Study on the effect of alloying elements on the hardenability of PM steels

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Abstract

The hardenability of steels is dependent on the type and amount of alloying elements present. Ni and Cu are commonly used in PM industry and can boost the hardenability of PM steels resulting in improved mechanical performance. In this study the effect of Cu or Ni additions on the hardenability of material grades pre-alloyed with Cr is investigated by generating and comparing the respective CCT diagrams. Results from mechanical testing from a previous study as well as metallographic investigation are used for getting a full picture regarding the hardenability of those steels. These results can be a useful tool for designing and controlling the heat treatment of PM steels.

Introduction

The ongoing efforts of the PM industry to expand translates into meeting the performance requirements of demanding applications [1]–[4] in a consistent and reliable manner. In the same time, cost-efficiency, flexibility in terms of component geometry and sustainable production must remain as the main advantages of the press-and-sinter process route.
The way to achieve the above is by tailoring the microstructure according to the desired properties as well as according to the existing process capabilities. The progress in compaction press and sintering furnace technologies as well as the incorporation of additional heat treatment steps, give the possibility of using powder grades in a more advanced manner and thus achieving higher performance. Therefore, an in depth understanding of the material behavior is needed along with the knowledge of basic material information and detailed microstructural analysis [1]–[6].
The following study is part of an ongoing effort of studying the material behavior in terms of hardenability by constructing CCT and TTT diagrams, performing Jominy hardenability testing and complementing with detailed metallographic investigation and mechanical testing for verification. The amount of obtained data is very large and therefore this work is focused on the hardenability of some alloys with respect to their alloying element content by studying their CCT diagrams and their metallography. Mechanical testing results from previous works, complemented with some new data are also used in order to connect the line between hardenability, microstructure and mechanical properties.

Experimental

The base material for this study was the commercially available grade Astaloy CrA (Fe-1.8Cr-prealloyed) which was admixed with Ni (INCO 123) and Cu (-100 mesh) in different amounts in order to study the effect of these alloying elements. The C-content and lubricant content were kept constant. The nominal compositions of the prepared blends are summarized in Table 1.

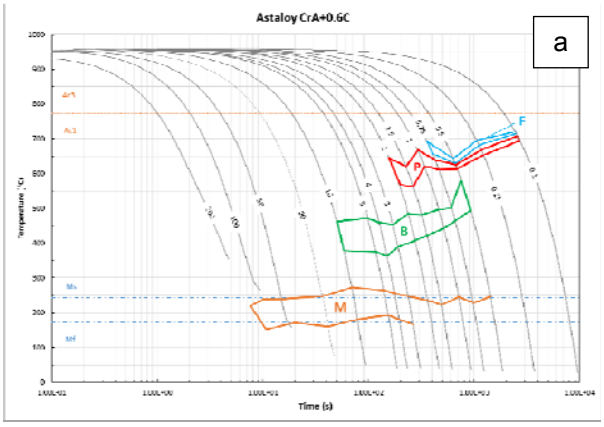
	Name	Composition (wt.%)			C (UF4) (%)	Lub HD (%)
		Cr	Ni	Cu		
1	Astaloy CrA	1.8	-	-	0.7	0.5
2	Astaloy CrA+1Cu	1.8	-	1 (admixed	0.7	0.5
3	Astaloy CrA+2Cu	1.8	-	2 (admixed)	0.7	0.5
4	Astaloy CrA+1Ni	1.8	1 (admixed)	-	0.7	0.5
5	Astaloy CrA+2Ni	1.8	2 (admixed)	-	0.7	0.5

Table 1. Composition of test mixes.

The construction of the CCT diagrams were done by performing quench dilatometry on cylindrical samples (Ø: 6mm and height: 10mm). The samples were pressed to a density of ~6.9 g·cm^{-3} and were then sintered at 1120°C for 30 min in an N_2/H_2 – 90/10% atmosphere prior to the testing. The dilatometry testing consisted of heating the samples with 10°C/s up to the austenisation temperature (960°C) followed by an isothermal holding for 3 minutes. After the isotherm the samples were cooled with different cooling rates ranging from 0.1ºC/s to 200ºC/s using He gas. The CCT curves were generated using the equipment software WinZTU after the phase transformation points were identified from every dilatometry curve. C-content was also measured for every dilatometer sample in order to ensure the consistency of the measurements.
For the purposes of this study, additional samples were produced in the exact same manner as described in [7] and were sintered in the same conditions but were cooled down with 1°C/s after sintering. Furthermore samples sintered in an industrial vacuum furnace were also produced and the applied cooling rate was 5°C/s with a significantly more linear behavior as compared to[7]. The results from the hardness testing are presented together with the results from [7] providing a more complete picture.

