Fatigue Performance of Molybdenum Prealloyed PM Steels

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ABSTRACT

A versatile range of molybdenum prealloyed PM steels were developed over the years to meet performance requirements in the marketplace. More recently, steels containing 0.3 and 0.5 w/o prealloyed Mo have become commercially available as a result of economic pressures driving cost reduction in manufacturing PM parts. Leaner alloys based on prealloyed Mo are capable of delivering attractive properties for many applications where optimization of performance, design, and cost is desired. The robust nature of these alloys permits the use of secondary processing to enhance their performance over conventional press and sinter properties. This study explores the static and dynamic properties of lean prealloyed Mo steels with admixed copper and nickel, both as sintered and heat treated in mixes with 0.6 w/o graphite. The as-sintered fatigue performance of a 0.3 or 0.5 w/o Mo prealloy is improved with additions of Ni (0.75 w/o) and further enhanced with Cu (0.5 w/o). Heat treating boosts the fatigue limit for all combinations studied in reference to the as-sintered results, and it was found that 0.3 w/o Mo performs as well as 0.5 w/o Mo prealloy when heat treated. Additions of Cu were found to be detrimental to heat-treated fatigue behavior, supporting prior studies on the effects of heat treating Cu-containing PM alloys [1]. Furthermore, this work demonstrates that a composition as lean as, 0.3 w/o Mo + 0.75 w/o Ni + 0.6 w/o Gr, has competitive heat-treated fatigue performance when compared with FN-0205HT and FLN2-4405HT.

INTRODUCTION

The continued initiative to reduce manufacturing costs in the PM industry is supported through providing the market with engineered steels that deliver sufficient properties at lower alloy contents. A significant driving force for cost reduction has been a result of the volatile metal market prices of Mo, Ni, and Cu – the most commonly used alloying elements in PM steels, apart from graphite. This has led to increased desire into either reducing the overall alloy content [2,3] or replacing these elements with inexpensive alternatives (i.e. Cr, Mn, or Si) [4]. The latter option, though, has additional processing challenges due to oxygen sensitivity, preventing large-scale displacement of Mo, Ni, and Cu in the market. Nevertheless, a recently developed series of binder-treated alloy grades, ANCORBOND FLM, successfully incorporates Mn to address the issue [4]. This study examines the impact of reducing admixed Ni and Cu on the static and fatigue performance of 0.3 and 0.5 w/o prealloyed Mo steel powder, in the conventionally sintered and heat-treated states.

Traditionally, alloys containing 0.85 to 1.5 w/o prealloyed Mo have been utilized for their high performance qualities, and as such, have prevailed in parts with large cross-sections. As a result, Mo has become an indispensible alloying element in PM steel metallurgy. The easily reducible Mo-oxide allows for Mo to be incorporated in PM processing where sintering in reducing atmospheres permits alloying with the iron particles to enhance properties. Prealloying Mo into the iron promotes a substantial improvement in hardenability and strength without negatively impacting compressibility of the powder, and is therefore suitable for applications where performance and higher density is desired. For certain applications with small part cross-sections, though, it may be desirable to reduce the Mo content in order to lessen the impact of market pricing fluctuation. Currently, considerable mechanical data is available in literature for reference on the behavior of Mo-based alloys [2,3]. There is, however, little work [3] offered on the fatigue performance of lean alloys based on 0.3 and 0.5 prealloyed Mo, allowing for a subjective approach in determining optimal alloy content aimed at fatigue applications.

Typical additions (either admixed or diffusion alloyed) of 2 – 4 w/o Ni to base irons have been standard in the industry for many years in applications where toughness and ductility in a part is needed, especially in conjunction with heat-treating practices. Nonetheless, the unstable pricing brought on by the recent supply issues, in combination with health related concerns with Ni powder, have led parts producers to re-evaluate the optimal amount of Ni needed to reach desired part performance. Under conventional sintering and heat-treating methods, Ni-rich regions and phases promote increased toughness and ductility at particle boundaries and serve to arrest crack propagation during cyclic loading. The benefits of using high (> 2 w/o) Ni content are well documented [5], yet reducing the amount may be desirable for many parts producers to meet market demands.

The addition of Cu to improve as-sintered strength and hardness has been a staple of the PM industry as well, where Fe-Cu-C alloys comprise upwards of 50% of sintered steel components [6]. A prior study on the effect of Cu on fatigue properties [5] promotes its use in improving the as-sintered fatigue limit. The increased fatigue performance is attributed to the rounding of pores by transient liquid phase and the solid solution strengthening effect created with diffused Cu in Fe. Typical Cu particle sizes (d_{50} = 40 µm), however, can leave significantly large pores behind after melting, and could be greater in size than the typical pore size distribution. These large voids are detrimental to heat-treated fatigue behavior, acting as stress risers for crack initiation and propagation, negating the effect brought on by solid solution strengthening and the rounding of smaller pores. This behavior was considered in this work, therefore, a finer Cu (d_{50} = 10 µm) was used to understand if a similar negative impact would be apparent in the heat-treated results.

Generally, a judicious approach to alloy selection for parts with thin cross sections would reveal that several lean alloy systems are capable of providing sufficient properties. A benefit in reducing overall alloy content, other than potential cost savings, is the possible increase in compressibility of the mix. While the opportunity to achieve increased density is improved, it is not addressed herein, yet should be recognized as a prospect to further enhance the results provided. It is well established that fatigue performance is greatly influenced by density [1] and, thus, compacting lean alloy systems to increased densities would enable their usefulness. It will be shown that lean PM ferrous alloys based on 0.3 or 0.5 w/o prealloyed Mo can be tailored to meet the critical static and dynamic properties demanded.

EXPERIMENTAL PROCEDURE

Commercially available powders, Ancorsteel 30 HP (30 HP) and Ancorsteel 50 HP (50 HP), were used as the base for the lean alloy formulations explored in this study which are listed in Table 1. All mixes were blended with 0.75 w/o Acrawax C lubricant and 0.6 w/o Asbury type 3203H graphite. Two copper types were used: ACuPowder type 8081 in mixes 3 and 4 and fine 10 µm particle size Cu in mixes 9 - 12. The admixed Ni is Inco T123. The diffusion alloy FD-0205 (Distaloy 4600A) was included as a benchmark material for comparison. Transverse rupture strength (TRS) bars, dogbone tensile bars, and unnotched charpy impact bars were compacted to 7.0 g/cm^3 green density to determine static mechanical properties of each mix.

