



Standard Specification for Molybdenum and Molybdenum Alloy Plate, Sheet, Strip, and Foil¹

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1. Scope

1.1 This specification covers unalloyed molybdenum and molybdenum alloy plate, sheet, strip, and foil as follows:

1.1.1 *Molybdenum 360*—Unalloyed vacuum arc-cast molybdenum.

1.1.2 *Molybdenum 361*—Unalloyed powder metallurgy molybdenum.

1.1.3 *Molybdenum Alloy 363*—Vacuum arc-cast molybdenum-0.5 % titanium-0.1 % zirconium (TZM) alloy.

1.1.4 *Molybdenum Alloy 364*—Powder metallurgy molybdenum-0.5 % titanium-0.1 % zirconium (TZM) alloy.

1.1.5 *Molybdenum 365*—Unalloyed vacuum arc-cast molybdenum, low carbon.

1.1.6 *Molybdenum Alloy 366*—Vacuum arc-cast molybdenum-30 % tungsten alloy.

1.1.7 *Drawing Grade*—A drawing grade is defined, which may be specified as a separate requirement by the purchaser.

1.2 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

2. Referenced Documents

2.1 *ASTM Standards*:²

E8 Test Methods for Tension Testing of Metallic Materials

E345 Test Methods of Tension Testing of Metallic Foil

E643 Test Method for Ball Punch Deformation of Metallic Sheet Material

3. Terminology

3.1 *Definitions of Terms Specific to This Standard*:

3.1.1 *plate, n*—any product $\frac{3}{16}$ in. or more in thickness.

¹ This specification is under the jurisdiction of ASTM Committee B10 on Reactive and Refractory Metals and Alloys and is the direct responsibility of Subcommittee B10.04 on Molybdenum and Tungsten.

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² For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

3.1.2 *sheet, n*—any product 0.187 in. (4.75 mm) or less in thickness, to a minimum of 0.005 in. (0.13 mm) in thickness.

3.1.2.1 *standard grade, n*—sheet ordered without additional requirements imposed for applications which require drawing to make a product.

3.1.2.2 *drawing grade, n*—sheet having thickness between 0.015 in. (0.38 mm) and 0.060 in. (1.52 mm), intended for applications which require drawing of the sheet to make a product.

3.1.3 *strip, n*—any product 0.187 in. (4.75 mm) or less in thickness and less than 5 in. (127 mm) in width.

3.1.4 *foil, n*—any product less than 0.005 in. (0.13 mm) in thickness.

4. Ordering Information

4.1 Orders for material under this specification shall include the following information as applicable:

4.1.1 Material number and temper designation (Section 1 and Table 1),

4.1.2 Product form and grade (Section 3),

4.1.3 Chemical requirements (Table 2 and Table 3),

4.1.4 Mechanical requirements (Section 7 and Table 1),

4.1.5 Softening temperature (Section 8),

4.1.6 Tolerances (Section 9, Table 4 and Fig. 1),

4.1.7 Workmanship and quality level requirements (Section 10),

4.1.8 Packaging (Section 16),

4.1.9 Marking (Section 15),

4.1.10 Certification and reports (Section 14), and

4.1.11 Disposition of rejected material (Section 13).

5. Materials and Manufacture

5.1 The various molybdenum mill products covered by this specification shall be formed with the conventional extrusion, forging, or rolling equipment normally found in primary ferrous and nonferrous plants. The ingot metal for Molybdenum 360 and 365 and Molybdenum Alloys 363 and 366 is vacuum arc-melted in furnaces of a type suitable for reactive, refractory metals and for Molybdenum 361 and Molybdenum Alloy 364, the metal is consolidated by powder metallurgy methods.



