WHITE PAPER

MP35N: A Superalloy for Critical Oil and Gas Applications

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INTRODUCTION

The attractive properties of MP35N® have led to its adoption into critical equipment in industries including aerospace, medicine, mining, offshore equipment, and oil and gas production. Typical applications include fasteners, springs, wire, cables, medical prostheses, pump shafts, valve stems, pressure housings, and cold-worked tubing. Even at yield strengths exceeding 200 ksi (1380 MPa), MP35N possesses excellent corrosion resistance in harsh oil and gas environments including seawater, chloride brines, sweet gas, and sour gas. It is the highest strength alloy approved in NACE MR0175 [1] for use in unrestricted sour service, offering an unmatched combination of strength and corrosion resistance. The unique capabilities of MP35N are derived from the alloy's chemistry, premium melting technology, cold-working, and heat treatment.

MP35N (UNS R30035) is a vacuum induction melted (VIM), vacuum arc re-melted (VAR) superalloy with cobalt, nickel, chromium, and molybdenum as its primary alloying elements. Its nominal chemical composition by weight is 35% cobalt, 35% nickel, 20% chromium, and 10% molybdenum. The VIM VAR melt practice provides superior cleanliness and reduces the presence of non-metallic inclusions and residual elements, like carbon, that have deleterious effects on mechanical properties and corrosion resistance. MP35N is unique in its ability to be simultaneously strong, tough, and ductile with superior corrosion resistance. It can be strengthened beyond the capabilities of stainless steels and nickel-based alloys like 718 with equal or better corrosion resistance in many environments.

The high strength of MP35N is created by a combination of work hardening and an age hardening heat treatment. Yield strength in the high-strength cold-worked-and-aged condition can exceed 260 ksi (1793 MPa) with ductility near 40% reduction of area. Much of the strengthening occurs during cold working, and the annealed properties are like many stainless steels. Typical properties in the annealed condition are 150 ksi ultimate tensile strength, 60 ksi yield strength, 68% elongation, and 75% reduction or area.

The vast array of MP35N applications has led to discrete processing routes, with clear distinctions between processes used for oil and gas and aerospace equipment. As with other alloys like nickel-based alloy 718, the tradeoff is between higher strength levels preferred for aerospace applications versus the resistance to stress corrosion cracking and hydrogen embrittlement required for oil and gas equipment. This paper seeks to inform the reader on the basic alloy systems that give MP35N its unique properties, the industry specifications created by the aerospace and oil and gas industries for MP35N, and the resultant properties.

MICROSTRUCTURE

MP35N has a face centered cubic (FCC) microstructure in the annealed condition. This is like other nickel and cobalt-based alloys. The primary strengthening mechanism is the partial transformation of the FCC structure to a hexagonal close-packed (HCP) structure. The HCP phase forms as thin platelets varying in thickness from 20 to 3,000 angstroms along planes of the FCC matrix. The spacing of the HCP platelets is directly related to strength – closer spacing results in higher strength. The platelets are difficult to detect metallographically, typically requiring transmission electron microscopy with magnification on the order of 20,000 times to visualize.

The FCC phase is stable above 1200°F, whereas the HCP structure is stable below 800°F. However, the transformation from FCC to HCP cannot occur by temperature alone and requires mechanical deformation. The extent of the transformation, and final strength level, depends on the amount of mechanical deformation imparted at temperatures below 800°F. The most common methods of introducing deformation are cold-working processes like drawing and forming.

After mechanically working the material, further strengthening up to an additional 40 ksi occurs via an age-hardening heat treatment. Peak strengthening occurs at ageing temperatures between 800°F and 1200°F due to precipitation of a cobalt-molybdenum phase. Age hardening without mechanically deforming the materials to form the HCP structure has little effect because the cobalt-molybdenum phase forms at the interfaces between HCP platelets and the FCC matrix. Yield strengths greater than 260 ksi (1793 MPa) are possible in the high-strength condition.