Table 1: Nominal composition of alloys studied (in w/o)

Mix	Base Alloy		Admixed		
	Designation	Prealloyed Mo Content	Ni	Cu	Graphite
1	30 HP	0.3	-	-	0.6
2	50 HP	0.5	-	-	0.6
3	30 HP	0.3	-	0.5	0.6
4	50 HP	0.5	-	0.5	0.6
5	30 HP	0.3	0.5	-	0.6
6	50 HP	0.5	0.5	-	0.6
7	30 HP	0.3	0.75	-	0.6
8	50 HP	0.5	0.75	-	0.6
9	30 HP	0.3	0.5	0.5	0.6
10	50 HP	0.5	0.5	0.5	0.6
11	30 HP	0.3	0.75	0.5	0.6
12	50 HP	0.5	0.75	0.5	0.6
13	FD-0205	0.5*	1.75*	1.5*	0.6

* Diffusion alloyed

All test bars were sintered in a high temperature Abbott continuous-belt furnace at 1120 °C (2050 °F) for 15 minutes in a mixed atmosphere of 90 v/o nitrogen and 10 v/o hydrogen (90/10). As-sintered properties were evaluated using a cooling rate of 0.7 °C/s from 650 °C to 315 °C. Heat treating was performed at 900 °C (1650 °F) for 45 minutes in synthetic disassociated ammonia, followed by quenching in a 65 °C (150 °F) circulating oil bath. All heat-treated samples were tempered at 205 °C (400 °F) for 1 hour prior to physical and mechanical measurements. The sintered density, dimensional change (DC), and apparent hardness were determined on TRS bars following MPIF Standards 42, 43, and 44 [7]. Tensile, impact, and TRS testing adhered to MPIF Standards 10, 40, and 41 [7]. Sintered carbon values were measured using a Leco 200 carbon-sulfur combustion gas analyzer with standards run before and after samples.

Two types of axial fatigue bars were used in this study. All as-sintered fatigue properties were evaluated using unnotched bars with a continuous radius between ends and a rectangular cross section, Figure 1 (a). To determine heat-treated fatigue properties, rectangular blanks (10 mm x 10 mm x 75 mm), compacted to 7.0 g/cm^3, were sintered and then machined into oversized cylinders with a 9.62 mm diameter and a 75 mm length. The cylindrical bars were then heat treated and tempered under the same conditions as previously mentioned. The final sample dimensions, Figure 1 (b), and surface finish were equivalent to specifications for rotating bending fatigue (RBF) specimens provided in MPIF Standard 56 [7], and conforming with ASTM E466 – 07 [8]. After machining to size, the cylindrical axial fatigue bars were stress relieved at 177 °C (350 °F) for 1 hour prior to testing. Axial fatigue testing was carried out using two different servo hydraulic MTS machines, model 858 for as-sintered bars and model 810 for heat-treated bars. All tests were performed at a frequency of 60 Hz and load ratio of -1. The fatigue endurance limit (FEL) was estimated based on the applied stress to achieve a runout, similar to performing a staircase method. The runouts were defined as 2 x 10^6 cycles with no failure.

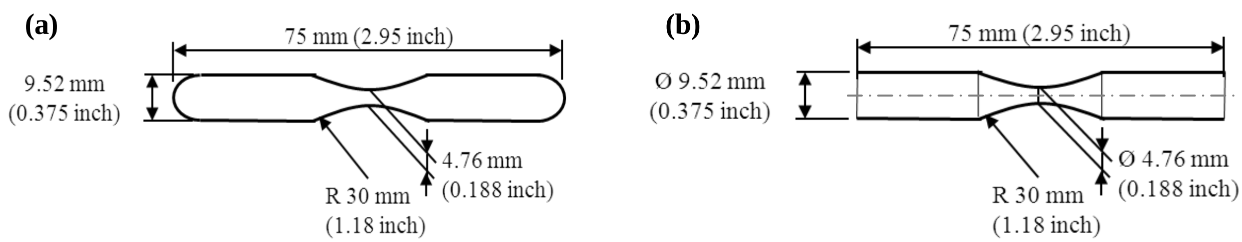

Figure 1: (a) Flat axial fatigue specimen design used to determine as-sintered fatigue limit, height = 5.75 mm (0.23 inch) ; (b) cylindrical axial fatigue specimen design used for heat-treated evaluation

RESULTS

Static Properties

In order to narrow the field of interest for performing fatigue measurements, the static properties for mixes presented in Table 1 were first determined. These results and subsequent analysis primarily focus on the effect of admixed alloy content on mechanical properties for 30 HP, being the leanest base alloy studied. It should be mentioned, though, that 50 HP is marginally better than 30 HP at comparable admixed alloying in the as-sintered state, as found in the summarized results in Table 2. A comparison of heat-treated properties for 30 HP and 50 HP, however, indicates the two base alloys are nearly equivalent under the conditions studied. The biggest difference will be found in hardenability, where 50 HP has greater hardenability [2] and would thus be better suited for parts with cross-sections of moderate thicknesses. Looking at Table 2, there is an increasing trend in the as-sintered properties as the alloy content is increased. FD-0205 is superior under these processing conditions, having at least 2 w/o more alloy than other alloys tested.

Table 2: As-sintered properties

	SD	DC	TRS	Impact	UTS	Elong.	Hardness
Mix	g/cm^3	%	MPa (ksi)	Joule (ft-lbf)	MPa (ksi)	%	HRA (HRB)
1	6.96	0.21	750 (109)	11 (8)	278 (40)	0.9	39 (58)
2	6.95	0.21	844 (122)	14 (10)	372 (54)	1.5	42 (64)
3	6.96	0.25	848 (123)	14 (10)	347 (50)	1.1	40 (60)
4	6.94	0.22	896 (130)	14 (10)	393 (57)	1.3	43 (67)
5	6.98	0.11	828 (120)	12 (9)	373 (54)	1.9	39 (58)
6	6.98	0.15	924 (134)	15 (11)	421 (61)	2.0	44 (69)
7	6.99	0.10	891 (129)	15 (11)	383 (56)	1.9	42 (64)
8	6.99	0.11	952 (138)	15 (11)	434 (63)	2.0	45 (71)
9	6.96	0.15	873 (127)	15 (11)	398 (58)	2.1	41 (62)
10	6.97	0.16	952 (138)	15 (11)	448 (65)	1.4	45 (71)
11	6.96	0.12	912 (132)	16 (12)	409 (59)	2.0	43 (67)
12	6.98	0.15	965 (140)	18 (13)	471 (68)	2.0	46 (73)
13	6.92	0.31	1190 (173)	22 (16)	581 (84)	2.6	51 (82)

The difference in properties between the lean alloys and FD-0205 is lessened, however, with the application of a heat treatment, as seen in Table 3. The heat-treated mixes 1 – 12 have, on average, a 62% increase in TRS and 110% increase in UTS from the as-sintered state. By comparison, FD-0205 has a 36% increase in TRS and 60% increase in UTS, yet still displays superior mechanical properties to the leaner alloys. Regardless, mixes 5 – 12 show potential in the heat-treated state, coming within 10% of the TRS and UTS of FD-0205. The heat-treated apparent hardness values are comparable for all alloys tested (around 68 HRA), which is largely dependent on sintered carbon content. All sintered and heat-treated carbon contents were measured to be within 0.54 ± 0.02 w/o.

