Lean alloy Nickel PM steels

T. Stephenson, M. Korotkin, S. Metcalfe
Vale Inco Limited
Canada

Abstract

High raw materials costs resulting from increased demand in developing countries are changing the traditional alloying approach to PM steels. To address the cost pressure faced by PM parts producers, an evolutionary approach to alloy design was used based on prealloyed Fe-Cr-Mo powder admixed with up to 2 wt% XF Ni powder and a hybrid Fe-Cr-Mo alloy diluted with prealloyed Fe-Mo and admixed Ni plus Cu powders. The objective of this work was to maintain reasonable compressibility of the base Fe powder, while lowering overall alloy cost with smaller than traditional additions of the more expensive alloying elements. Properties of nominal 7.05 g/cm^3 steels sintered at 1140 °C were compared in the sinter hardened condition, using variable cooling rate. The effect of part thickness on the hardenability of these alloys was characterized under sinter hardening conditions. Finally the improvement in dimensional precision, particularly in sinter-hardened alloys containing Cu and fine Ni was demonstrated. Ni additions improved tensile properties and hardenability, allowing the potential for lower Cr-content steels to be sinter-hardened with conventional sintering temperatures and slower cooling rates.

Introduction

The search for alternative PM alloy systems has apparently come full swing with the recent introduction of new grades of powder containing combinations of Ni, Cr and Mo, albeit at lower concentrations than alloys introduced 10-20 years ago during times of much lower raw material costs. Instead of seeking a competitive alternative to Ni-Mo alloys, Fe powder producers are recognizing the additional processing difficulty experienced by parts makers in using Cr-based Fe powders. The PM industry appears to be moving in the direction of leaner alloys containing a combination of elements at lower concentration in order to improve processability, while keeping costs low. This balance between raw material and processing costs is necessary in order to keep PM technology competitive with alternative metal forming technologies such as machined wrought steels.

High Ni prices and the persistent high cost of Mo are forcing PM powder suppliers and parts makers to use these elements more wisely. In quench & temper parts, Mo has been reduced from 0.85 to 0.5 wt.% or lower where possible. Ni has been reduced to the allowable lower limits of standard compositions or eliminated entirely by changing alloy grades. The processing cost advantages promised by sinter hardening are being re-evaluated in light of the higher alloy content needed in these alloys to provide the hardenability required at slower cooling rates than heat-treated steels. However many of the new alloying systems being proposed containing prealloyed Cr, offer lower cost at the expense of more complicated processing and reduced compressibility than Ni-Mo alloys.

The desire for more effective use of higher cost alloying additives such as Ni and Cu is also driving the need for finer powders. Extra-fine Ni powder (XF Ni) has been introduced and with improved diffusion of Ni during conventional sintering, offers several performance advantages over conventional Ni powder including: higher hardenability, improved dimensional precision and more homogeneous microstructures desirable for sinter-hardening applications [1-2]. In work reported recently on lean Ni-Mo PM steels, the authors demonstrated that in reducing Mo from 0.85 to 0.5 wt.% and Ni from 2 to 1 wt.%, similar mechanical properties and hardenability can be achieved by increasing carbon content and/or by using extra-fine Ni in place of standard grade admixed Ni powder [1]. The Jominy curves in Figure 1 show that reduced Mo and Ni content limits hardenability of these alloys and application to smaller part sizes.