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CORROSION RESISTANCE

MP35N uniquely combines the corrosion resistance of stainless steels and nickel-based alloys with the strength levels of high-strength steels. It is the highest strength alloy approved in NACE MR0175 for use in sour service. It has excellent seawater corrosion resistance at all strength levels, and is resistant to attack in most mineral acids and hydrogen sulfide. The high levels of chromium and molybdenum give MP35N pitting and crevice corrosion resistance in chloride environments that exceeds the performance of 316 stainless steel and is like that of nickel alloy 625. NACE MR0175 [1] permits the use of MP35N processed per the specification for any in-situ combination of temperature, H_2S partial pressure, chloride concentration, and pH occurring in downhole production environments.

The VIM VAR melt practice limits the presence of elements like carbon, manganese, silicon, and aluminum that can form intermetallic phases, like chromium carbides, at grain boundaries that locally reduce corrosion resistance. The precipitation of these unwanted phases depletes chromium from the surrounding matrix in a process known as sensitization. This problem is pronounced in alloys like 316 stainless steel, particularly if high-temperature processes like welding are used during fabrication. The chemical composition of MP35N, combined with premium melting, alleviates these concerns.

The alloy is considered virtually immune to general, crevice, and stress corrosion, regardless of strength level or processing condition [2]. The FCC crystal structure of the MP35N matrix gives it excellent resistance to hydrogen embrittlement due to tight atomic spacing. This is especially true when compared to high-strength alloy steels with body centered cubic microstructures (tempered martensite) and precipitation hardened nickel alloys like 718. MP35N is resistant to hydrogen embrittlement at high strength levels compared to these alloys, and is typically susceptible only in the presence of cathodic protection systems or galvanic coupling to more active materials like alloy steels [2].

MP35N's resistance to hydrogen embrittlement is influenced by the thermal treatment applied after cold work. Kane et al. [3] demonstrated that MP35N is resistant to hydrogen embrittlement in many combinations of cold-work and thermal treatments in sour environments. However, the authors also discovered that cold-worked MP35N aged at 1100°F, near the peak-aged condition, was susceptible to hydrogen embrittlement from galvanic coupling to alloy steel in solutions both with and without H2S. This effect was only observed on samples stressed transverse to the direction of cold-working. Further work by Kane [4] and Kane and Berkowitz [5] showed that higher ageing temperatures dramatically increased resistance to hydrogen embrittlement. This work was foundational to the establishment of the heat treatment practices now approved in NACE MR0175 [1].

To summarize, ageing between 1000°F and 1200°F maximizes strength, but also increases susceptibility to hydrogen embrittlement in the transverse direction, particularly when yield strength exceeds 250 ksi. Conversely, ageing temperatures near 1400°F considerably reduces the risk of hydrogen embrittlement, but yield strength is typically below 200 ksi [2]. As with precipitation-hardening nickel alloys, hardness is a poor predictor of environmental cracking resistance, as microstructural properties are the primary performance driver. In a study by Kolts [6], samples with heavy cold reduction but no ageing were shown to fail in a hydrogen-charging environment, while samples with the same level of cold reduction aged at 1500°F did not. The hardness values for these two conditions were roughly identical but showed disparate performance.

Krishnan et al. [7] examined the effect of various corrosive media relevant to oil and gas subsurface safety valves on MP35N torsion springs cold-worked and aged at 1200°F for 4 hr to a hardness of 51.6 HRC per the limits in NACE MR0175 [1] for MP35N springs. The authors found that a simulated sour gas production environment had no effect on the springs. A simulated acid-flowback environment produced localized corrosion only detectable via scanning electron microscope in regions with relatively rough surface finish, and no crack propagation or secondary cracking was observed. These springs were then subjected to 200 loading cycles following exposure to the corrosive media and did not fail. Further testing with galvanic coupling of the MP35N springs to alloy steel in a sour environment also failed to produce any noticeable corrosion damage. Failure of these springs was only induced by intentional exposure to 38% hydrochloric acid at 180 F with a solution pH of 0.5. The authors concluded that MP35N is a suitable material for subsurface safety valves in sour and acidized production environment, but emphasized the importance of a smooth surface finish. Evidence of hydrogen embrittlement was only found after exposure to an extreme environment following galvanic coupling to steel, as was the case in previous work.