Table 3: Heat-treated and tempered properties

	SD	DC	TRS	Impact	UTS	Elong.	Hardness
Mix	g/cm^3	%	MPa (ksi)	Joule (ft-lbf)	MPa (ksi)	%	HRA (HRC)
1	6.94	0.11	1371 (199)	12 (9)	727 (105)	< 1	67 (33)
2	6.96	0.10	1310 (190)	11 (8)	717 (104)	< 1	68 (35)
3	6.94	0.17	1341 (194)	12 (9)	752 (109)	< 1	68 (35)
4	6.94	0.14	1379 (200)	14 (10)	738 (107)	< 1	68 (35)
5	6.95	0.03	1464 (212)	12 (9)	854 (124)	< 1	66 (31)
6	6.96	0.06	1448 (210)	14 (10)	821 (119)	< 1	69 (37)
7	7.00	-0.01	1458 (211)	14 (10)	901 (131)	< 1	69 (37)
8	6.99	0.05	1460 (212)	14 (10)	821 (119)	< 1	68 (35)
9	6.96	0.02	1442 (209)	14 (10)	870 (126)	< 1	66 (31)
10	6.97	0.06	1456 (211)	14 (10)	841 (122)	< 1	68 (35)
11	6.95	0.02	1507 (219)	15 (11)	879 (127)	< 1	66 (31)
12	6.97	0.01	1494 (217)	15 (10)	890 (129)	< 1	68 (35)
13	6.95	0.12	1614 (234)	19 (14)	928 (135)	1.1	67 (33)

The sintered and heat-treated DC of selected mixes is plotted in Figure 2 (a). By using mix 1 (30 HP + 0.6 w/o Gr) as the baseline DC from die size (0.21%), Cu additions lead to growth (0.25% for mix 3), while Ni additions result in shrinkage (0.10% for mix 7) from the given baseline. The DC for combinations of Cu and Ni reflect the impact of both constituents, leading to shrinkage with respect to 30 HP alone, yet less shrinkage than Ni only (0.12%). FD-0205 exhibits the greatest growth as sintered, 0.31 %, and moderate growth heat treated (0.11%). A more detailed analysis of Cu and Ni interaction and their impact on DC at different carbon contents is reported elsewhere [9]. All mixes, both as-sintered and after heat treatment, show growth from die size except for mix 7, where the heat-treated DC is nearly equivalent to the original die size.

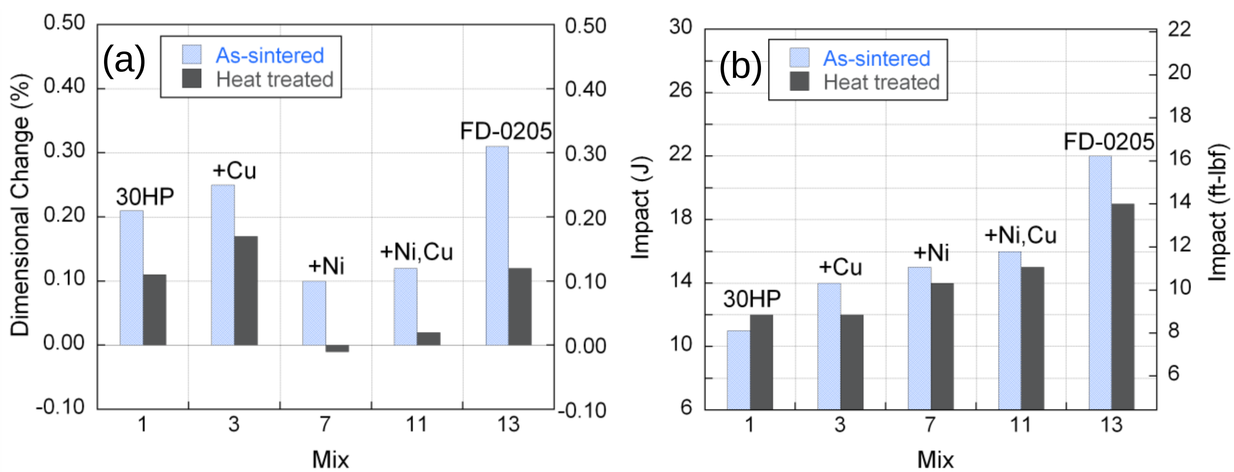

Figure 2: Sintered and heat-treated (a) dimensional change from die size and (b) impact strength for 30 HP based mixes and FD-0205

Figure 2 (b) provides the impact strength of mixes based on 30 HP compared with FD-0205, revealing more energy is required to fracture material with increased admixed alloy content in the as-sintered state. This trend holds true for the heat-treated counterparts where Ni promotes toughness, although Cu addition alone appears to provide no benefit. Conversely, mix 11 combines Cu with Ni to incrementally improve the impact behavior in comparison to mix 7. Nonetheless, all lean mixes studied fall short on impact strength in comparison to FD-0205. This is largely a result of the diffusion alloy having at least 1 w/o more Ni than any combination studied. The effect of Ni content is powerful in both the as-sintered and heat-treated trends, further supporting its usefulness in PM.

Figure 3 (a) depicts the as-sintered and heat-treated trend in TRS with 30 HP (mix 1) as the baseline. Additions of Cu (mix 3) and/or Ni (mix 7 and 11) improve the as-sintered strength. The corresponding heat-treated results, however, indicate that Cu provides no benefit, as was found with the impact result, and is perhaps detrimental to strength. Additions of Ni lead to significant improvement in heat-treated transverse strength even more so. The addition of Cu, though, does not appear to have the same negative influence when Ni is present and instead marginally improves heat-treated strength compared with mix 7.