TABLE 1 Mechanical Requirements

| Type | Temper Condition ^A | Thickness, in. (mm) | Tensile ^B Strength, min, ksi (MPa) | Yield Strength 0.2 % Offset, min, ksi (MPa) | Elongation in 2 in. or 50 mm, min, % | Minimum Bend Radius |
|------------------------------|-------------------------------|-------------------------------------|-----------------------------------------------|---------------------------------------------|--------------------------------------|---------------------|
| 360, 361, 365 | SR | to 0.001 (0.025) | 115 (795) | 95 (655) | 1 | ... |
| | | over 0.001 to 0.002 (0.025 to 0.05) | 115 (795) | 95 (655) | 2 | ... |
| | | over 0.002 to 0.003 (0.05 to 0.075) | 115 (795) | 95 (655) | 3 | ... |
| | | over 0.003 to 0.004 (0.075 to 0.1) | 115 (795) | 95 (655) | 4 | ... |
| | | 0.005 to 0.010 (0.13 to 0.25) | 110 (760) | 90 (620) | 5 | 2 ^C |
| | | over 0.010 to 0.020 (0.25 to 0.5) | 110 (760) | 90 (620) | 6 | 2 ^t |
| | | over 0.020 to 0.060 (0.5 to 1.5) | 105 (725) | 85 (585) | 10 | 2 ^t |
| | | over 0.060 to 0.100 (1.5 to 2.5) | 100 (690) | 80 (550) | 14 | 2 ^t |
| | | over 0.100 to 0.187 (2.5 to 4.75) | 100 (690) | 80 (550) | 18 | 2 ^t |
| | | 3/16 to 1/2 (4.75 to 12.7) | 100 (690) | 80 (550) | 10 | ... |
| over 1/2 to 1 (12.7 to 25.4) | 95 (655) | 80 (550) | 2 ^D | ... | | |
| over 1 to 1 1/2 (25.4 to 38) | 95 (655) | 80 (550) | 1 ^D | ... | | |
| 363, 364 | SR | 0.010 to 0.025 (0.25 to 0.635) | 120 (830) | 100 (690) | 6 | 2 ^t |
| | | over 0.025 to 0.060 (0.635 to 1.5) | 120 (830) | 100 (690) | 7 | 2 ^t |
| | | over 0.060 to 0.090 (1.5 to 2.3) | 120 (830) | 100 (690) | 9 | ... |
| | | over 0.090 to 0.187 (2.3 to 4.75) | 120 (830) | 100 (690) | 10 | ... |
| | | 3/16 to 1/2 (4.75 to 12.7) | 120 (830) | 100 (690) | 10 | ... |
| | | over 1/2 to 1 (12.7 to 25.4) | 110 (760) | 95 (655) | 10 | ... |
| over 1 to 1 1/2 (25.4 to 38) | 100 (690) | 85 (585) | 8 | ... | | |
| 360 | RX | 3/16 to 1 1/2 (4.75 to 38) | 55 (380) | 25 (170) | 20 | ... |
| 363, 364 | RX | 3/16 to 1 1/2 (4.75 to 38) | 75 (515) | 45 (310) | 10 | ... |

^A SR = stress-relieved. RX = essentially fully recrystallized.

^B Both longitudinal and transverse tests between 65 and 85°F (18 and 29°C).

^C Material thickness = *t*.

^D Transverse elongation variable due to cross rolling limitations.

TABLE 2 Chemical Requirements

| Element | Composition, % | | | | | |
|---------------------|-----------------|-----------|-------------|-------------|-----------|-----------|
| | Material Number | | | | | |
| | 360 | 361 | 363 | 364 | 365 | 366 |
| C | 0.030 max | 0.010 max | 0.010–0.030 | 0.010–0.040 | 0.010 max | 0.030 max |
| O, max ^A | 0.0015 | 0.0070 | 0.0030 | 0.030 | 0.0015 | 0.0025 |
| N, max ^A | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 |
| Fe, max | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 |
| Ni, max | 0.002 | 0.005 | 0.002 | 0.005 | 0.002 | 0.002 |
| Si, max | 0.010 | 0.010 | 0.010 | 0.005 | 0.010 | 0.010 |
| Ti | ... | ... | 0.40–0.55 | 0.40–0.55 | ... | ... |
| W | ... | ... | ... | ... | ... | 27–33 |
| Zr | ... | ... | 0.06–0.12 | 0.06–0.12 | ... | ... |
| Mo | balance | balance | balance | balance | balance | balance |

^A Pending approved methods of analysis, deviations from these limits alone shall not be cause for rejection.