Results

From the acquired CCT diagrams the first clear indication of how additional alloying elements can affect the microstructure is the absence of ferrite from the additionally alloyed Astaloy CrA samples (Figure 1). Both Cu and Ni as alloying elements are “γ-stabilizers” but belong to different sub-groups, Cu leads to *expanded* γ-field whereas Ni leads to *open* γ-field [8]. Therefore both Cu and Ni help avoiding the nucleation of ferrite and in the same time shift the position of the bainite curve towards slower cooling rates. Ni shows a greater effect on the martensitic transformation in comparison with Cu. Martensite appears even for the lowest cooling rates whereas for Cu at least 0.75°C/sec are required in order for martensite to appear.
The temperature for the start of the martensitic transformation “M_s” is also affected only from the amount and the type of the additional alloying element added although in different extent as shown in Figure 2 In the same figure the theoretical M_s of these alloys calculated with the software JMatPro v. 10.1 is also plotted. This software uses a mechanistic model for the calculation of the bulk M_s base on the work of Ghosh and Olson [9]. It is evident that there is a relatively constant difference between the experimental and theoretical values. This difference however is about 50°C in the case of Cu-alloyed material and 25-30°C for the Ni-alloyed material. The smaller difference in the case of Ni-alloyed material can be attributed to the better description of the effect of Ni compared to Cu. The model described in [9] makes some assumptions and therefore has some expected limitations. Therefore an overall difference between theoretical and experimental M_s is expected and can be attributed to different reasons: the porosity of PM samples, the fact that for the theoretical calculations one grain size (15μm) was chosen whereas in reality we have a number of different grain sizes, some small variations in the C-content in the samples or finally the fact that in the simulations the distribution of Ni and Cu is considered uniform whereas in reality there will be local composition gradients.