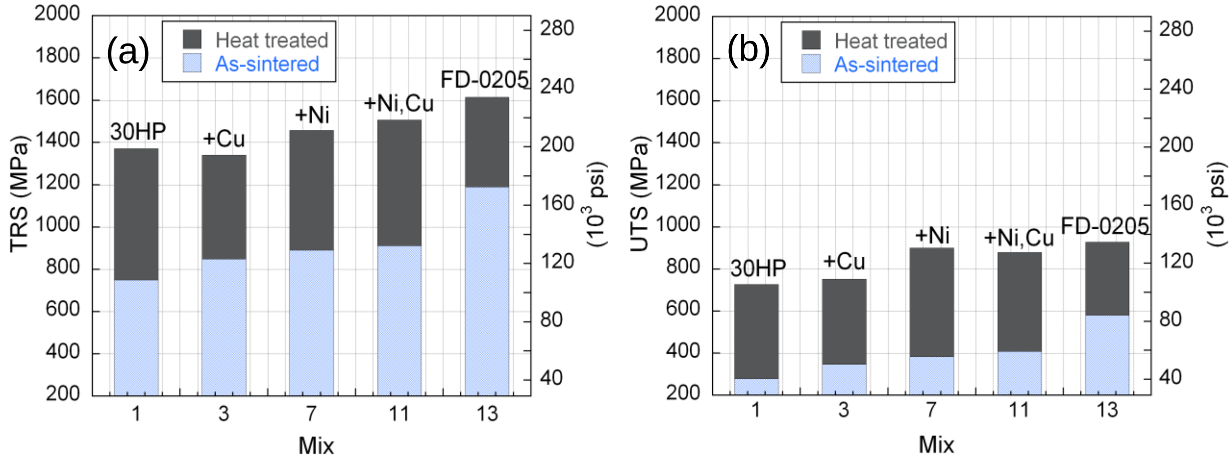

Figure 3: Sintered and heat-treated (a) transverse rupture strength and (b) ultimate tensile strength for 30 HP based mixes and FD-0205

Figure 3 (b) provides the ultimate tensile strength of 30 HP mixes and FD-0205. The as-sintered results show a gradual increase in tensile strength at increasing alloy content, with FD-0205 being superior. As with other static properties, heat treating enhances the strength for all mixes compared with their respective as-sintered value. The addition of Cu has negligible improvement to enhance heat-treated tensile strength beyond which is achieved with just the addition of Ni. Furthermore, 30 HP mixes with at least 0.75 w/o Ni nearly match the level of heat-treated strength as FD-0205HT, indicating this leaner alloy combination could be competitive in applications where FD-0205HT provides significantly more performance than required.

Microstructures

In order to further understand the effect on properties with increased alloy content, Figure 4 offers etched as-sintered microstructures of select alloy combinations with 0.6 w/o graphite. 30 HP is predominantly comprised of divorced pearlite, fine pearlite, and ferrite, while 50 HP is mostly divorced pearlite. The addition of Ni results in Ni-rich regions between particle and pore boundaries and even finer pearlite regions in close proximity to the Ni-rich regions for both base alloys. The presence of Cu is indicated with the brown tint around particle surfaces where the Cu diffused into the Fe. In localized areas where Cu and Ni alloyed with the Fe, there is evidence of alloy-rich martensite, though the volume of martensite is small. 50 HP has much finer pearlite spacing than 30 HP with increased admixed alloying and more particle cores reveal a finer structure, supporting that 50 HP is marginally better as sintered. The heat-treated microstructures are addressed later; however, all alloy combinations studied are fully martensitic. The only difference lies in the number of Ni rich regions and phases as a direct result of the amount of Ni added.

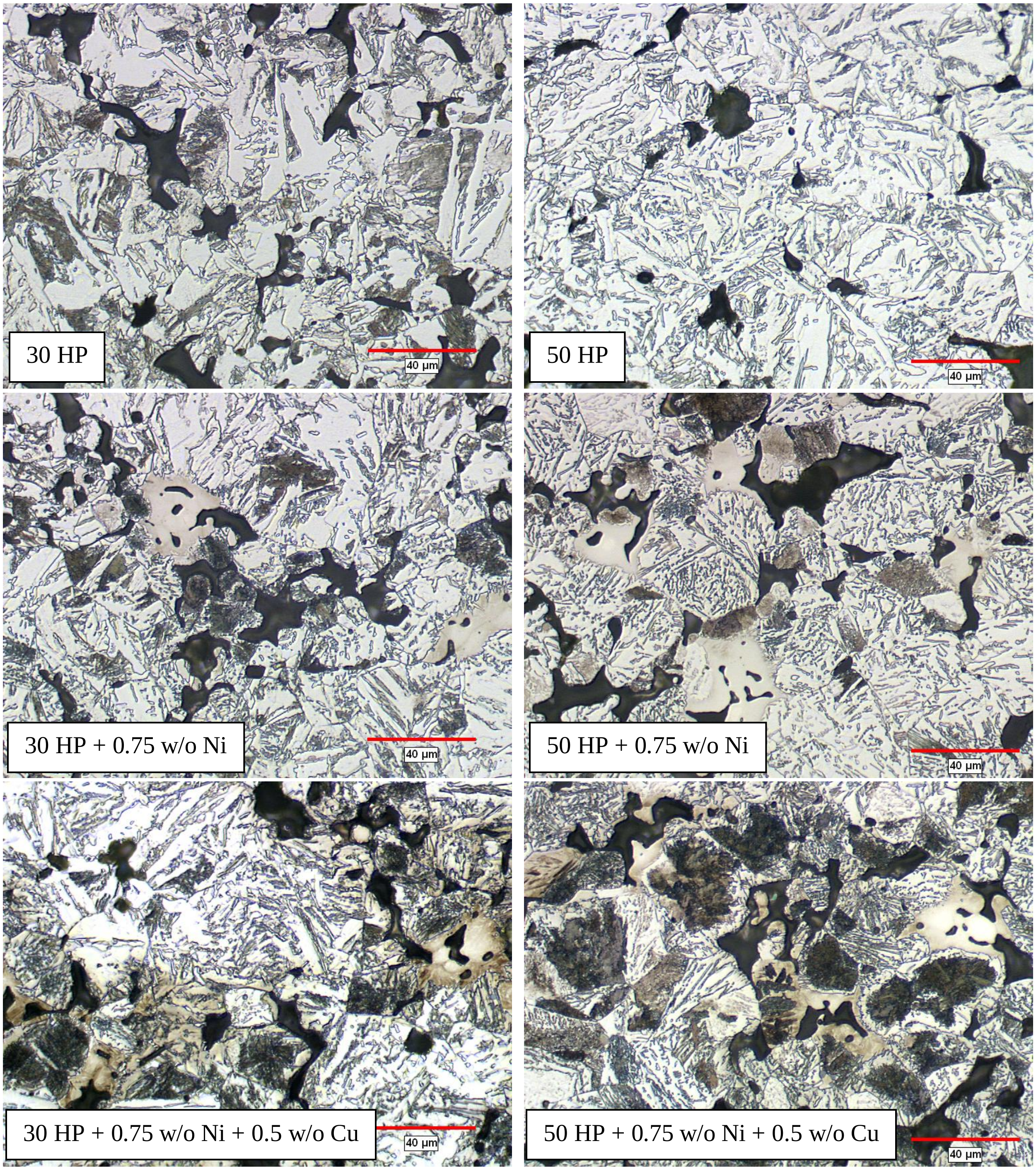

Figure 4: As-sintered microstructures of selected lean alloys containing nominally 0.54 w/o sintered carbon; the trend in microstructure reflects the increasing alloy content from top to bottom; etched with 2 v/o Nital - 4 w/o Picral

Fatigue Properties

Axial fatigue trends for selected compositions are represented using S-N graphs in Figures 5 through 8. Ongoing work aims to further refine the estimated fatigue endurance limits suggested herein. Figure 5 (a) shows the influence of adding 0.75 w/o Ni and 0.75 w/o Ni + 0.5 w/o Cu on the as-sintered fatigue limit to 30 HP. The additions of Ni and Ni + Cu improve the fatigue resistance with respect to 30 HP alone. In changing the base alloy from 30 HP to 50 HP, adding nominally 0.2 w/o prealloyed Mo, the fatigue endurance limit is enhanced as seen in Figure 5 (b).