KEY INDUSTRY SPECIFICATIONS

There are several industry specifications that are leveraged to control MP35N manufacturing within the oil and gas and aerospace industries; these include AMS 5844 [8], AMS 5845 [9], AMS 5758 [10], NACE MR0175 [1], and API 20F [11]. The properties required for fitness for service in sour and hydrogen charging environments typical of oil and gas production are enumerated in NACE MR0175 and API 20F. There has been some confusion in the oil and gas industry because these specifications sometimes reference limits like alloy chemistry and solution heat treatments in the AMS documents. In some cases, like the use of MP35N for springs per NACE MR0175, the ageing heat treatments overlap with the AMS limits. The following sections highlight the requirements of each specification and the key differentiations. A synopsis is shown in Table 1:

Table 1: Major Aerospace and Oil and Gas Specifications for MP35N

Specification	Description
SAE AMS 5844	**Solution treated and cold worked bar up to 1.75" diameter**
SAE AMS 5845	**Solution treated, cold worked, and aged bar up to 1.75" diameter**
SAE AMS 5758	**Solution treated bar up to 1.75" diameter**
NACE MR0175	**Heat treatment and hardness limits for use in sour service**
API 20F	**Processing requirements for corrosion resistant alloys used for bolting**

SAE AMS 5844 Rev. H

AMS 5844 covers MP35N round bar up to 1.75 inches in diameter supplied in the solution treated and work strengthened condition. Chemistry limits are established as shown in Table 2 and VIM VAR melting is required for cleanliness.

Table 2: Chemistry Limits for MP35N in AMS 5844

Element	min	max	Element	min	max
CARBON	-	0.025	**NICKEL**	33	37
MANGANESE	-	0.15	**MOLYBDENUM**	9	10.5
SILICON	-	0.15	**TITANIUM**	-	1
PHOSPHORUS	-	0.015	**IRON**	-	1
SULFUR	-	0.01	**COBALT**	remainder	
CHROMIUM	19	21			

AMS 5844 requires that bars be solution heat treated by heating to a temperature within the range 1900 to 1925 °F (1038 to 1052 °C), holding at the selected temperature within ±25 °F (±14 °C) for 4 to 8 hours, and cooling in air to room temperature. The hardness of the solution treated and cold worked bar shall be 38 HRC or greater per ASTM E18 and the grain size per ASTM E112 shall be 4 or finer.

Mechanical property requirements for material following an age hardening heat treatment within the range 1000 to 1200 °F (538 to 649 °C), holding at the selected temperature within ±25 °F (±14 °C) for 4 to 4-1/2 hours, and cooling in air to room temperature are as follows in Table 3:

Table 3: Mechanical Properties after Ageing Required by AMS 5844

Property	Value
Tensile Strength	**260 ksi (1793 MPa)**
Yield Strength at 0.2% Offset	**230 ksi (1586 MPa)**
Elongation in 4D	**8%**
Reduction of Area	**35%**

Mechanical property requirements for bars larger than 1.75 inch (44.4 mm) diameter shall be agreed upon between purchaser and producer. The mechanical properties after ageing are required as a capability demonstration, but the material is supplied in the solution treated and cold worked condition with the age hardening heat treatment at the supplier omitted.