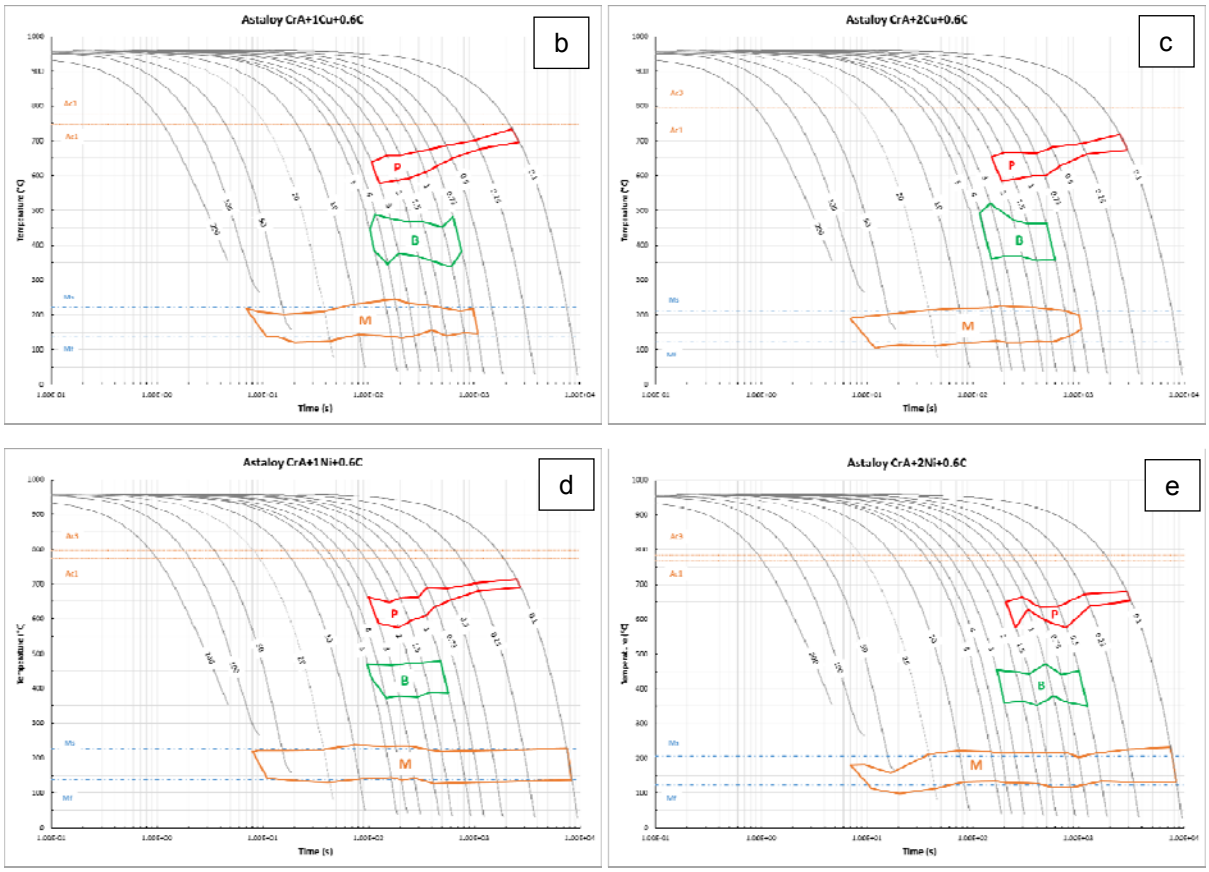


Figure 1. experimental CCT diagrams for a) Astaloy CrA (Fe-1.8Cr)-0.6C, b) Astaloy CrA (Fe-1.8Cr)-1Cu-0.6C, c) Astaloy CrA (Fe-1.8Cr)-2Cu-0.6C, d) Astaloy CrA (Fe-1.8Cr)-1Ni-0.6C, e) Astaloy CrA (Fe-1.8Cr)-2Ni-0.6C

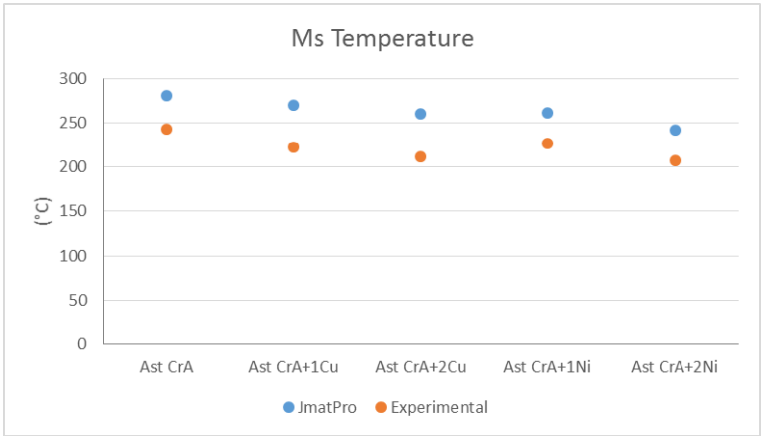
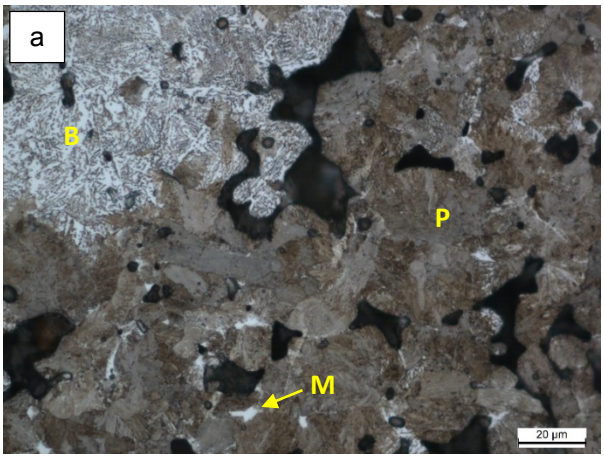
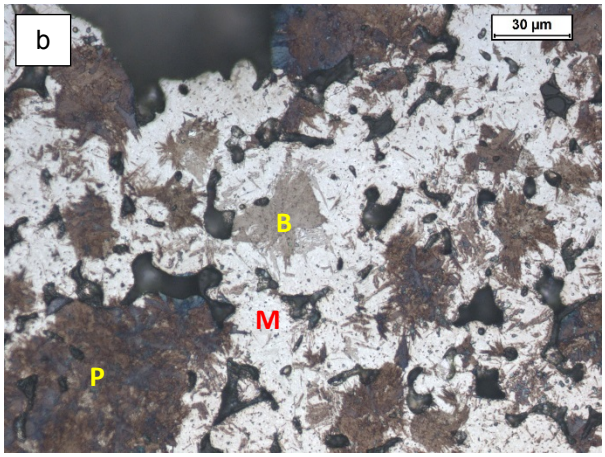


