Effect of Post-Sintering Cooling Rate on Properties of Diffusion Bonded Steel Materials

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Abstract

Diffusion bonded powders based on the Fe-Cu-Ni-Mo systems are well known to the P/M industry for combining high compressibility and dimensional stability with a potential for high sintered strength. In applications where strength and hardness become critical variables, material composition and post-sintering cooling rate must be optimized to meet application requirements.

Diffusion bonded steel powders produced under different processing routes were compared at different combined carbon contents (0.30, 0.55, 0.75%) under normal and rapid cooling rates to optimize tensile properties and apparent hardness. The microstructure and distribution of alloying elements were determined by optical metallography and SEM, and related to the mechanical properties of the sintered specimens. Results show that apparent hardness increases with carbon concentration and cooling rate and the highest values were reached for diffusion alloys with pre-alloyed molybdenum. The highest tensile strength was observed at a carbon level of 0.55% and a cooling rate of 5.0°C/s with no significant difference between the way the molybdenum was alloyed (diffusion or pre-alloyed). The highest yield strength was observed at 0.55%C and a cooling rate of 1°C/s, however with a better value when molybdenum was pre-alloyed.

Introduction

P/M parts made with diffusion bonded powders exhibit a heterogeneous microstructure after sintering due to the presence of Ni-rich phases. The degree of heterogeneity varies with the carbon concentration, sintering temperature and post-sintering cooling rate [1,2]. Therefore, mix formulation and sintering condition must be well defined in order to optimize material properties in specific field applications. In addition to these factors, the manner in which alloying elements are added may also affect the sintered properties due to modification of the sintered microstructure.

Therefore, the objective of the study is to evaluate the effect of carbon concentration and cooling rate after sintering on properties of diffusion bonded powders produced under different conditions. More specifically, the effect of addition route of molybdenum will be discussed in a more detailed manner.

Experimental Procedure

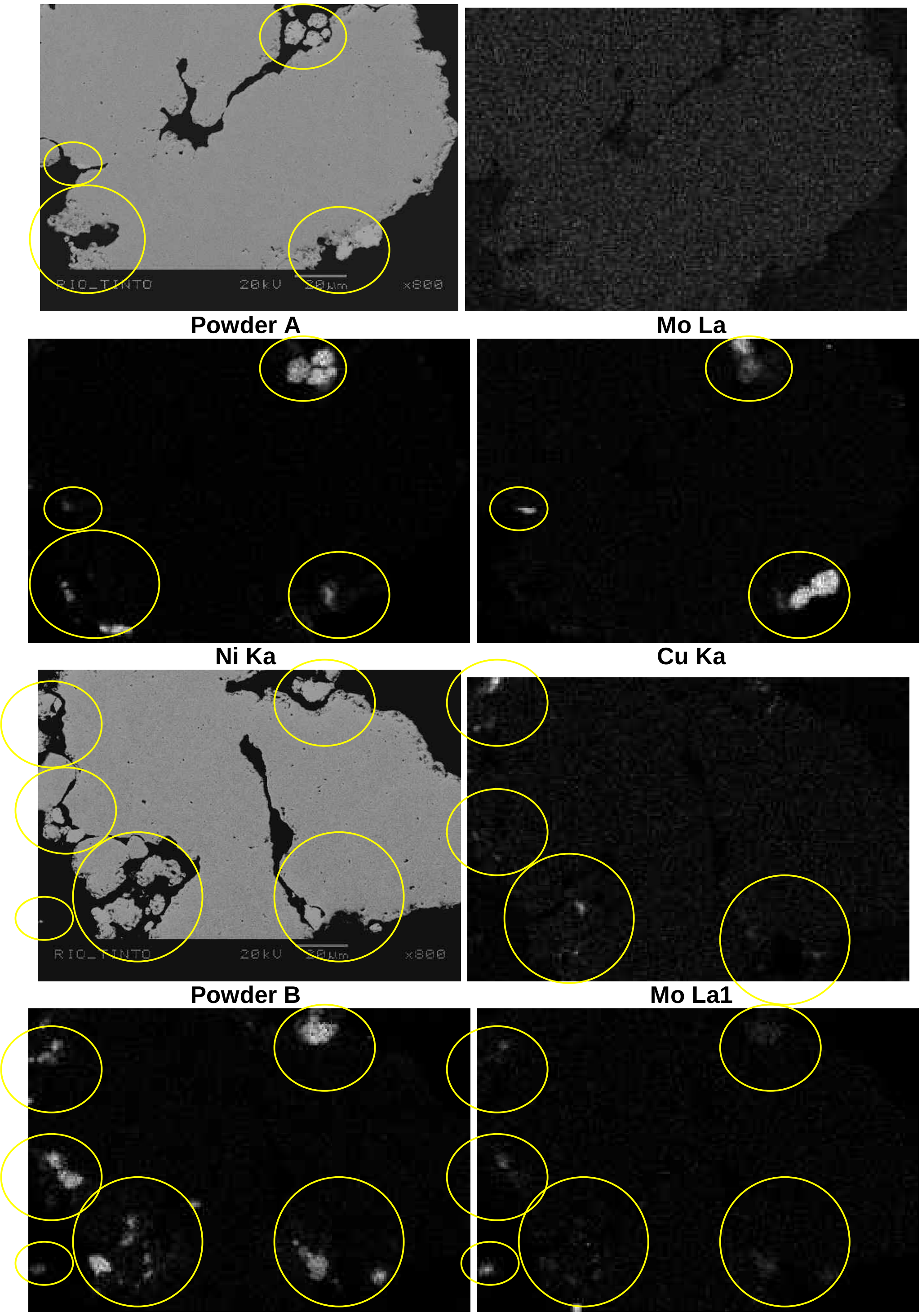
Two diffusion bonded powders grades were used in this study. The first powder is ATOMET DB48 and is identified as powder A in this work. The second grade, powder B, is also a commercially available diffusion bonded alloy and is referred as powder B. Both powders contained 0.5% Mo, 1.5% Cu and 4.0% Ni. Mixes were prepared with 0.35, 0.65 and 0.85% graphite in order to reach about 0.30, 0.55 and 0.75% carbon after sintering. All mixes contained 0.75% EBS wax as lubricant.

