LEAN NICKEL PM STEELS FOR HIGH PERFORMANCE APPLICATIONS

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ABSTRACT

Recent increases in the price of raw materials have put a lot of pressure on PM part makers to reduce the alloy content of steel powders in order to remain cost competitive with alternative metal forming technologies. Nickel, molybdenum and copper have all undergone large price increases over the past two years. This study examines the effect of lowering Ni and Mo content on the properties of as-sintered and heat-treated PM steels. Steels with both extra-fine and standard Ni powder were compared. Ni content varied from 1 to 2 wt.% and Mo from 0.5 to 0.85 wt.%. Samples were compacted at 680 MPa (50 tsi). Green bars were sintered at 1120 ^oC for 30 minutes in 95/5 N_2/H_2. Nominal sinter density was 7.2 g/cm^3. Hardenability was most affected by lower wt.% of Ni and Mo with implications of reduced allowable part thickness to achieve a given hardness. Reduced hardenability of lean Ni-Mo steels can be compensated by small wt% additions of lower cost alloying elements, such as prealloyed Cr and admixed Cu.

INTRODUCTION

Lean alloy PM steels are gaining the attention of the PM industry, as the rise in raw materials prices increase pressure on the PM industry to remain cost competitive with alternative metal forming technologies. PM processing has a competitive advantage over machined wrought steel parts by offering near net shape parts and thereby more efficient usage of material. However, the alloy content of PM steels is often higher than wrought steels to compensate for lower density and limitations on secondary processes to increase mechanical performance such as rolling or extrusion of wrought steels. In addition, wrought steels tend to take advantage of less expensive alloying elements such as Si, Cr and Mn, which are difficult to process by PM technology.

In the PM industry the synergetic effect of adding Ni and Mo together in steels has long been recognized [1]. The combination of Ni-Mo alloying elements in steels promotes the formation of tougher and harder martensite, resulting in enhanced strength and hardenability [2, 3]. Ni also increases sinter density and improves toughness. As Ni does not readily form carbides, it does not strongly alter the steel microstructure but reduces cementite spacing, making the steel stronger and tougher. Mo increases both the stability of martensite and the hardness of ferrite by solid solution strengthening. Mo also prevents growth of austenitic grains during tempering [4]. Previous studies demonstrated that tensile properties of test bars were similar for 0.5 and 0.85%Mo heat-treated Ni-Mo steels [5, 6]. However reduced hardenability of 0.5%Mo PM steels limits application to thinner parts or parts not requiring through hardening. These studies also demonstrated that admixed extra-fine nickel improved hardenability and strength compared to standard grade Ni powder in 2%Ni-0.5%Mo-0.5%C PM steels.

The objective of the present study was to investigate the properties of reduced Ni and Mo alloy content PM steels. In order to compensate for lower admixed Ni content, an extra-fine grade of Ni powder was used to increase the number of particles allowing more homogeneous distribution of Ni and increased diffusion of Ni during sintering. By admixing extra-fine Ni powder in steels the strength and hardness approached that of prealloyed Ni-Fe powder without the associated loss in compressibility. In particular the Ni-Mo-C PM steels in the current work included the following ranges of alloy content: Mo = 0.5-0.85 wt.%; carbon = 0.6-0.8 wt.%; Ni = 0, 1 and 2 wt.%.

New developments in Fe-based powders and sintering technologies are now allowing the PM industry to take advantage of lower cost-alloying elements (Cr, Si, Mn) particularly in moderate density sinter hardening grade steels not requiring secondary heat treatment, during which these elements are sensitive to oxidation. In order to maintain compressibility of prealloyed Cr-Mo-Fe powders, admixed Cu is often added to 1.5%Cr-0.2%Mo-Fe to improve mechanical properties. However the amount of Cu is typically less than 2% in order to control dimensional change. Additional dimensional precision can be obtained with admixed extra-fine Ni and/or Cu additions, accompanied by increased tensile strength and hardenability [2]. With the goal of providing cost effective, higher compressibility sinter hardening steels requiring enhanced hardenability, some additional work on low alloy XF Ni-Cu-Cr-Mo steels is referred to at the end of the paper and is the subject of ongoing work.