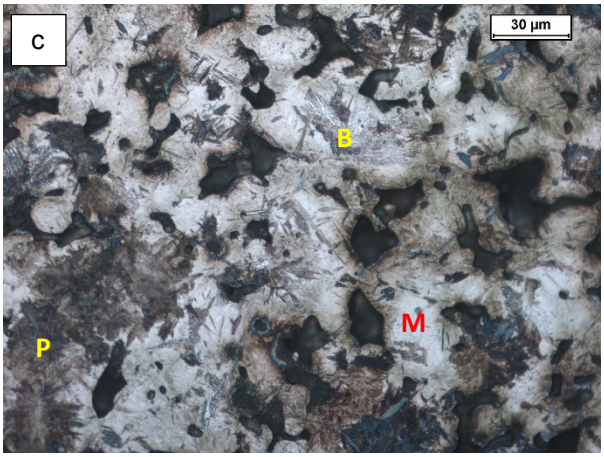
Figure 2. Experimental and theoretical Ms temperature

In Figure 3 the light optical micrographs of the samples cooled with 1°C/s are presented. All the samples exhibit a complex microstructure where pearlite, bainite and martensite transformation products are present at the same time. The amount of each phase however differ among the samples i.e for the sample without any additional alloying element the prevailing phase is pearlite (brown areas marked with P in Figure 3a) with a few areas of bainite (grey areas marked with B in Figure 3a) appearing as well as some traces of martensite (white). On the other hand, with increasing Cu content the amount of martensite (white areas in Figure 3b and c) increases as well. The same trend stand for

the presence of bainite as well, it increases with increasing Cu content and the opposite is valid for pearlite. Similar microstructural evolution is encountered for the samples alloyed with Ni as well (Figure 3 d and e). The amount of martensite (white phase) increases with increasing Ni content. Dense bainite (light brown) and pearlite (dark brown) are forming a mixture which is difficult to discern in some cases. Nevertheless the amount of bainite increases with increasing Ni content whereas the opposite trend is observed for the amount of pearlite.
Comparing Figure 3 b and d it is obvious that the amount of pearlite is larger in the Ni-alloyed material (Figure 3d). This is connected with the distribution of the additional alloying elements in the material. Cu will melt already at 1083°C and this melt phase is easier and faster to distribute homogeneously in the sample. On the other hand Ni will diffuse the matrix by means of solid state diffusion which is of course mush slower and thus Ni will be inhomogeneously distributed. As soon as more Ni is added (Figure 3 e) the amount of sites where Ni diffuses into the matrix are also increased and therefore the difference in the final microstructure is very large. In the case of further increasing the Cu content from 1% to 2% the difference in the microstructure is not as significant as in the case of Ni. The amount of martensite essentially remains the same but bainite increases in the expense of pearlite.