The base powders were characterized by scanning electron microscopy to visualise the bonding of the additives. Dog bone specimens were pressed to 7.0 g/cm³ and sintered 35

minutes at 1125°C under a 90% nitrogen based atmosphere. Specimens were cooled at either 0.6, 1.0 or 5.0°C/s in a temperature range of 600 to 400°C and then, tempered 60 minutes at 190°C in air before evaluation of tensile properties and apparent hardness.
Metallography characterization was carried out on the sintered specimens cooled at various rates by optical and scanning electron microscopy.

Results and discussion

Figure 1 shows the distribution of Mo, Ni and Cu alloying elements in powder A and B. The main difference between both powders relates to the distribution of Mo. Powder A shows a very good homogenisation of Mo, while in powder B, areas rich in Mo can be observed at the surface of the iron particles. In powder A, Mo is pre-alloyed in the melt prior to atomization while with powder B, Mo is bonded to the steel particles. This could lead to difficulty in obtaining a uniform Mo distribution in the steel matrix after sintering, because Mo diffuses slowly in iron. Indeed, the coefficient of diffusion of Mo in iron is lower than that of Ni and significantly lower than that of copper [3].
Figure 2 illustrates the effect of carbon concentration and cooling rate on tensile properties and apparent hardness of specimens made with powder A and B. At 0.6 and 1.0°C/s, tensile strength (UTS) increases with carbon content to level off at about 0.55%. For these cooling rates, both materials exhibit similar UTS with however higher values when cooling at 1.0°C/s, 850 vs 740 MPa. At 0.55%C and 5.0°C/s, UTS of about 925 MPa is achieved with both materials. Subsequently, UTS decreases for both materials with however a larger reduction for material A. This loss of strength at higher carbon content and cooling rate can be explained by the increase of notch sensitivity impact of the pores as the hardness and amount of martensite increase [4,5].
For a cooling rate of 0.6°C/s, the yield strength (YS) increases with carbon content for both materials, with material A exhibiting values 10 to 22% higher than material B. At 1.0°C/s, YS also increases with carbon content to reach a maximum at about 0.55% and then decreases at 0.75%C. It is worth mentioning that the reduction of YS at that carbon level is more important with material A than with material B. At 5.0°C/s, YS also decreases when the carbon content is increased from 0.55 to 0.75% and the reduction is larger with material A. The highest YS, 570 MPa, is reached at 0.55%C and 1.0°C/s with material A.
Elongation decreases when the carbon concentration and cooling rate increase. Material B exhibit better elongation values than material A, but the difference is reduced as the cooling rate increases. Finally, apparent hardness increases with the carbon content and cooling rate for both materials, with material A showing higher apparent hardness than material B. Furthermore, this difference increases as the cooling rate is raised.
Such differences can only be explained by modification of the microstructure, even if both materials exhibit similar chemistry. Figure 3 shows the microstructure achieved with both materials at a carbon concentration of 0.30% and cooling rates of 0.6 and 1.0°C/s. For material A, at 0.6°C/s, the microstructure is mainly composed of divorce pearlite with a few areas of fine pearlite, bainite, Ni-rich phases and ferrite. Similar microstructure is observed with material B, with however a larger the amount of ferrite compared to material A. As also shown on this figure, EDX analyses of Mo and Ni reveals that material A shows a good homogenization of Mo with areas rich in Ni. For material B, the Mo is concentrated at the particle periphery with almost no diffusion in the core of the particles. Areas rich in Ni are also visible. Therefore, the lower concentration of Mo in the core of the particles in material B most likely promotes the formation of ferrite, which probably explains the higher elongation values but lower yield strength reached with this material at that level of carbon and this cooling rate. Raising the cooling rate to 1.0°C/s only marginally affects the microstructure of both materials and explains why mechanical properties of each material were similar for these cooling rates and this carbon concentration.