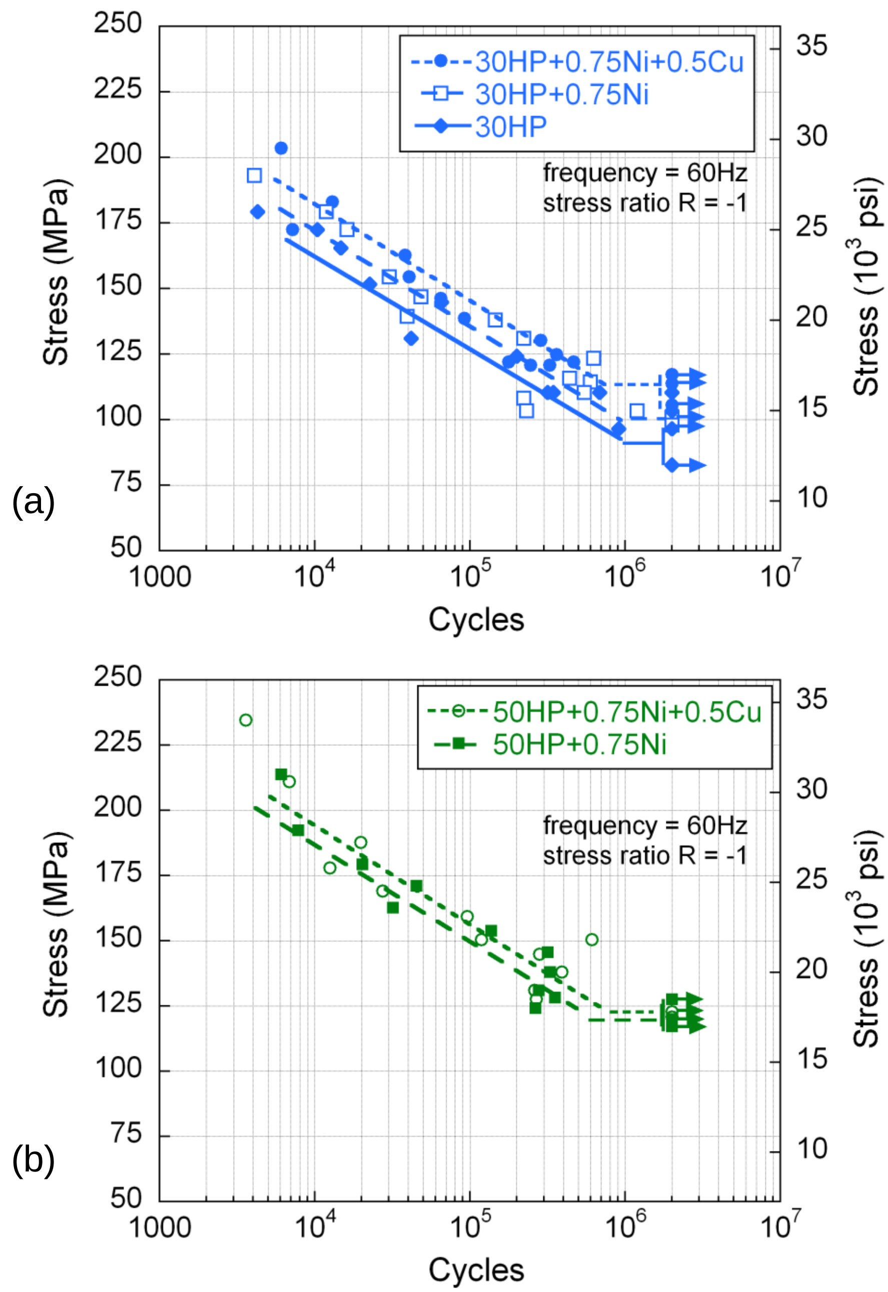

Figure 5: As-sintered axial S-N fatigue trends for (a) 30 HP and (b) 50 HP alloy combinations with 0.6 w/o graphite

The heat-treated fatigue response of 30 HP in reference to the as-sintered trend, shown in Figure 6 (a), indicates that heat treating boosts the fatigue limit by as much as 152%. Looking at Figure 6 (b), adding 0.75 w/o Ni increases the limit by an additional 13%. Modifying the composition further with 0.5 w/o Cu, however, proves to have a negative impact on heat-treated fatigue performance. Cu was found to lower the limit by approximately 5% in comparison to 30 HP + 0.75 w/o Ni.