EXPERIMENTAL

In this paper prealloyed Fe-Mo steels use the following MPIF based material designations: (a) FLN-4005 = 0.5 wt.% Mo-Fe (Ancorsteel 50 HP) and (b) FLN-4405 = 0.85 wt.% Mo-Fe (Ancorsteel 85 HP) [7]. The content of XF Ni (IncoT110D) or STD Ni (Inco T123 PM) powders admixed with Fe-Mo powders was 0, 1 or 2wt.% according to the test matrix in Table 1. The admixed carbon content was 0.6 - 0.75 wt.% (Asbury, Southwestern 1651), corresponding to combined carbon in the sintered alloy of 0.55 and 0.7wt% respectively. The lubricant content was 0.6 wt.% of EBS (Lonza, Acrawax C).

Table 1. Test Matrix for lean Ni-Mo PM steels with 0.6 wt% C (left) and 0.75 wt.% C (right)

Materials Designation	Mo [wt%]	Ni [wt%]	C [wt%]
FL-4005	0.45	-	0.55
FLN1-4005 XF	0.45	1.0	0.55
FLN1-4405 XF	0.85	1.0	0.55
FLN1-4405 STD	0.85	1.0	0.55

Materials Designation	Mo [wt%]	Ni [wt%]	C [wt%]
FL-4008	0.45	-	0.7
FLN1-4008 XF	0.45	1.0	0.7
FLN2-4008 XF	0.45	2.0	0.7
FLN1-4408 XF	0.85	1.0	0.7

Transverse rupture strength (TRS) and flat tensile bar (thickness 6.25 mm or ¼’’) samples of Ni-Mo steels were fabricated and tested according to MPIF Standards 41 and 10 respectively [8]. Powder blends were prepared using a Turbula double axis blender, and then compacted at 690MPa (50tsi) achieving densities from 7.05 to 7.15 g/cm^3, dependent on composition. Samples were delubricated at 430 °C (800 °F) for 30 minutes and sintered at 1120 °C (2050 °F) for 30 minutes in 95/5 N_2/H_2 atmosphere. The effective cooling rate was estimated to be 0.7 °C/s from 870 °C to 300 ^oC.

Two types of heat treatment were employed: (a) TRS bars were heat treated in vacuum at 850°C (1560^{o} F) for 40 minutes, oil quenched (60°C) and tempered at 220°C (420^{o} F) for 90 minutes in air; (b) to minimize distortion, flat dog-bone tensile bars were heat-treated at 870°C (1600^{o} F) in 90/10 N_2/H_2 atmosphere for 60 minutes then gas quenched (Ar) at a gas pressure of 10 bars (estimated cooling rate = 1.2 °C/s from 870 °C to 300 ^{o}C), and then tempered in air at 220°C (420^{o} F) for 90 minutes.

Jominy hardenability was measured for both XF Ni and STD Ni PM steels [9]. Jominy bars (25 mm (1") diameter x 155 mm (6.25") length) were made by double press, double sintering (DPDS). Samples were pre-pressed at 550 MPa (40 tsi) and sintered at 843 °C (1550 °F) for 30 minutes in dissociated ammonia. Samples were then repressed to 7.3g/cm^3 nominal density and sintered at 1120 °C (2050 °F) for 30 minutes in a 90/10 N_2/H_2 atmosphere.

RESULTS AND DISCUSSION

Sintered Ni-Mo PM Steels

Admixed nickel improved tensile properties and hardness of sintered Ni-Mo PM steels. XF Ni was more effective than STD Ni, particularly at lower contents of Mo and C (Figure 1). Most noticeable improvements were in increased densification, tensile properties and apparent hardness. Mechanical properties of FLN1-4005 made with XF Ni were only slightly below those of FLN1-4405 steels made with STD Ni (TRS = 1130 vs. 1145 MPa). Therefore Mo content can be reduced from 0.85 to 0.5% if XF Ni is used in place of STD Ni. Higher carbon increased TRS and apparent hardness of 0.5%Mo steels (FLN-4008), however 0.7%C had a slightly adverse effect on the tensile strength of 0.85%Mo steels (FLN-4408).

