspan="2">4 in. diam single tooth</td><td rowspan="2">0.060</td><td rowspan="2">2</td><td>0.010 in./tooth</td><td>100</td></tr>
<tr><td>Face Milling</td><td>C-2 Carbide</td><td>0.005 in./tooth</td><td>350</td></tr>
<tr><td>End Mill Slotting</td><td>T-15 HSS</td><td rowspan="2">Helix: 30° RR: 10° CA: 45° Clearance: 10°</td><td rowspan="2">3/4 in. diam four-tooth HSS end mill</td><td rowspan="2">0.125</td><td rowspan="2">0.750</td><td rowspan="2">0.004 in./tooth</td><td rowspan="2">190</td></tr>
<tr><td>End Mill Peripheral Cut</td><td>M-3 HSS</td></tr>
<tr><td>Drilling</td><td>M-33 HSS</td><td>118° Plain Point Clearance Angle: 7°</td><td>0.250 in. diam drill, 2½ in. long</td><td rowspan="3">½ Through Hole</td><td>—</td><td>0.005 in./rev</td><td>150</td></tr>
<tr><td>Reaming</td><td>M-2 HSS</td><td>Helix Angle: 0° CA: 45° Clearance: 10°</td><td>0.272 in. diam six-flute chucking reamer</td><td>0.010 depth on hole radius</td><td>0.015 in./rev</td><td>60</td></tr>
<tr><td>Tapping</td><td>M-10 HSS</td><td>Four-flute plug 75% Thread</td><td>5/16-24 NF tap</td><td>—</td><td>—</td><td>70</td></tr>
</table>

Much heavy machining, such as ingot scalping and rough turning, is accomplished without lubrication. For best finishing work, lubrication flushes dust away from the tool-workpiece interface and provides cooling as well. Chlorinated solvents were once the coolant of choice for fine finish machining of molybdenum and its alloys, but environmental and health concerns them to reduce their using such coolants.

Other machining processes such as grinding, photo-etching, and electrical discharge machining are also commonly performed on Mo and its alloys. Grinding process has the potential to cause overheating and surface cracking in these materials if isn't enough amounts of coolant. It's very important in choosing adequate grinding wheel and abrasive to obtain a good finished surface of workpiece and in safety conditions.

Moly and its alloys can be formed by all common metalworking practices such as bending, punching, stamping, drawing, and spinning. It's important to know the mechanical behavior materials. The ductile-brittle transition temperature of molybdenum and its alloys is increased by such factors as increased strain rate and triaxiality of applied stresses. The ability to work the material successfully will thus depend upon the surface condition of the material, the size of the section being formed, and the speed of the deformation. In bending operations, this means that the bend radius which can be successfully bent without cracking will be a function of the sheet thickness. Thicker sections may require heating above room temperature to remain in the ductile regime

Molybdenum and its alloys are typically anisotropic in their ductility properties, unless special processing has been employed to equalize the directionality of deformation in the material.

In fig.1 is depicted recommended temperatures to be used when forming molybdenum metal of varying section thicknesses [2]. Forming temperatures for the carbide-strengthened alloys are 50-100^{0}C higher for any section thickness, due to their greater sensitivity to embrittling factors.

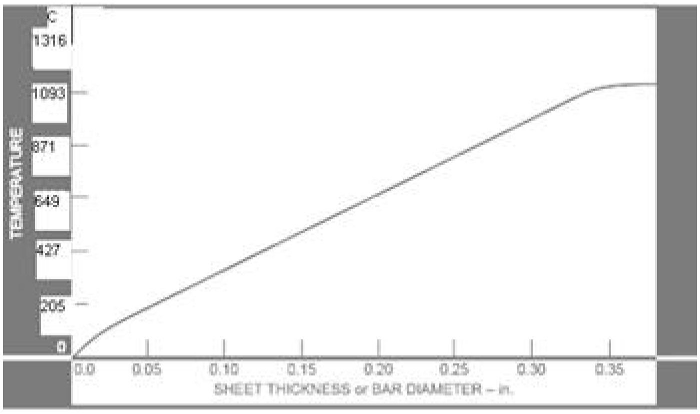

Fig. 1. Diagram with required temperatures at Mo forming.

The shearing operations, such as stamping, punching, and blank shearing, are particularly sensitive to the formation of planar cracks in the sheet being formed. These defects are called delaminations, which they are inter-granular cracks that propagate along the planar grain boundaries. Clearances between blades, or between punch and die in stamping operations, should be in the range of 5-8% per side to minimize delamination. Sheet up to 0.5 mm thick can be successfully sheared at ambient temperature. Preheat temperatures of 65-95 C are recommended for sheet between 0.5 and 1.2 mm thick. In the range of 1.5 mm-3.2 mm, the preheat temperature should be increased to about 350 C, and 600 C preheat is necessary to shear plate of 6.3 mm thick. The method of heating is very large, can be used: linear gas burners, infra-red lights, air furnaces, hand-held torches, and hot plates as heat sources for shearing operations.