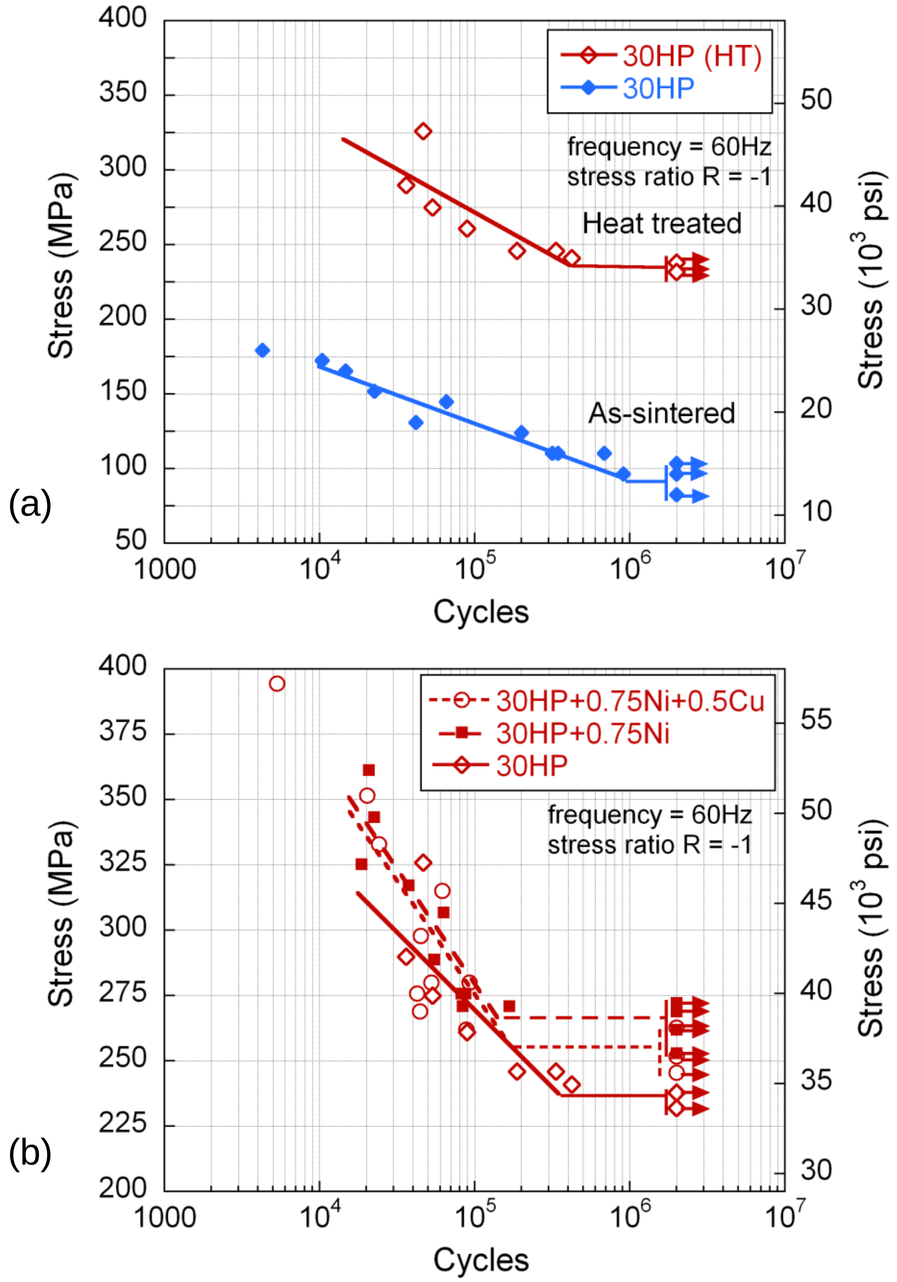

Figure 6: Axial S-N fatigue trends of (a) as-sintered versus heat-treated 30 HP; and (b) heat-treated 30 HP alloy combinations with 0.6 w/o graphite

In Figure 7, the impact of Cu on heat-treated fatigue was further explored by increasing the Mo content in the base alloy to determine if a similar effect was found. The results indicate that either there is little difference between 30 HP and 50 HP base alloys in the heat-treated state or that the Cu addition has a larger negative impact on heat-treated fatigue behavior, opposing any measurable improvement brought about through increasing Mo by 0.2 w/o. While the fatigue data for 50 HP + 0.75 w/o Ni is currently unavailable, an alloy containing as little as 0.3 Mo and 0.75 w/o Ni was found to have the best heat-treated performance among the lean alloys examined for fatigue analysis. Table 4 lists the estimated fatigue endurance limits (FEL) as determined within this study. FD-0205HT has the highest FEL, but also the greatest amount of alloying to achieve this behavior. At less than one third the alloy content of FD-0205, heat-treated 30 HP + 0.75 w/o Ni is within 4% of the measured FEL for FD-0205HT.

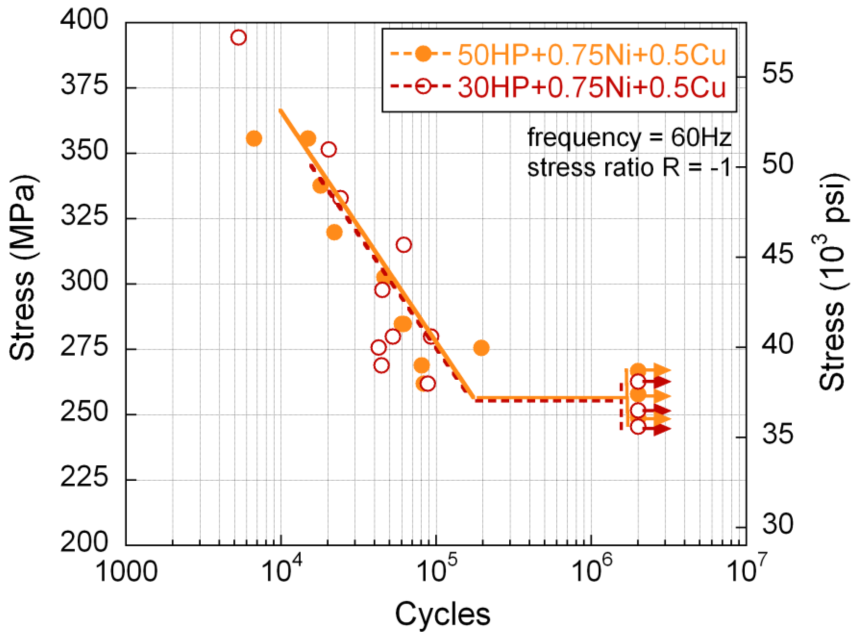

Figure 7: Axial S-N fatigue trends of heat-treated 30 HP and 50 HP with 0.75 w/o Ni + 0.5 w/o Cu and 0.6 w/o graphite

Table 4: Summary of Estimated Fatigue Endurance Limits (FEL)

Alloy (+ 0.6 w/o graphite)	Total Alloy %	As sintered MPa (10^3 psi)	Heat Treated MPa (10^3 psi)
30 HP	0.3	93 (13.5)	238 (34.5)
30 HP + 0.75 w/o Ni	1.05	100 (14.5)	269 (39.0)
30 HP + 0.75 w/o Ni + 0.5 w/o Cu	1.55	114 (16.5)	255 (37.0)
50 HP + 0.75 w/o Ni	1.25	117 (17.0)	-
50 HP + 0.75 w/o Ni + 0.5 w/o Cu	1.75	121 (17.5)	255 (37.0)
FD-0205	3.75	155 (22.5)	279 (40.5)

DISCUSSION

It is evident from the results provided that heat treating the lean alloys greatly enhances their static and dynamic performance. The addition of Cu boosts properties in the as-sintered state; however, there is little benefit in adding Cu for heat-treating applications. It was found that Cu alone was detrimental to heat-treated static properties and in combination with Ni, Cu provided marginal static performance improvement. Furthermore, heat-treated fatigue analysis revealed that additions of Cu markedly reduced the fatigue limit, as seen in Figure 6 (b). Therefore, it is suggested that heat-treated 30 HP with at least 0.75 w/o Ni provides a suitable combination of properties to compete with costly alloys currently used in parts with thin cross-sections. In larger parts, where increased hardenability is needed, 50 HP can equally meet the demand in performance.