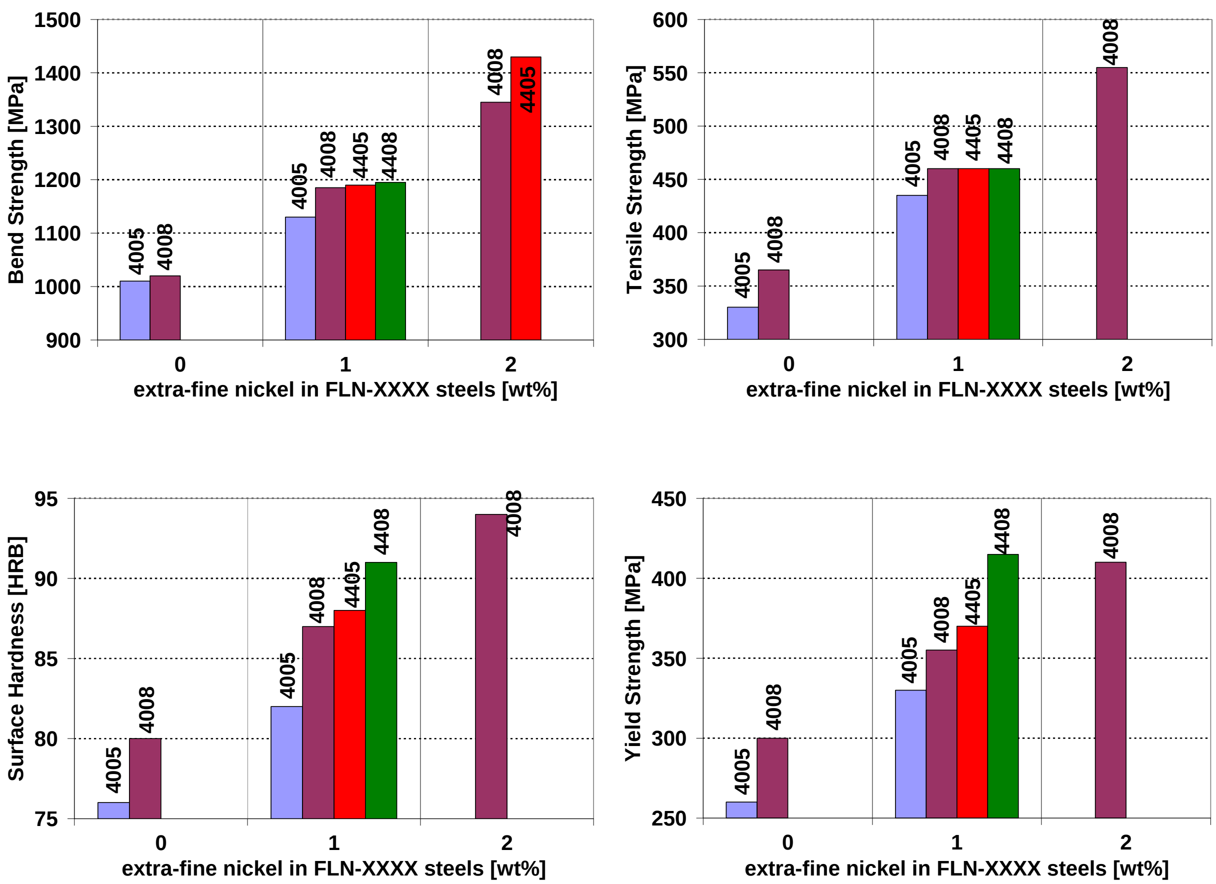
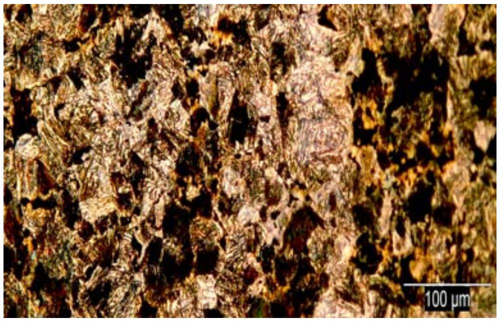


Figure 1 Mechanical properties of sintered Ni-Mo-C steels containing XF Ni.

The microstructures of as-sintered Ni-Mo steels were mainly a mixture of pearlite-bainite. The amount of bainite increased with increased Ni and carbon content. Martensite appeared in as-sintered steels only at 2 wt.%XF Ni. Increasing C content to 0.7 wt.% in 0.85%Mo steels induced coarsening of pearlite (Fig. 2).



FLN1-4405

FLN1-4408

Figure 2. Microstructure of sintered XF Ni-0.85%Mo PM steels showing effect of increasing combined carbon content 0.55 to 0.75 wt.%. Microstructure coarsens with increasing C content. Etched 2% nital.