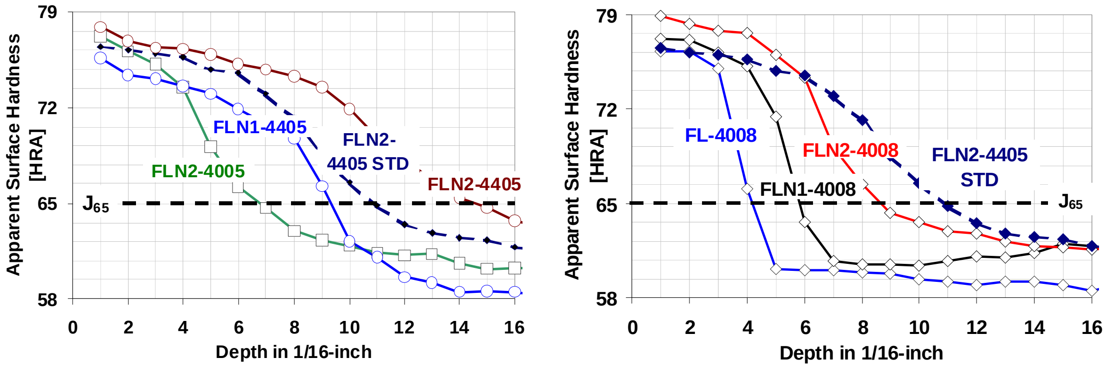

Figure 1. Jominy hardenability of lean Ni-Mo alloys with XF Ni. Alloy designations based on MPIF Standard 35 [3]. Steels double-pressed, double sintered to nominal density = 7.3 g/cm^3

To reduce alloy content further or to increase hardenability for sinter hardening grades in particular, a different alloy design approach is required. The objective of this work was to determine the effect of admixing extra-fine Ni with prealloyed Cr-Mo steels. A secondary objective was to reduce prealloyed Cr content Fe powders in order to improve compressibility and to allow more conventional annealing and sintering conditions of prealloyed Fe-Cr powders, thereby reduce processing costs. Relatively low wt% of Ni and/or Cu powders were admixed as a means to improve mechanical properties and provide flexibility in alloy composition not available with fully prealloyed Fe powders.

The beneficial synergetic effects obtained by combining different alloying metals are well known [4-6]. The properties of Cr-based steels can be improved with Ni and Cu additions [5,7]. Previous work by the authors on Ni+Cu additions to prealloyed Cr-Mo PM steels using conventional cooling rates demonstrated that high apparent hardness and bend strengths could be obtained at dilute Cr contents of 0.75 – 0.5 wt% [2].

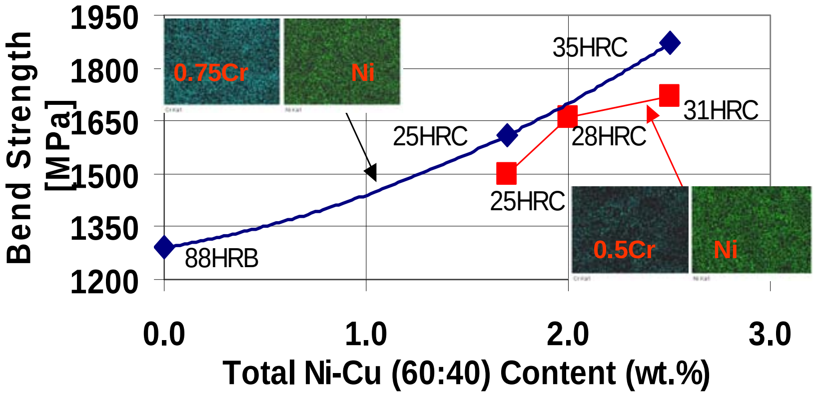

Figure 2. TRS and apparent hardness Cr-Mo-Ni-Cu PM steels. Cooling rate = 0.8 °C/s. Sinter density = 7.0 – 7.1 g/cm^3.

The present work explores the effect of alloy composition and cooling rate on the structure/property relationships of prealloyed Fe-Cr-Mo + admixed Ni-Cu powder PM steels. Target lean PM steel compositions were designed to be comparable to wrought gear steels; total alloy content was from 1.7 to 3.7 wt.%. Steels were made by using prealloyed Fe-1.5%Cr-0.2%Mo as a base and combining it with Fe-Mo powders to obtain the desired Cr and Mo contents, then admixing with XF Ni and/or Cu powders to boost mechanical properties and hardenability.

Experimental

The target compositions included 0-2% XF Ni additions to prealloyed 1.5Cr-0.2Mo and one “hybrid” steel, namely 0.75Cr-1Ni-0.75Cu-0.6C. Total combined carbon content in the sinter hardened and tempered steels was confirmed by chemical analysis to be 0.6 wt.%. Steels were made from a combination of the following powders to arrive at the target composition:

> Fe powders: 0.5% Mo (Atomet 4001[1]), 1.5% Cr - 0.2% Mo, 3%Cr-0.5%Mo (Astaloy CrL, CrM[2])
> Nickel: Inco ® T123 PM (STD Ni); T110 D (XF Ni)
> Cu: AcuPowder 301
> 0.65 % Graphite: Asbury SW 1651
> 0.6 - 0.75% lubricant: Lonza Acrawax C

Powders were mixed in 75 kg batches in a V-cone blender and compacted at 580 to 630 MPa (42-46 tsi) to nominal 7.0 g/cm^3 green density. All steels were sinter hardened at 1140 °C for 30 minutes in a 95/5 N_2/H_2 atmosphere using an industrial furnace equipped with accelerated cooling. Cooling rate was referenced solely by the cooling fan speed in Hertz. The exact cooling rate for these samples is not known at this time, but will be determined in future work. As-sintered steels were tempered at 205 °C for 1 h.