6. Chemical Composition

6.1 The molybdenum and molybdenum alloy ingots and billets for conversion to finished products covered by this specification shall conform to the requirements of the chemical composition prescribed in Table 2.

6.2 Check Analysis:

6.2.1 Check analysis is an analysis made by the purchaser or the manufacturer of the metal after it has been processed into finished mill forms, and is either for the purpose of verifying the composition of a heat or lot or to determine variations in the composition within a heat or lot.

6.2.2 Check analysis tolerances do not broaden the specified heat analysis requirements but cover variations between laboratories in the measurement of chemical content.

6.2.3 The manufacturer shall not ship material that is outside the limits specified in Table 2 for the applicable type,

TABLE 3 Permissible Variations in Check Analysis

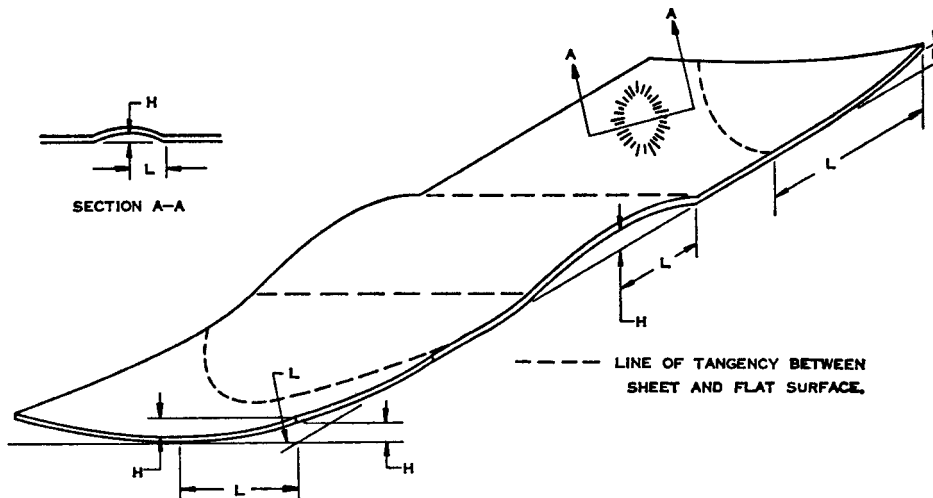
| | Material No. | Check Analysis Limits, max or range, % | Permissible Variations in Check Analysis, % |
|----------------|------------------------------|----------------------------------------|---------------------------------------------|
| C | 360, 363, 364, 366, 361, 365 | 0.010–0.040 | ±0.005 |
| | | 0.010 | ±0.002 |
| O ^A | 361 | 0.0070 | +10 % relative |
| | 360, 363, 365, 366, 364 | 0.0030 | +10 % relative |
| N ^A | 361, 364, 365 | 0.0020 | +10 % relative |
| | 360, 363, 366 | 0.0010 | +0.0005 |
| Fe | 360, 361, 363, 364, 365, 366 | 0.010 | +0.001 |
| Ni | 360, 361, 363, 364, 365, 366 | 0.005 | +0.0005 |
| Si | 360, 361, 363, 364, 365, 366 | 0.010 | +0.002 |
| Ti | 363, 364 | 0.40–0.55 | ±0.05 |
| W | 366 | 27.0–33.0 | ±1.0 |
| Zr | 363, 364 | 0.06–0.12 | ±0.02 |