<u>Hardenability</u>

Hardenability of the sintered steels was determined by the standard Jominy water quench end test [9]. XF Ni increased J_{65} significantly in 0.85%Mo-0.5%C PM steel (Table 2, Fig. 3). The J_{65} depths of FLN1-4405 XF Ni and FLN2-4008 XF Ni steels were similar to MPIF standard FLN2-4405. Increasing carbon helped to compensate for the loss in hardenability at lower Mo content in FLN-4008 steels (Fig. 3).

Table 2. Jominy hardenability Ni-Mo PM steels

Designation Code	Density [g/cm3]	Depth in 1/16 inch [J_{65}]
FLN2-4005 XF	7.35	7.5
FL-4008	7.30	4.3
FLN1-4008 XF	7.30	5.8
FLN2-4008 XF	7.30	8.8
MPIF FL-4405	7.20	4.5
FLN1-4405 XF	7.30	9.3
FLN2-4405 XF	7.35	14.5
FLN2-4405 STD	7.3	11.0

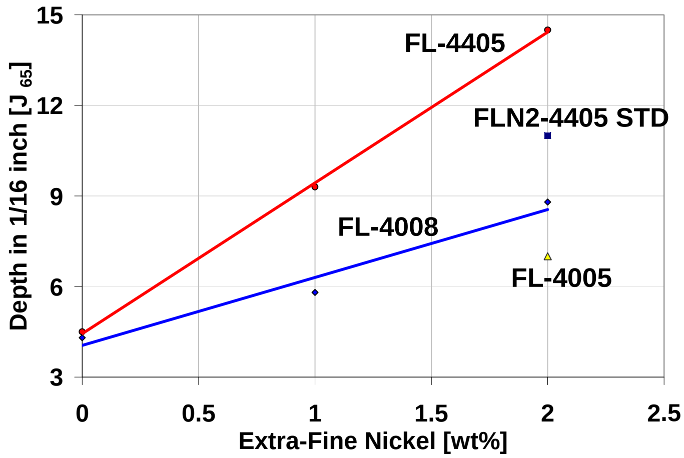


Figure 3. Summary of effect of XF nickel content on Jominy hardenability

Tensile samples were cut from the "quenched"- end vs. "cold"- end along the axis of tested Jominy hardenability bars. High cooling rates at the quenched end produced a predominantly martensitic microstructure and increased UTS by 15-20% relative to the slower cooling rate end (hanger). Increasing Ni content toughened the brittle martensitic microstructure and improved tensile properties even at high C content and low cooling rate (Fig. 4).

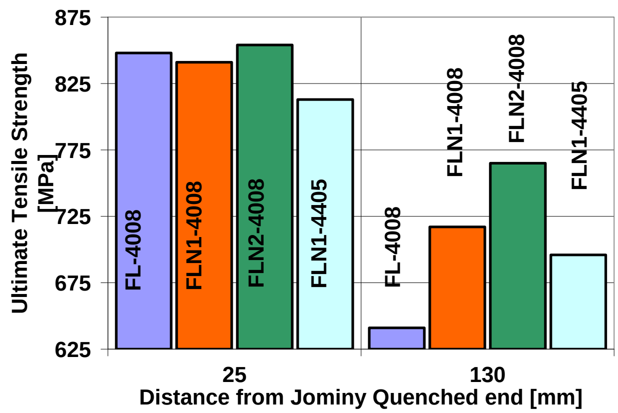


Figure 4. Effect of cooling rate on tensile properties of Ni-Mo PM steel samples cut from water quenched Jominy hardenability bars

In Figure 5, the microstructure of the Jominy bar at the quenched end ("5 mm") is essentially martensite and independent of composition due to very high cooling rates. On the other hand, the microstructure in the slowly cooled end ("130 mm") can be seen to depend on composition, with a pearlitic structure in FL-4008 and increasing amount of martensite/bainite with the addition of Ni. More martensite appears in FLN2-4008 or increasing Mo content from 0.5% to 0.85% in FLN1-4405 steels.