The density, transverse rupture strength (TRS), tensile strength and apparent hardness of sinter hardened and tempered PM steels were evaluated according to MPIF standard test methods [3], and compared with the properties of the standard and published data for 1.5Cr-0.2Mo steels [7,8].

Results

The choice of prealloyed Cr content for the hybrid steel composition was determined by a compromise between improvement in compressibility and loss in hardenability anticipated at lower wt% Cr. In Figure 3, various Cr-Mo-C powder blends were made into 6 mm thick dog-bone tensile bars by cold compaction. Cr content < 1.5% was obtained by diluting with prealloyed 0.5%Mo-Fe powder. Metal powders were admixed with 0.7% C and 0.6% EBS.

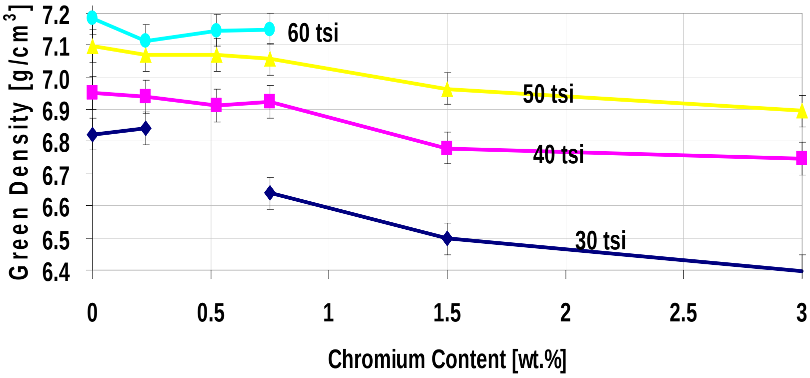

Figure 3. Compressibility of prealloyed Cr-Mo Fe powders as a function of Cr content.

In addition, compaction trials on a 150 ton mechanical press confirmed an approximately 0.5 – 0.7 g/cm^3 increase in green density at similar compaction pressure for the lower Cr content

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[1] Atomet 4001 is a registered trade name of Quebec Metal Powders

[2] Astaloy CrL, CrMareregistered trade names of Hoganas AB

steels. Or in other words, a compaction pressure reduction of approximately 60 MPa (4-5 ton/in^2) can be realized to achieve the same 7.0 g/cm^3 green density of 1.5Cr vs. 0.75Cr steels. Previous work reported mechanical properties of conventionally cooled hybrid alloys at both 0.75% and 0.5% Cr [2]. Based on these results, 0.75% Cr was chosen in order to meet both the nominal target 7.05 g/cm^3 sinter density at 50 tsi compaction pressure and sufficient hardenability to reach 30 HRC at this density and cooling rates.

The apparent surface hardness of a 1.5Cr-0.2Mo-0.6C steel increased with the addition of nickel and with cooling rate (Fig. 4). 65HRA (30HRC) was achieved at 60 Hz with 1% admixed XF Ni powder addition. At low cooling rate (25 Hz), 2% XF Ni was required to reach approximately the same apparent hardness. In the hybrid alloy, reducing Cr to 0.75% lowered the surface hardness to that obtained with approximately 20 Hz lower cooling rate despite the additional of 2% Ni+Cu. These results were obtained at constant green density and the increased compressibility of the hybrid alloy would likely compensate for the loss in alloy content if compacted at the same pressure as the undiluted Cr steels.

The addition of XF Ni also improved bend strength at each cooling rate. TRS was most sensitive to cooling rate at lower alloy content, with similar results (2000 MPa) obtained at 2% XF Ni additions for all three cooling rates. As with apparent hardness, the lower Cr content of the hybrid steel was not fully compensated by the 2% Ni+Cu addition. The TRS of the hybrid steel would again compare more favourably if the steels were all compacted with the same pressure, due to higher compressibility of the prealloyed Mo-Fe powder.