Moly and its alloys can be welded and brazed [2], but welding is doing only for applications not subjected to great stress. The weld and surrounding recrystallized zone in the base metal have significantly lower strength, and a much higher ductile-brittle transition temperature than the surrounding material which is unaffected by the welding process. This tends to concentrate the deformation in the weld zone, and the triaxial stresses produced by the constraint of the base metal can result in brittle fracture. There are applications where welded structures perform quite well, and all common welding techniques have been employed to join molybdenum and its alloy. Electron-beam welds, with their narrow weld and heat-affected zones, are less susceptible to failure than GTA welds which require large amounts of heat input. Oxygen is also a bad factor in welded components. It tends to segregate to grain boundaries, further reducing ductility. For this reason, the arc-cast alloys which generally contain higher carbon levels are somewhat more readily welded than the powder metallurgy analogues. The carbide-strengthened alloys are also more forgiving than pure molybdenum for the same reason. Most welding of molybdenum components is performed inside high purity inert gas chambers to minimize oxygen pickup.

Brazing is also in common use for joining Mo and its alloys. Commercial brazing alloys are available that have flow points ranging from 630^0C through 1400^0C. Compositions varied widely, with most containing precious metals. Nickel-base alloys are also available. This is another area where manufacturers of brazing compounds and equipment can provide excellent technical assistance. In most cases, it will be desired that the brazing temperature be below the recrystallization temperature of the alloy to be brazed. In this manner, the improvement in strength and ductile-brittle transition behavior which accrues with mechanical working can be retained.

3. THE APPLICATIONS OF MOLYBDENUM AND ITS ALLOYS

The electrical and electronic devices market [2,4] is the largest for molybdenum and its alloys. It includes applications such as mandrel wire for manufacturing lamp filaments, wire leads and support structures for lighting and electronic tube manufacture, powders for specially formulated circuit inks and the tooling used to apply them to multi-layer circuit boards, internal components for microwave devices, high-performance electronic packaging, and heat sinks for solid state power devices. A subset of this market is comprised of electrical and electronic equipment used in the medical industry. Many of the internal components of X-ray tubes, from the target itself to support structures and heat shields, are manufactured from molybdenum and molybdenum metal alloys. Mo also finds its way into X-ray detectors, where sheet with precisely controlled gauge is used.

Fig.2.Molybdenum anodes.

Fig.3. Molybdenum semiconductors.

A significant amount of molybdenum powder is consumed by thermal spray applications. In this technology, molybdenum metal powder is blended with binders rich in chromium and nickel, then plasma-sprayed on piston rings and other moving parts where wear is a critical performance issue.

The ceramic processing industry also makes extensive use of molybdenum components for fixtures and sintering boats. Molybdenum and its alloys are the materials of choice for sintering ceramic nuclear fuels, while the oxide ceramics processed by the electronics industry are nearly universally sintered in hydrogen on Mo carries.

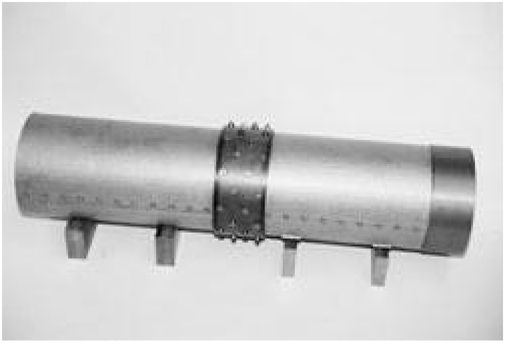

Fig.4. Furnace with molybdenum elements.

Many high temperature industrial furnaces (fig.4) use molybdenum components for such things as elements, element supports, power terminators, and process fixtures. Hot Isostatic Press (HIP) construction relies on inner shells fabricated from molybdenum sheets. These are used to contain the workload and support the heating elements. Likewise, flat heating elements made from moly sheet are used in vacuum and hydrogen furnaces. Heat shielding and other furnace structures help round out the use of moly in the furnace industry.

Elmet Technology Inc is a great company from US [4] which produces a variety of Moly parts such as: high temperature furnace tooling, fixtures and heat shields, also, moly-firing boats of folded, welded and riveted construction are used in processing alumina ceramics as well as uranium oxide nuclear fuel pellets. In the semiconductor, electronics and lighting industries, moly has such varied application as: silicon rectifier mounts (diode heat sinks), glass-to-metal sealed parts, grids, wire and rod support components for power tubes and mandrels for tungsten lamp filament production.

Tabel 2. Molydenum wire composition-typical ppm.

	Pure Molybdenum	**Potassium Doped**
Molybdenum	99.95%	99.95%
W	300 (ppm max)	300 (ppm max)
Si	25	300
O	50	200
Ni	50	50
Na	20	20
N	20	20
K	30	150
Fe	50	50
Cu	15	15
Cr	20	20
C	50	50

Elmet produces two types of molybdenum wire (Tabel 2); pure and HCT. Diameter sizes range from 0.001 inches (0.025 mm) to 0.250 inches (6.35 mm). The pure wire products find use in most standard applications for production of mandrels, supports, furnace elements, furnace windings and formed parts. HCT is a potassium silicate doped product which has a higher recrystallization temperature and for diameters below 0.090 inches (2.3mm) it exhibits better ductility after recrystallization. It is used in more demanding applications such as for halogen lamp leads where it provides superior weldability and glass-to-metal seal properties.

4. CONCLUSIONS

The properties that have made these materials so attractive–strength at high temperature, high stiffness, excellent thermal conductivity, low coefficient of thermal expansion, and chemical compatibility with a variety of environments–will continue in the future to be required in demanding applications.

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