^A See Table 2, Footnote^A

TABLE 4 Permissible Thickness Variations of Plate, Sheet, Strip and Foil

| Specified Width, in. (mm) | Specified Thickness, in. (mm) | Thickness Tolerance, ^A in. (mm) |
|-----------------------------------|------------------------------------------------------------------------------------------------------|-----------------------------------------------|
| 12 (305) and under | 0.005 to 0.010 (0.13 to 0.25), incl over 0.010 to 0.020 (0.25 to 0.51), incl over 0.020 (0.51) | ±0.001 (±0.0254) ±0.002 (±0.0508) ±10 % |
| Over 12 to 24 (305 to 610), incl | over 0.010 to 0.025 (0.25 to 0.64), incl over 0.025 (0.64) | ±0.0025 (±0.0635) ±10 % |
| Over 24 to 30 (610 to 762), incl | over 0.016 to 0.030 (0.41 to 0.76), incl over 0.030 (0.76) | ±0.003 (±0.0762) ±10 % |
| Over 30 to 48 (762 to 1219), incl | 0.040 (1.02) and over 0.1875 (4.762) and over | ±10 % ±10 % |

^A Tolerances for foil shall be as agreed upon between producer and purchaser.



$$\text{Flatness Deviation, \%} = (H/L) \times 100$$

H = maximum distance between flat surface and lower surface of sheet.

L = minimum distance between highest point on sheet and point of contact with flat surface.

FIG. 1 Plate and Sheet Flatness Tolerances

with the exception of oxygen and nitrogen, whose percentage may vary with the method of fabrication.

6.2.4 Check analysis limits shall be as specified in Table 3.

7. Mechanical Properties

7.1 Material supplied under this specification shall conform to the mechanical property requirements given in Table 1, when tested in the transverse direction to final working at test temperatures between 65 and 85°F (18 and 29°C).

7.2 Tension test specimens shall be prepared and tested in accordance with Test Methods E8 or E345 for foil. Tensile properties shall be determined using a strain rate of 0.002 to 0.005 in./in.-min (or mm/mm-min) through 0.6 % offset and 0.02 to 0.05 in./in.-min (or mm/mm-min) to fracture.

7.3 For sheet and strip, the bend test specimens shall withstand being bent at a temperature between 65 and 85°F (18 and 29°C) through an angle of 90° or more without fracture. The bend shall be made on a radius equal to that shown in Table 3 for the applicable type. The bend test specimen shall be at least 0.5 in. (12.7 mm) wide and deburred. The speed of the ram shall be 5 to 10 in. (127 to 254 mm)/min.

7.4 For sheet ordered as drawing grade, ball punch deformation tests shall be performed in accordance with Test

Method E643. Drawing grade sheet shall meet the requirements of Fig. 2.

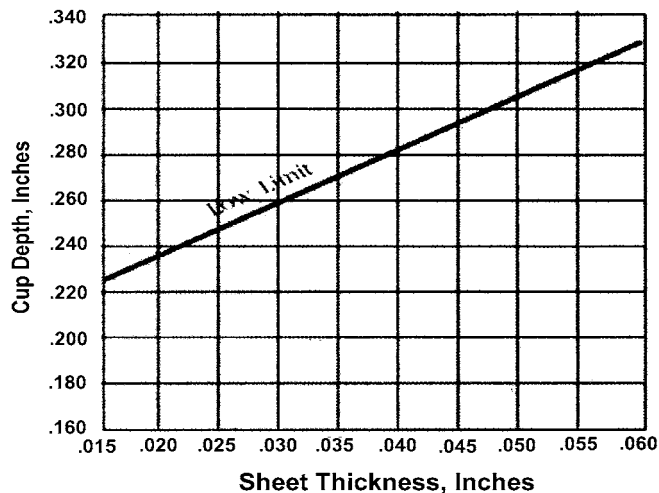


FIG. 2 Ball Punch Deformation Requirements for Drawing Grade Sheet



8. Softening Temperature

8.1 If specified, the material supplied under this specification shall have mechanical properties not lower than those shown in **Table 1** after reheating in a protective atmosphere to the following temperatures for a period of 30 min.

| Alloy Type | °F | °C |
|------------|------|------|
| 360 | 1650 | 900 |
| 361 | 1650 | 900 |
| 363 | 2100 | 1150 |
| 364 | 2100 | 1150 |
| 365 | 1650 | 900 |
| 366 | 1900 | 1040 |

9. Permissible Variations in Dimensions

9.1 Thickness tolerances on molybdenum and molybdenum alloy material covered by this specification shall be as specified in **Table 4**.