SAE AMS 5845 Rev. J

SAE AMS 5845 covers MP35N round bar up to 1.75 inches in diameter in the solution heat treated, work strengthened, aged, and centerless ground condition. The VIM VAR melt practice and chemistry limits are identical to those in AMS 5844, shown in Table 2. The solution annealing and age hardening heat treatments are also identical to those in AMS 5844 and are summarized in Table 4:

Table 4: Summary of Heat Treatments for AMS 5844/5845	
Heat Treatment	**Procedure**
Solution Annealing	**1900 to 1925 °F (1038 to 1052 °C), hold the selected temperature within ±25 °F (±14 °C) for 4 to 8 hours, and air cool to room temperature**
Age Hardening	**1000 to 1200 °F (538 to 649 °C), hold the selected temperature within ±25° F (±14 °C) for 4 to 4.5 hours, and air cool to room temperature**

The required mechanical and microstructural properties after ageing are shown in Table 5:

Table 5: MP35N Property Requirements in AMS 5845	
Property	**Value**
Tensile Strength	**260 ksi (1793 MPa)**
Yield Strength at 0.2% Offset	**230 ksi (1586 MPa)**
Elongation in 4D	**8%**
Reduction of Area	**35%**
Hardness per ASTM E18	**44 HRC min**
Grain Size per ASTM E112	**4 or finer**

Mechanical property requirements for bars larger than 1.75-inch (44.4 mm) diameter shall be agreed upon between purchaser and producer as in AMS 5844.

SAE AMS 5758 Rev. J

AMS 5758 covers MP35N in the solution treated condition. The chemical composition limits are identical to those in Table 2 for AMS 5844 and AMS 5845, and VIM VAR melting is required. The solution annealing heat treatment is identical to that listed in Table 4 for AMS 5844 and AMS 5845. AMS 5758 requires that mechanical properties in the solution treated condition be within the limits listed in Table 6.

Table 6: MP35N Property Requirements in the Solution Treated Condition per AMS AMS 5758	
Property	**Value**
Tensile Strength	**115 to 145 ksi (793 to 1000 MPa)**
Yield Strength at 0.2% Offset	**35.0 to 65 ksi (241 to 448 MPa)**
Elongation in 4D, min	**50%**
Reduction of Area, min	**65%**
Hardness per ASTM E10	**241 HB max**
Grain Size per ASTM E112	**4 or finer**

The material shall achieve the mechanical properties shown in Table 3 and when cold worked on a straight draw bench to 53% ± 1% cold reduction based on cross-sectional area and age hardened between 1000 to 1200°F per the heat treatment listed in Table 4. Like AMS 5844, the testing in the cold worked and aged condition is for capability testing only, and the material is supplied to the customer in the solution treated condition absent of cold work or ageing treatment.

NACE MR0175/ISO 15156 Third Edition, 2015

NACE MR0175 controls the ageing treatment of MP35N to limit its susceptibility to environmental cracking in the presence of hydrogen sulfide. There are two sets of approved processing and property limits for MP35N: one governs its use for any equipment or component, the other for use as springs. The chemistry limits listed in MR0175 are identical to those listed in AMS specifications 5844, 5845, and 5758, and shown in Table 2. The AMS specifications will sometimes be listed to control melt practice, chemistry, and solution annealing on orders for material complying to the ageing and hardness limits in NACE MR0175.

MP35N shall have a maximum hardness of 51 HRC in the solution-treated, cold-worked, and aged condition when used for any equipment or component. The required ageing treatments for MR0175 are listed in Table 7. MP35N has a hardness limit of 35 HRC if it is not aged per Table 7. It is worth noting that the maximum allowable hardness for cold worked material in NACE MR0175 is less than the minimum of 38 HRC allowed for the same condition in AMS 5844.

NACE MR0175 permits a higher hardness limit of 55 HRC when MP35N is used for springs in the cold-worked-and-aged condition. The permissible age hardening treatment is also different, as shown in Table 8. The ageing treatment for springs can create some confusion with the AMS specifications, as the temperature and time limits fall within the range listed in AMS 5844, 5845 and 5758.