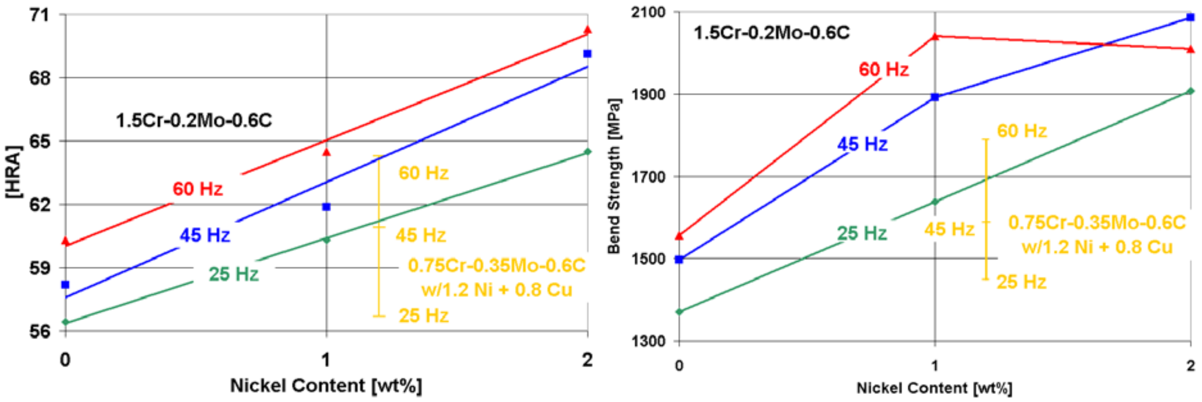


Figure 4. Apparent hardness and TRS of sinter hardened Cr-Mo-(Ni/Cu) PM steels.

Microindentation hardness profiles were measured on steel ring samples (20 mm cross section thickness) using the HV$_{50gf}$ scale. Measurements were made at 10-25 micrometre spacing intervals in the compaction direction, with a minimum 20 points per profile. The change in microindentation hardness from 1 to 12 mm centre depth from the surface was insignificant, indicating a uniform microstructure was obtained between the surface and core of these parts. In Figure 5 below, microindentation hardness values were averaged to show the effect of admixed Ni content and cooling rate. The error bars in Figure 5 indicate the standard deviation in the microindentation hardness measurements.

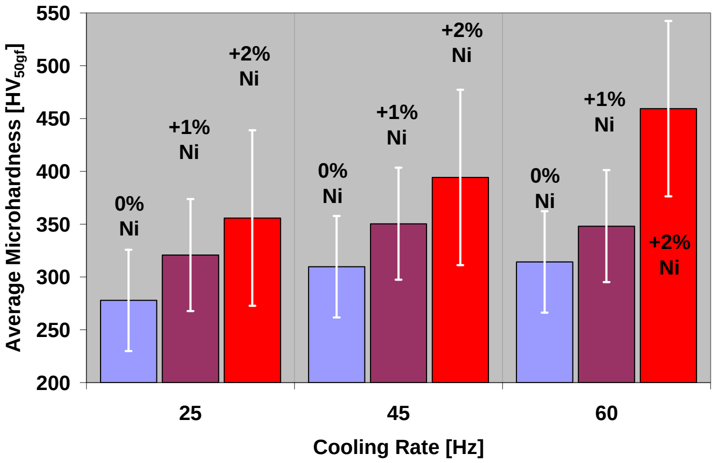
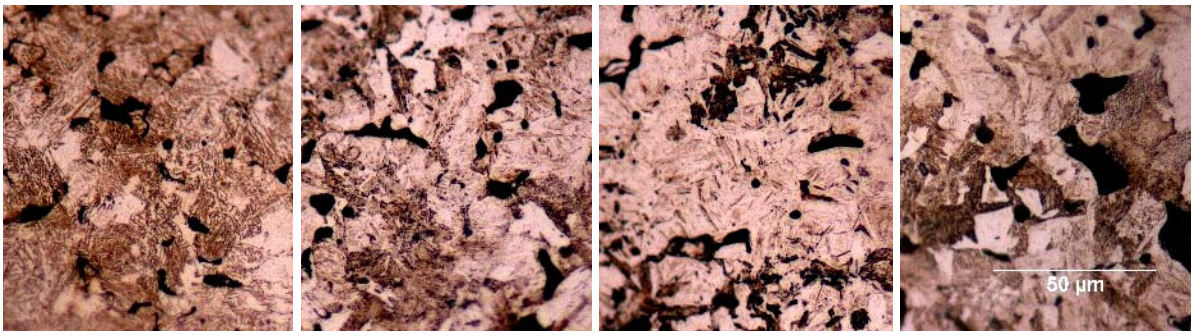