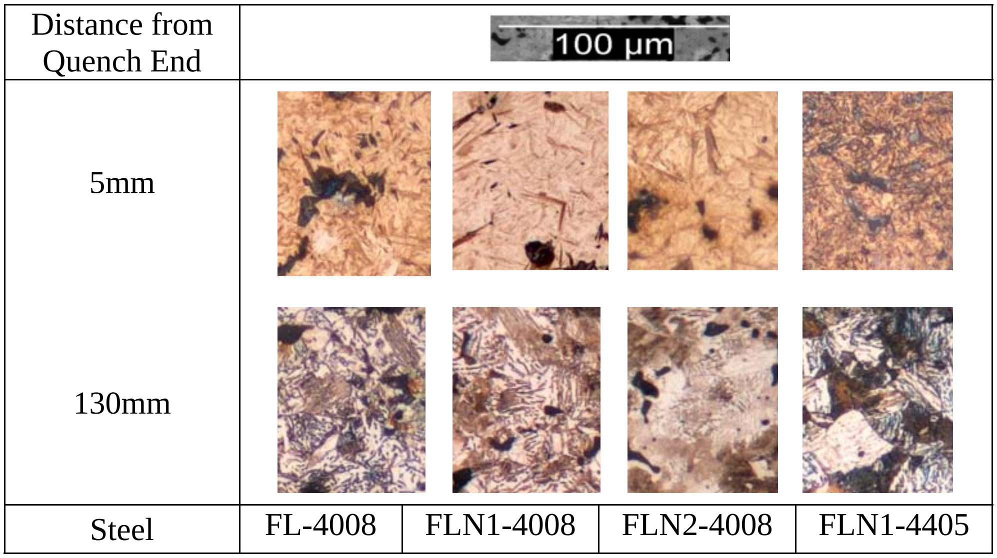


Figure 5. Effect of cooling rate on microstructure of Ni-Mo PM steel samples machined from water quenched Jominy hardenability bars.

<u>Heat-treated Ni-Mo PM Steels</u>

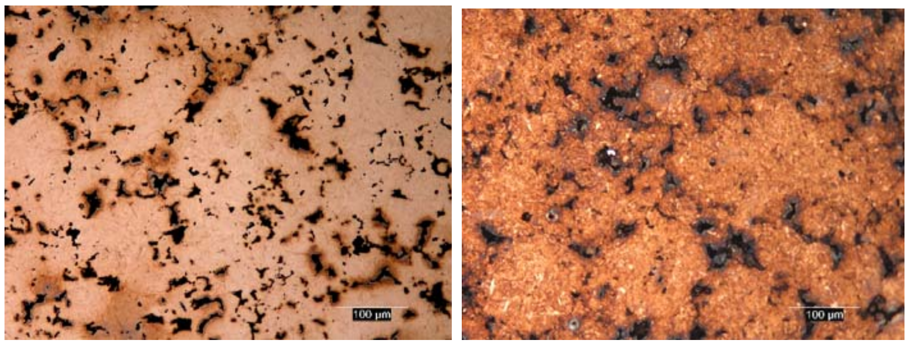
As previously mentioned, the heat treatment of test samples was performed in one of two ways: (a) tensile samples were gas quenched to minimize distortion and (b) TRS bars were oil quenched. The trends in the effect of alloying elements on mechanical properties were similar for as-sintered and heat treated Ni-Mo PM steels. Admixed Ni addition improved UTS and TRS of base FL-4005 and FL-4008 steels. XF Ni proved advantageous compared to STD Ni in all tested steels, with a stronger effect in 0.5%Mo than in 0.85%Mo steels (Table 3). FLN2-4008 XF Ni steels achieved TRS similar to MPIF standard FLN2-4405 steel (2100 MPa).

Table 3. Properties of heat-treated lean Ni-Mo PM steels, tempered 220 °C 90 minutes

Type of Samples	**TRS bars, oil quench**		**Tensile samples, gas quench**	
Properties	**TRS [MPa]**	**Apparent Hardness [HRC]**	**UTS [MPa]**	**Apparent Hardness [HRB]**
FL-4005	1520	34	510	85
FLN1-4005 XF	1780	34	1060	95
FLN1-4005 STD	1550	33	900	86
FL-4008	1680	41	550	26 HRC
FLN1-4008 XF	1700	40	1020	26 HRC
FLN2-4008 XF	2070	41	1040	97
FLN1-4405 XF	1700	36	870	87
FLN1-4408 XF	1700	41	820	26 HRC
FLN1-4405 STD		34	720	86
FLN2-4405 STD	1990	36	920*	94

* sinter hardened 1140 °C, gas quenched

Increasing carbon from 0.55 to 0.7% in 0.5%Mo steels maintains apparent hardness that are similar to higher Mo steels at the lower carbon content. However, increasing carbon content in 0.85%Mo steels to compensate for lower wt% of Ni induced the widening of carbide plates within the martensite (Fig. 6), which is detrimental to the tensile properties. Microstructures of heat-treated and gas quenched tensile FLN-4005/4008 samples with XF Ni were through hardened, consisting of uniform, dense martensite. The structure of oil quenched TRS samples was mainly tempered martensite with some light etching austenite/martensite Ni-rich regions.