Table 7: MP35N Age Hardening Times and Temperatures per NACE MR0175

Minimum Time (hrs)	Temperature °C (°F)
4	704 (1,300)
4	732 (1,350)
6	774 (1,425)
4	788 (1,450)
2	802 (1,475)
1	816 (1,500)

Table 8: MP35N Age Hardening Treatment for Springs per NACE MR0175

Time	Temperature
4 hrs minimum	649 °C (1,200 °F) minimum

API 20F Second Edition, 2018

The second edition of API specification 20F became effective in November 2018 and covers bolting manufactured from corrosion resistant alloys. The scope of the document includes the precipitation hardened nickel alloys covered in API 6ACRA, alloy A286 (ASTM A453 grade 660), and MP35N. This specification draws on processing and property requirements from AMS 5844 and NACE MR0175. API 20F increases the rigor of quality and process controls applied to critical bolting for the oil and gas industry.

For MP35N, the bolting manufacturer is required to have a written specification that complies with the SAE AMS 5844 chemistry, melting practice, solution annealing, furnace tolerances, and average grain size. The ageing procedures and hardness limitations are dictated by those in NACE MR0175. Solution-treated-and-cold-worked material is limited to a maximum hardness of 35 HRC as in MR0175. Material supplied in the solution treated, cold worked, and aged condition must be aged per one of the conditions listed in NACE MR0175 (see Table 7) with a maximum allowable hardness of 51 HRC. Furthermore, heat treatment of MP35N is only to be performed by the raw material supplier/mill. A summary of the MP35N hardness limits in API 20F and NACE MR0175 is provided in Table 9.

Table 9: Summary of MP35N Hardness Limits in API 20F and NACE MR0175

Condition	Hardness Limit		
	API 20F	NACE MR0175 Any Equipment	NACE MR0175 Springs
Solution treated and cold worked	35 HRC max	35 HRC max	-
Solution treated, cold worked, and aged	51 HRC max	51 HRC max	55 HRC max

Bolting manufacturers are responsible for qualifying raw material suppliers, defined as a melting mill in API 20F, for each grade and heat treatment condition, based on quality assurance and technical practices. They must also ensure that raw material suppliers have appropriate controls over critical processes and must ensure on-site technical and quality audits are performed at least every three years. On-site audits of raw material suppliers are optional for bolting specification level (BSL) two, and mandatory for BSL three. Raw material suppliers are responsible for maintaining quality management systems and process controls with documented procedures. Bolting manufacturers are also responsible for developing material specifications to document raw material requirements. Specification of the chemistry limits, melt practice, ladle refinement, heat treatment, mechanical properties, and inspection criteria are required for MP35N. Specification of the cold work practice for MP35N is not required.

Bolting manufacturers are also responsible for qualifying bolting for service at BSLs two and three. Changes to manufacturing processes, including those at the raw material supplier related to equipment and processing, require requalification via a qualified laboratory. Changes to MP35N total cold reduction also triggers requalification. The practices have been implemented to place quality and process controls around the most critical fasteners for the oil and gas industry.

PROCESSING MP35N FOR OIL AND GAS APPLICATIONS

Solution Annealing

The chemistry and solution annealing treatments used for oil and gas applications are identical to the limits in AMS 5758, 5844, and 5845. However, the subsequent cold work and ageing steps must be modified to meet the limits of NACE MR0175 and API 20F. Furthermore, the AMS specifications only govern bar up to 1.75 inches in diameter and raw material for many oil and gas applications exceeds this limit.