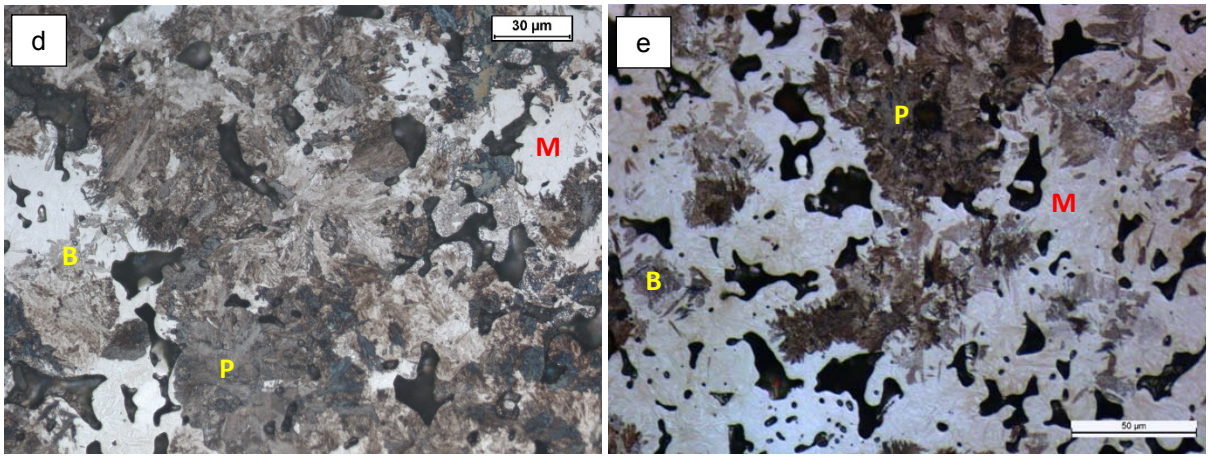


Figure 3. Optical micrographs of samples cooled with 1°C/s for a) Astaloy CrA (Fe-1.8Cr)-0.6C, b) Astaloy CrA (Fe-1.8Cr)-1Cu-0.6C, c) Astaloy CrA (Fe-1.8Cr)-2Cu-0.6C, d) Astaloy CrA (Fe-1.8Cr)-1Ni-0.6C, e) Astaloy CrA (Fe-1.8Cr)-2Ni-0.6C

The hardness (HV10) which as a property is directly connected with the microstructure is presented in Figure 4. For the high cooling rate (5°C/s) the differences are very small between all the materials which have a martensitic microstructure with some traces of bainite for Astaloy CrA+1Ni and 1Cu. For Astaloy CrA without any additional alloying element the amount of bainite is larger and this is reflected on the hardness values as well. The effect of the microstructure is more pronounced in the lower cooling rates. Any additional alloying element leads to significant improvement in the hardness values. The increasing alloying content also reflected on the increasing hardness values for up to 1.5°C/s cooling rate and is connected with the pearlite content. With 3°C/s the difference in hardness for the difference in alloying content is decreased in comparison with 1.5°C/s since now the microstructure is a mixture of bainite and martensite.