9.2 Width tolerances shall be as agreed upon between the manufacturer and the purchaser. In general, shearing tolerance will be $\pm 1/16$ in. (± 1.6 mm) and slitting tolerance will be $\pm 1/32$ in. (± 0.8 mm).

9.3 Length and camber tolerances shall be as agreed upon between the manufacturer and the purchaser. In general, length and camber tolerances will show a maximum deviation of $\pm 1/16$ in. (1.6 mm) per foot length.

9.4 Flatness tolerances on molybdenum and molybdenum alloy flat products shall be as follows:

| Thickness, in. (mm) | Flatness Deviation, max, % |
|-------------------------------------|----------------------------|
| 0.005 to 0.187 (0.13 to 4.75) | 4 |
| $3/16$ to $1/2$ (4.75 to 12.7) | 5 |
| Over $1/2$ to 1 (over 12.7 to 25.4) | 8 |
| Over 1 to $1 1/2$ (over 25.4 to 38) | 8 |

9.4.1 Determine flatness deviation as follows: (**Fig. 1**)

$$\text{Flatness deviation, \%} = (H/L) \times 100 \quad (1)$$

where:

H = maximum vertical distance between a flat reference surface and the lower surface of the flat product, and

L = minimum horizontal distance between the highest point of the flat product where H is determined, and the point of contact of the lower surface of the flat product with a flat reference surface.

10. Workmanship, Finish and Appearance

10.1 Molybdenum and molybdenum alloy plate, sheet, strip, and foil shall be free of injurious external and internal imperfections of a nature that will interfere with the purpose for which it is intended.

10.2 Material may be supplied with as rolled, as cleaned, as machined, or as ground finish.

10.3 The manufacturer shall be permitted to remove surface imperfections provided such removal does not reduce the dimensions below the minimum permitted by the tolerances for that dimension.

11. Sampling

11.1 Care shall be exercised to ensure that the sample selected for testing is representative of the material and form and is not contaminated by the sampling procedure.

12. Methods of Chemical Analysis

12.1 The chemical composition enumerated in this specification shall in case of disagreement, be determined in accordance with the methods approved for referee purposes by ASTM. Where such methods are not available, methods of analysis as mutually agreed upon by the manufacturer and the purchaser shall be employed.

13. Rejection

13.1 Material not conforming to this specification or to authorized modifications shall be subject to rejection. Unless otherwise specified, rejected material may be returned to the manufacturer at the manufacturer's expense unless the purchaser receives, within 4 weeks of notice of rejection, other instructions for disposition.

14. Certification

14.1 If requested, the manufacturer shall supply at least three copies of a report of the chemical analysis of each heat (Types 360, 363, 365, and 366) or powder metallurgy product from the powder lot (Types 361 and 364) represented in the shipment, and reports of the result of tests of each size of each heat or powder lot to determine properties required in Sections 7 and 8.

14.2 The report shall include the purchase order number, heat or powder lot number, this specification number, type and temper condition, nominal thickness, and quantity and number of items covered by the shipment.

15. Product Marking

15.1 Unless otherwise specified, each plate, sheet, or strip shall be legibly and conspicuously marked or tagged with the number of this specification, material type and temper condition, heat or lot number, manufacturer's identification, and the nominal thickness gage in inches. All markings must withstand ordinary handling and shall be capable of removal with standard cleaning solvents.

15.2 Coiled sheet, strip, and foil shall be similarly marked at the outside end of each coil.

16. Packaging and Package Marking

16.1 Unless otherwise specified, material purchased under this specification must be packaged by box or other suitable protective containers and shall be so marked as to indicate the nature of any special handling required.

17. Keywords

17.1 drawing grade sheet; foil; molybdenum; molybdenum alloy; plate; sheet; strip



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