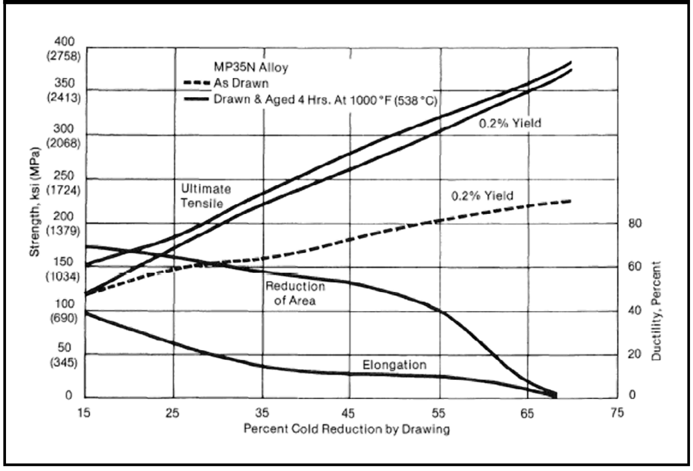
Cold Working

The cold working of MP35N is the most critical step in the manufacturing process. The precipitation of nano-scale HCP platelets in the FCC microstructure is the primary strengthening mechanism, and this cannot occur without cold working the material. The degree of transformation, and the amount of strengthening, is directly proportional to the amount of cold work. This effect is illustrated in Figure 1.

The HCP platelets can be formed by working the material at temperatures as high as 800°F. The HCP platelets are thermodynamically stable up to about 1200°F, at which point they begin to dissolve, and the material loses strength. This causes the lower strength levels in material conforming to NACE MR0175 compared to aerospace product per AMS 5844/5845/5758. The one exception to this case is material used to make mechanical springs, which can be aged at 1200°F per NACE MR0175.

There are several methods available for cold working MP35N including drawing, cold forging, cold rolling, metal spinning, pilgering, and flow forming. Drawing is the most common method used for MP35N production in the bar form. However, limitations on tooling and safety concerns limit the maximum practical finished bar diameter to around three inches. Cold forging operations, particularly rotary

FIGURE 1: Tensile Properties of Cold Drawn and Aged MP35N (Cold-Drawn Bar)



forging, can also be utilized for larger bar sizes, but this entails considerable challenges with tooling and machine wear. Cold rolling of MP35N sheet is common and enables fabrication of MP35N components of considerable size, but with sheet metal wall thickness. Cold-rolled plates of smaller planform area are also possible up to thicknesses of approximately 2.5 inches. Flow forming is a similar process that begins with a thicker annealed sheet and cold works it into axisymmetric thin-walled products like nose cones for missiles. Flow forming and pilgering enable manufacturing of cold-worked, seamless tubulars of much larger diameter than possible with bored bar, but these processes are typically limited to cold-worked wall thicknesses of one inch or less.

Age Hardening

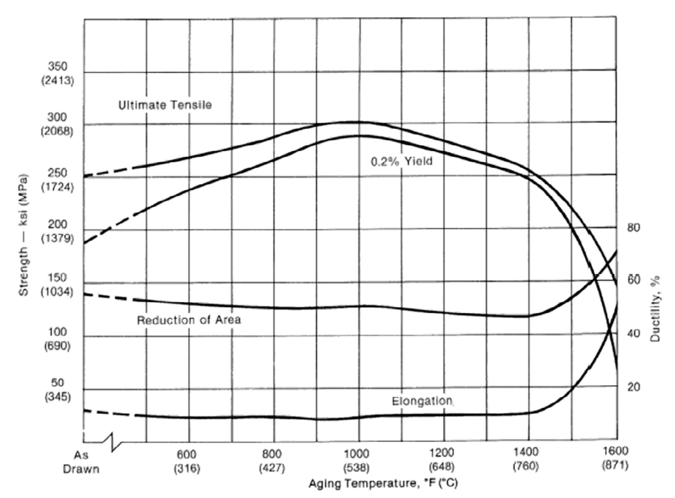
Further strengthening can be achieved by ageing MP35N following cold work. This effect is illustrated by the yield strength curves in Figure 2, where further strengthening beyond cold work is achieved. This effect is amplified as the amount of cold work increases.