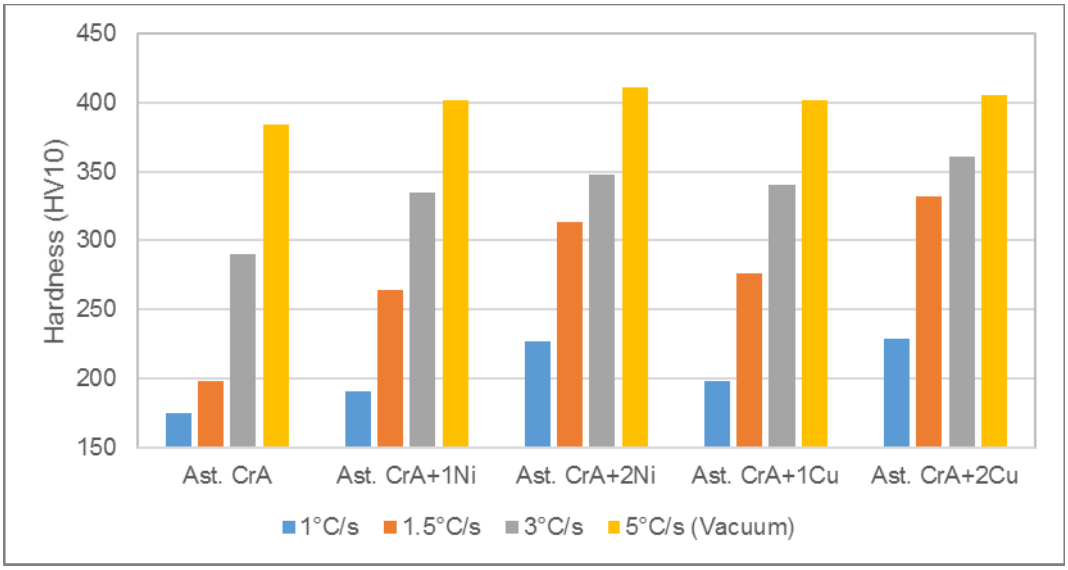


Figure 4. Hardness values for the materials cooled with different cooling rates

In Figure 5 the results from the tensile testing are presented. The tensile strength as a property is affected by both the microstructure as well as the density of the samples. This needs to be taken into consideration for the materials which are additionally alloyed with Cu and will exhibit some swelling during sintering which in turn will result in lower sinter densities as shown in […]. On the other hand the addition of Ni will lead to some slight densification which will be positive in terms of tensile strength. However the increasing additional alloying content and the relevant microstructure will

increase the strength of the material as seen from the comparison of the values for the each additional alloying element.

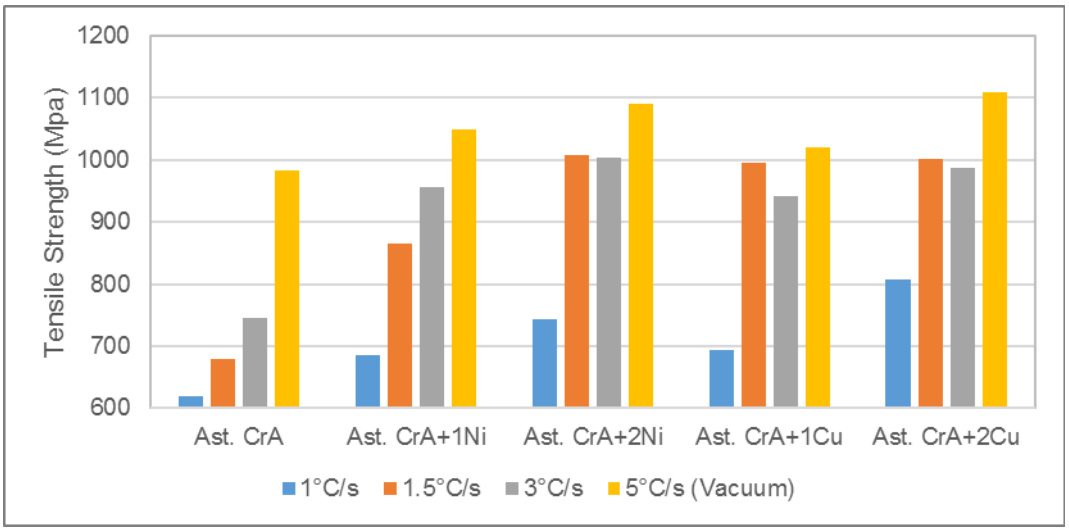


Figure 5. Tensile strength of materials cooled with different cooling rates

Conclusions

In this study the effect of commonly used alloying elements, such as Cu and Ni, on the hardenability of PM steels is investigated by generating CCT diagrams and examining carefully the obtained microstructures. The results are also compared with theoretical calculations and the reasons for the observed differences are explained. Results from hardness and tensile testing are also used in order to connect the microstructural observations with the mechanical performance. Shortly some key conclusions are:

- Ni has a stronger effect in getting harder transformation products (martensite) at lower cooling rates.
- Both Ni and Cu show similar decrease in M_s.
- The easier dissolution of liquid Cu during sintering is beneficial for the hardenability of PM steels when lower amounts (1%) of alloying elements are used.
- The effect of additional alloying elements on hardenability is more easily observed on low or intermediate cooling rates. The latter also reflects on the hardness values for the respective cooling rates.
- The flexibility in alloying in connection with the processing capabilities available can be a key for obtaining components with improved performance that can meet the demands for new applications.

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