Figure 5. 1.5Cr-0.2Mo-0.6C PM steels admixed with 0, 1 and 2% XF Ni. Sintered density = nominal 7.00 g/cm^3.

The microstructures of sinter hardened and tempered Ni-Cr-Mo steel rings appeared similar at the edges and in core areas at all cooling rates, consistent with the microindentation hardness measurements reported above. The structure of 1.5Cr-0.2Mo steel rings cooled at high (60 Hz) cooling rate consisted mostly of pearlite with small amounts of ferrite and bainite. Addition of 1wt.% XF Ni lead to a substantial formation of martensite at medium cooling rate (45 Hz) and a nearly complete martensitic structure at high cooling rate (60 Hz). Addition of 2wt.% XF Ni resulted in predominantly martensitic microstructures at low cooling rate (25 Hz). The microstructure of 1.5Cr-0.2Mo-2Ni-0.6 C steels was complete martensite (at edge and in core) at medium (45 Hz) and high (60 Hz) cooling rates. The hybrid alloy 0.75Cr-0.35Mo-1.2Ni-0.75Cu-0.6C steel structure consisted mostly of martensite/bainite with small amount of residual pearlite at medium (45 Hz) cooling rate, and was predominantly martensite with some bainite areas in steels cooled at high (60Hz) rate.



1.5Cr-0.2Mo 1.5Cr-0.2Mo-1Ni 1.5Cr-0.2Mo-2Ni 0.75Cr-0.35Mo-1Ni-0.7Cu

Figure 6. Optical images of Cr-Mo-Ni PM steel 20 mm ring cores, made at 500 X. Cooling rate - 60Hz.

Conclusions

Admixed XF Ni powder additions to prealloyed 1.5Cr-0.2Mo steels greatly increased hardenability and bend strength. Lean 0.75Cr-0.35Mo-0.6C + XF Ni PM steels based on prealloyed Fe-Cr + Fe-Mo powders had slightly higher hardenability and mechanical properties compared to the undiluted prealloyed 1.5Cr-0.2Mo not containing admixed Ni. The addition of XF Ni powder to 0.75Cr-0.35Mo-0.6C steels sinter hardened at 1140 °C increased apparent hardness by 3-4 HRA and tensile strength from 100 to 200 MPa relative to 1.5Cr-0.2Mo-0.6C steels.

Microstructures of the base 1.5Cr-0.2Mo-0.6C steels were predominantly pearlitic with small amounts of bainite / ferrite at all cooling rates. The addition of 1 - 2% XF Ni transformed the microstructure into predominantly martensite, with the amount of martensite dependent on cooling rate and Ni content. Sinter hardening at 1140 °C of Ni-Cr-Mo steels through hardened steels to 20 mm depth at medium/high cooling rates with 1 wt.% admixed XF Ni and at all cooling rates considered with 2 wt.% admixed XF Ni. Steels made by blending base Fe-Cr and Fe-Mo powders had an inhomogeneous microstructure, with one predominant phase rich in Cr and the other in Mo. Ideally a prealloyed powder containing 0.5 to 0.75% Cr and 0.35 to 0.5% Mo would improve the mechanical performance of similar composition alloys.

XF Ni powder therefore provides additional flexibility in sinter hardening alloy design. Relatively small additions (1-2%) of XF Ni can compensate for inadequate hardenability of the base Cr-Mo material, enabling larger and thicker parts to be sinter hardened or increasing the mechanical properties that can be obtained. In addition, the combination of XF Ni with admixed Cu can provide both improved dimensional precision and high mechanical performance in cost effective sinter hardening PM steels.

Acknowledgements

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