Increased strength in the aged condition is achieved by the precipitation of Co_3Mo particles that interact with the FCC matrix. These precipitates nucleate due to segregation of molybdenum atoms at temperatures above 800°F at the interface between the FCC matrix and the HCP platelets formed by cold work. The Co_3Mo phase inhibits the interaction of dislocation sources, improving the strength of the alloy.

Peak ageing occurs at approximately 1000°F, and breakdown of the HCP platelets begins above 1200°F. The heat treatments included in NACE MR0175 for equipment other than springs put the material in an over-aged condition.

It is critical to note that the formation of the Co_3Mo precipitates can only occur when the HCP phase is present. Thus, ageing the alloy without cold work will not strengthen the material. It is impossible to recover strength in an MP35N part in its finished form if it is solution annealed following cold work. For this reason, bolting manufacturers conforming to API 20F are only allowed to machine fasteners from material delivered by the raw material supplier in the cold-worked-and-aged condition.

FIGURE 2: Effect of Ageing Temperature on Tensile Properties of MP35N Cold Drawn 53% and Aged 4hrs. (Cold-Drawn Bar)



CARPENTER TECHNOLOGY'S MILL-MINIMUM PROPERTIES

The following minimum properties apply to MP35N supplied as bar product. It is also possible to convert MP35N into additional forms like plate, strip, sheet, wire, plate, and tubular products through other conversion processes. Carpenter Technology Corporations standard product forms for MP35N are annealed billet and cold-worked and aged bar, wire, and strip.

AMS 5844

Carpenter Technology performs capability testing on MP35N bar ordered per AMS 5844 in the solution treated and work-strengthened condition and has established the minimum properties shown in Table 10 following age hardening per AMS 5844. The as-shipped hardness is based on properties following solution annealing and cold work, prior to age hardening.

Table 10: Carpenter Technology's Minimum Properties for MP35N per AMS 5844

Age Temperature	Bar Diameter	YS (ksi)	UTS (ksi)	% EL	% RA	HRC (as shipped)
1000°F to 1200°F	< 1.75 in	230	260	8	35	38 minimum
1000°F to 1200°F	> 1.75" to 2.00 in	225	235	8	35	38 minimum
1000°F to 1200°F	> 2.00" to 3.25 in	185	195	10	40	Information Only

AMS 5845

The properties listed in Table 11 are minimums for MP35N bar ordered per AMS 5845. As-shipped hardness is guaranteed only up to 1.75 inches, which is the upper size limit of the AMS 5845 specification.

Table 11: Carpenter Technology's Minimum Properties for MP35N per AMS 5845

Age Temperature	Bar Diameter	YS (ksi)	UTS (ksi)	% EL	% RA	HRC (as shipped)
1000°F to 1200°F	< 1.75 in	230	260	8	35	44 minimum
1000°F to 1200°F	> 1.75" to 2.00 in	225	235	8	35	Information Only
1000°F to 1200°F	> 2.00" to 3.25 in	185	195	10	40	Information Only

NACE MR0175

Carpenter Technology's minimum properties for material in the cold-worked-and-aged condition per NACE MR0175 are shown in Table 12. The 1425°F/6hr age condition is popular for subsea bolting, particularly for bar sizes 2 inches and below. Most NACE-compliant cold-worked-and-aged material above 2 inches diameter is supplied in the 1300°F/4hr aged condition, which achieves the highest strength in this size range. Cherry-picking distributors' inventory is done to supply material with higher strength levels than the guarantees below for specific applications. As expected, the minimum yield strength increases as ageing temperature decreases.