To contrast the heat-treated fatigue performance between 30 HP and FD-0205HT, Figure 8 demonstrates the axial S-N trends as measured during this study. Through adding 0.75 w/o Ni to 30 HP, a 13% increase in fatigue limit is realized. By comparison, FD-0205HT, with 3.45 w/o more alloy content, is approximately 17% greater than 30 HP alone, but only 4% better than 30 HP with 0.75 w/o Ni. Therefore, this alloy can be reduced by 1% Ni, 1.5% Cu, 0.2% Mo, have similar hardenability, and be within 4% of the measured FEL. Interestingly enough, the FEL for both FD-0205HT and 30 HP with only 0.75 w/o Ni exceed that of FD-0405HT found in MPIF Standard 35 [10]. This suggests the total alloy content could be better optimized in order to reach acceptable fatigue performance and meet demand in cost reduction for manufacturing.

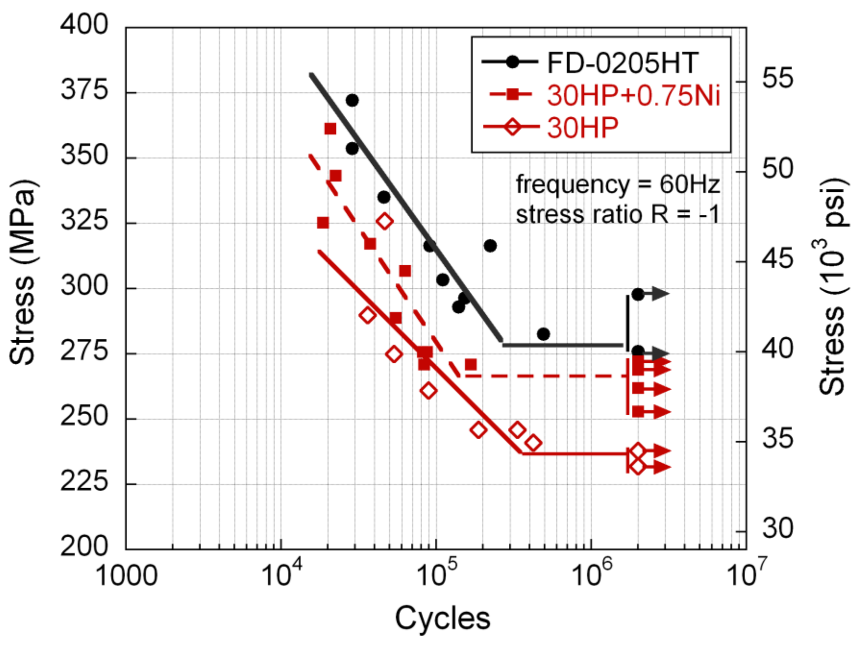

Figure 8: Axial S-N fatigue trends of heat-treated 30 HP and FD-0205HT

To better understand the increase in fatigue performance going from 0.3 w/o Mo + 0.75 w/o Ni to FD-0205HT, the microstructures are provided in Figure 9 for comparison. Figure 9 (a_1) and (b_1) represent the etched as-sintered microstructures of 0.3 w/o Mo + 0.75 w/o Ni and FD-0205, where it is evident FD-

0205 has more alloy rich regions and Ni-rich martensite at particle interfaces. The core of the particles, however, are a mix of fine pearlite and divorced pearlite, similar to those found in the 0.3 w/o prealloyed Mo base particles. The heat-treated structures, Figure 9 (a_2) and (b_2), are predominantly martensite with Ni-rich regions (indicated by the un-etched white areas) dispersed throughout. While the type of martensite is identical between the two alloys, as a result of having the same carbon content, the volume of Ni-rich regions is noticeably greater in FD-0205HT. This supports the fact that the heat-treated strengths are comparable between the two alloys, given that martensite is the primary phase and carbon contents are equivalent. With 1 w/o more Ni, though, FD-0205HT has slightly better toughness, ductility, and fatigue endurance limit, all of which are heavily influenced by Ni content.