FLN1-4405 FLN1-4408

Figure 6. Microstructures of sintered and heat treated (gas quenched) Ni-Mo PM steels with XF Ni and C content - 0.5 and 0.7 wt%, showing coarsening of 0.85Mo steel structure with increased C content; etched 2% nital

The lower hardenability associated with lean PM steel compositions can therefore be partially compensated by either increasing carbon content and/or use of extra-fine admixed Ni depending on the application and required physical properties. Carbon increases hardenability at the expense of tensile properties, while Ni increases both hardness and toughens of the steel resulting in higher tensile strength. To further improve hardenability while meeting the overall objective of lower alloy cost, other alloying elements must be considered. Relatively small amounts of prealloyed chromium and/or admixed copper can dramatically improve the hardenability of lean Ni-Mo steel. Improved properties of Cr-based steels with Ni additions have been noted before [11].. Recent work by the authors demonstrated that Fe-(0.5-0.75)%Cr-(0.35-0.5)%Mo-(1-1.5)%XF Ni PM steels possess a combination of reasonable compressibility, increased hardenability and enhanced mechanical properties compared to standard prealloyed Cr steels [12].

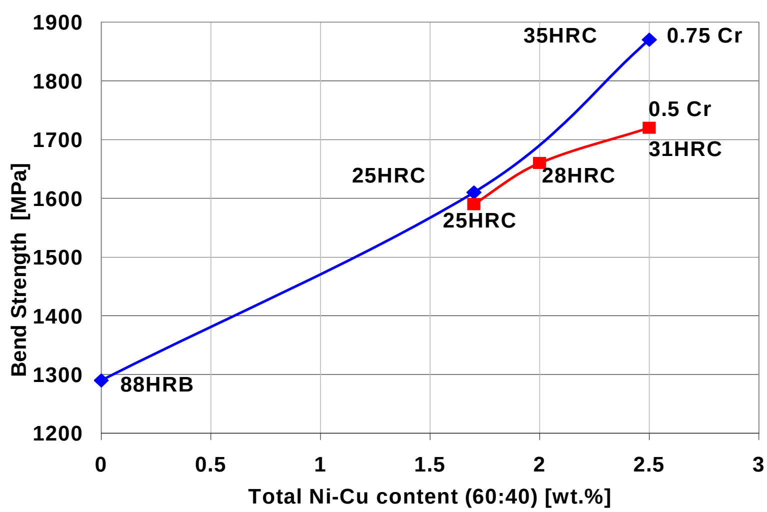


Figure 7. Effect of Ni-Cu additions on bend strength and apparent hardness of lean Cr-Mo steels (density = 7.05 g/cm^3; effective cooling rate = 0.9 °C/s)

The addition of 1.5 wt% of XF Ni to Fe-0.75%Cr-0.5%Mo-0.6%C steels sinter hardened at 1140 °C, increased apparent hardness by 7 HRA (to 65HRA) and tensile strength from 580 to 830 MPa. In Figure 7 the addition of 2 – 2.5 wt% admixed Ni:Cu in a 60:40 ratio increased apparent hardness of the base 0.75%Cr-0.35% prealloyed Cr-Mo steel to over 30 HRC, with TRS exceeding 1700 MPa and UTS > 900 MPa [13]. Ongoing work is investigated the effect of accelerated cooling rate on the sinter-hardened properties of these alloys.

CONCLUSIONS

1. Admixed XF Ni improved tensile properties and apparent hardness of sintered and heat treated Ni-Mo PM steels. The effect was more pronounced at lower contents of Mo and C in concentration ranges 0.5-0.85%Mo and 0.5-0.7%C.

2. Hardenability loss in lean Ni-Mo steels can be partially compensated in lower Mo content alloys by increasing carbon content. However, increasing carbon to compensate for reduced Ni content in 0.85% Mo steels was detrimental to the tensile properties.

3. Jominy (J_{65}) depths of FLN1-4405 XF Ni and FLN2-4008 XF Ni steels were similar to industrial standard FLN2-4405 STD Ni steel.

4. Additions of up to 2.5 wt% admixed XF Ni+Cu to lean prealloyed (0.5-0.75%)Cr-(0.35-0.5%)Mo steels achieved high hardenability and mechanical properties suitable for sinter hardening applications.

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