Table 12: Carpenter Technology's Minimum Properties for MP35N per NACE MR0175

Age Temperature	Time	Diameter (in)	YS (ksi)	UTS (ksi)	% EL	% RA	HRC
1425°F	6 hrs	≤ 2.00	180	190	10	40	51 max
1425°F	6 hrs	> 2.00 to 3.25	160	170	12	40	51 max
1350°F	4 hrs	≤ 2.00	200	210	10	40	51 max
1350°F	4 hrs	> 2.00 to 3.25	165	175	12	40	51 max
1300°F	4 hrs	≤ 1.50	210	220	10	40	51 max
1300°F	4 hrs	> 2.00 to 3.25	175	185	12	40	51 max

MACHINING

The machinability of MP35N varies depending on the condition of the material and is like that of the nickel-cobalt-chromium alloy Waspaloy®. MP35N can be machined in the cold-worked-and-aged condition. The following speeds and feed rates are recommended for drilling [2]: 7.6 m/min (25 sfm) and 0.10 mm/rev (0.005 in./rev) feed. The following are recommended for turning: 9.1 m/min (30 sfm) and 0.254 mm/rev (0.010 in./rev) feed. High-speed steels and carbide tools can be used. Recommended cutting fluids include soluble oil, sulfurized oil, or chlorinated oil.

WELDING

The welding of MP35N is like that of 304 stainless steel and the same preparations and precautions may be used [2]. The following parameters have been recommended for gas tungsten arc welding (GTAW) based on work with 1.5 mm (0.060 in.) thick sheet and 6.4 mm (1.250 in.) thick plate:

- Argon gas flow rate: 9.4 to 11.8 L/min (20–25 ft3/h)
- Weld speed: 140 mm/min (5.5 in./min)
- Voltage: 10 V
- MP35N filler wire feed: 355 to 560 mm/min (14–22 in./min)

It is important to keep the heat input per pass low: approximately 50% to 65% of that used for type 304 stainless steel. The following parameters were used for the GTAW trials: currents of 50 to 60 A were used for the sheet. Total heat input was 2165 to 3740 J/cm (5500–9500 J/in). For plate, the current ranged from 100 to 160 A and heat inputs were 4330 to 7480 J/cm (11,000–19,000 J/in).

The weld's heat affected zone (HAZ) will have been weakened by the elevated temperatures in the near-weld region. Unfortunately, it is not possible to recover strength in the HAZ simply by using a post-weld heat treatment. The weld can be solution treated to relieve residual stresses from welding but strengthening is only possible through a subsequent cold work process.

CONCLUSIONS

MP35N possesses excellent corrosion resistance in harsh environments including seawater, chloride brines, sweet gas, and sour gas. MP35N is the highest strength alloy approved in NACE MR0175 for use in sour service. MP35N derives its strength from a combined cold-work and heat treatment process.

- MP35N cannot be strengthened by heat treatment alone
- The heat treatment of MP35N for oil and gas applications typically complies with the procedure in NACE MR0175
- Oil and gas applications typically use the chemistry and solution annealing limits in AMS 5844. Material is sometimes ordered to AMS 5844, then aged to comply with NACE MR0175. However, this is not a recommended practice as the cold work processes used in the mill for AMS and NACE MR0175-compliant material may be different and hardness after ageing cannot be guaranteed to fall within NACE MR0175 limits.
- The second edition of API 20F was released in 2018 and governs bolting made from MP35N. Bolting manufacturers are required to purchase MP35N in the mill-heat-treated condition and no additional forging is allowed.
- Machining MP35N in the cold-worked-and-aged condition can be difficult but is readily done with the proper combination of feeds, speeds, cutting tools, and cutting fluids.
- MP35N can be welded easily, but the strength of the heat affected zone must be considered.

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[10] AMS 5758 - Aerospace Material Specification, "Alloy, Corrosion-Resistant, Bars 20Cr - 35Ni - 35Co - 10Mo Vacuum Induction Plus Consumable Electrode Vacuum Remelted Solution Heat Treated for Work Strengthening," SAE International, Warrendale, PA, 2014.

[11] API Specification 20F, "Corrosion-resistant Bolting for Use in Petroleum and Natural Gas Industries," American Petroleum Institute, Washington, D.C., 2018.

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