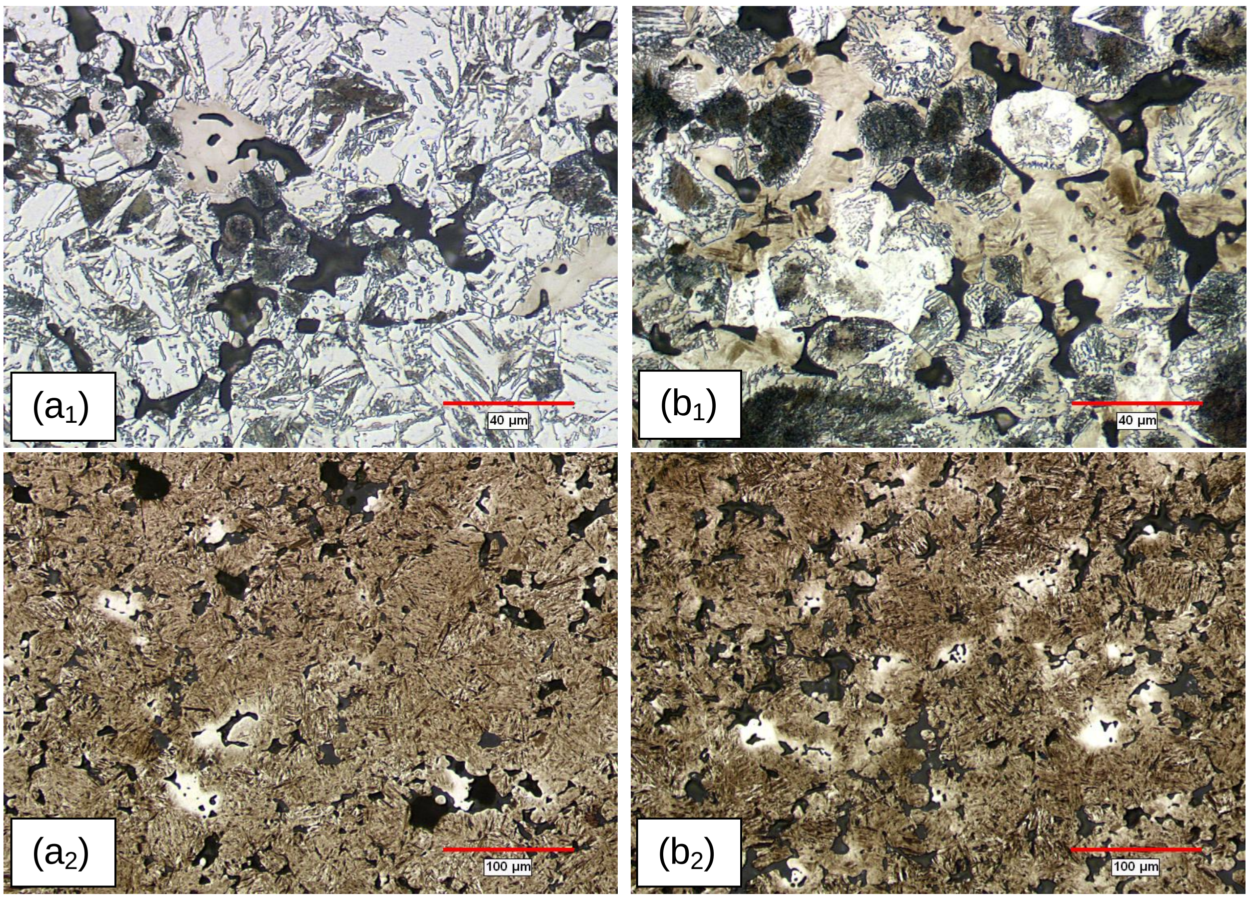

Figure 9: As-sintered and heat-treated microstructures of (a) 30HP + 0.75Ni + 0.6Gr and (b) FD-0205; etched with 2 v/o Nital - 4 w/o Picral

Traditionally, axial fatigue values measure lower in comparison to rotating bending fatigue (RBF) measurements as a result of the type of stresses applied to the sample. The relationship determined by Sanderow et al. [11], where axial FEL ≈ 0.84 x RBF FEL, was applied to convert the 90% FEL of materials listed in MPIF Standard 35 for comparison to results of this study. A recent paper by Lipp et al. [12] supports this relationship in that axial specimens have a lower endurable load than bending or torsional loaded bars due to stress concentration factors. Therefore, Figure 10 compares the as measured axial FEL with converted RBF heat-treated data for select alloys from standard 35. The calculated FEL trend for FD-0205HT was compared with the value measured in this study and found to be within approximately 10% of each other at a density of 6.95 g/cm^3. While it has been expressed that the relationship may not be as accurate for diffusion alloy materials [11], the results agree within reason, permitting further comparison of other data. Plotting the estimated FEL for heat-treated 30 HP + 0.75 w/o Ni highlights the performance this lean alloy is capable of with respect to popular alloys FLN2-4405HT and FN-0205HT. The lean heat-treated alloy based on 30 HP outperforms FN-0205HT at a 7.0 g/cm^3 density and competes with the heavily alloyed FLN2-4405HT. In addition, these trends further demonstrate the significant influence density has on fatigue performance, as it does with other PM alloy properties. Through compacting parts to higher density in combination with a leaner alloy, a much enhanced fatigue endurance limit can be achieved in addition to the results measured in this study.

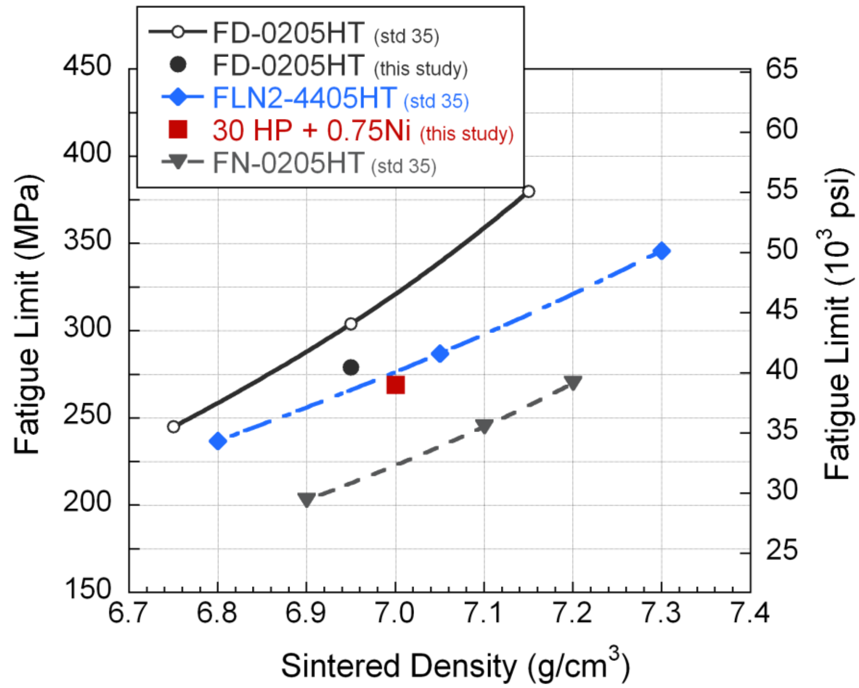

Figure 10: Comparison of measured heat-treated axial FEL from this study to converted RBF 90% FEL data from MPIF Standard 35 [10]

CONCLUSION

It has been shown that lean alloys based on as little as 0.3 to 0.5 w/o prealloyed Mo are capable of providing sufficient properties for applications where current alloy contents are underutilized and cost outweighs the material performance. The as-sintered fatigue performance of 0.3 and 0.5 w/o Mo alloys is improved with additions of Ni (0.75 w/o) and further enhanced with Cu (0.5 w/o). Heat treating these alloy grades promotes a substantial increase in both static and dynamic response as is commonly found when applying a secondary processing step to produce a martensitic microstructure. The fatigue limit is boosted by as much as 152 % for an alloy with only 0.3 w/o prealloyed Mo when heat treated in reference to the as-sintered performance. Within the scope of this study, it was found that 0.3 w/o Mo performs as well as 0.5 w/o Mo in the heat-treated condition. The benefit of increasing Mo content, however, yields an improvement in hardenability. The required Mo content would be dictated by part size and the desire to develop a fully through-hardened structure. Additions of Cu were found to be detrimental to heat-treated fatigue behavior, although marginal improvements in static heat-treated properties were observed with additions of both Ni + Cu. Furthermore, this work demonstrated that a composition as lean as 0.3 w/o Mo + 0.75 w/o Ni + 0.6 w/o Gr has competitive heat-treated fatigue performance when compared with FN-0205 and FLN2-4405. It is therefore recommended that the total alloy content found in popular heat-treating alloys could be reduced and still provide acceptable fatigue performance, while meeting demand in cost reduction for manufacturing.

ACKNOWLEDGEMENTS

The authors wish to thank Michael McGuire for collecting the data and Barry Diamond for contributing the microstructures presented within the manuscript.

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