Powder A

Mo La

Ni Ka

Cu Ka

Powder B

Mo La1

Ni Ka

Cu Ka

Figure 1. Distribution of Mo, Ni and Cu in powder A and B.

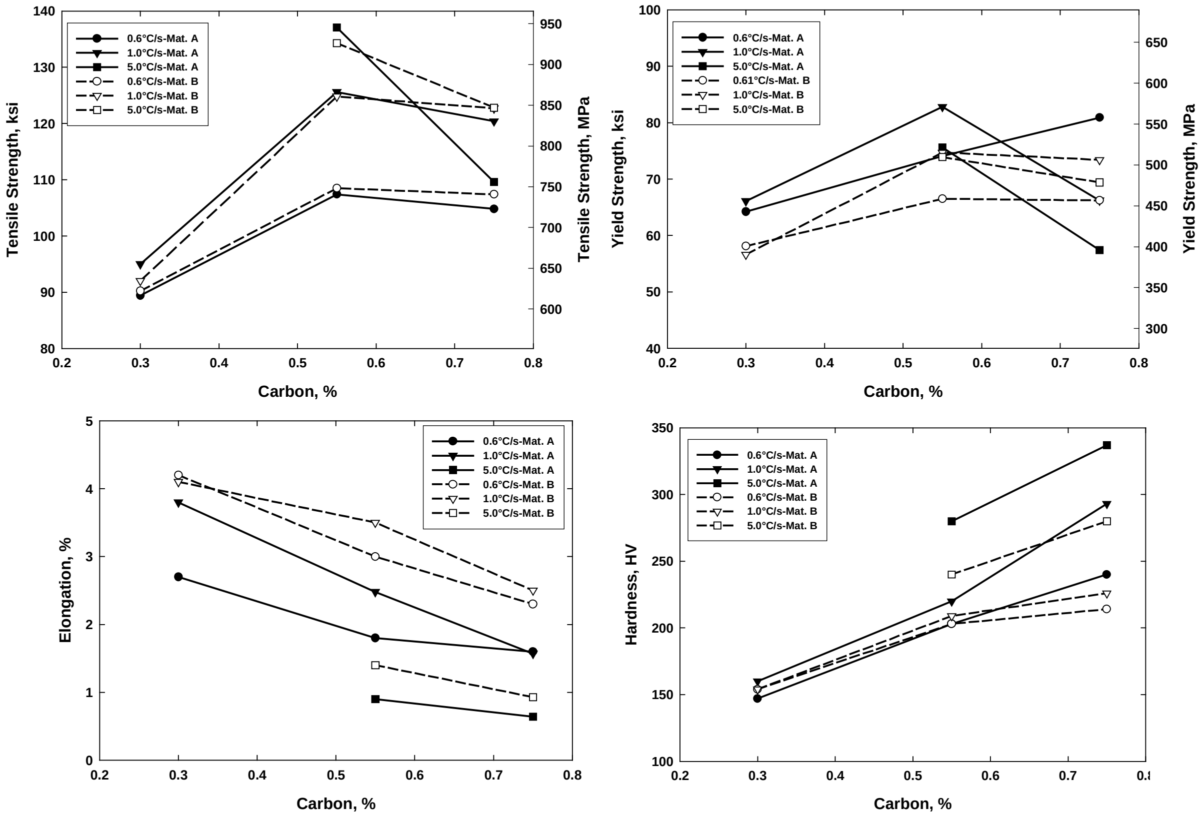
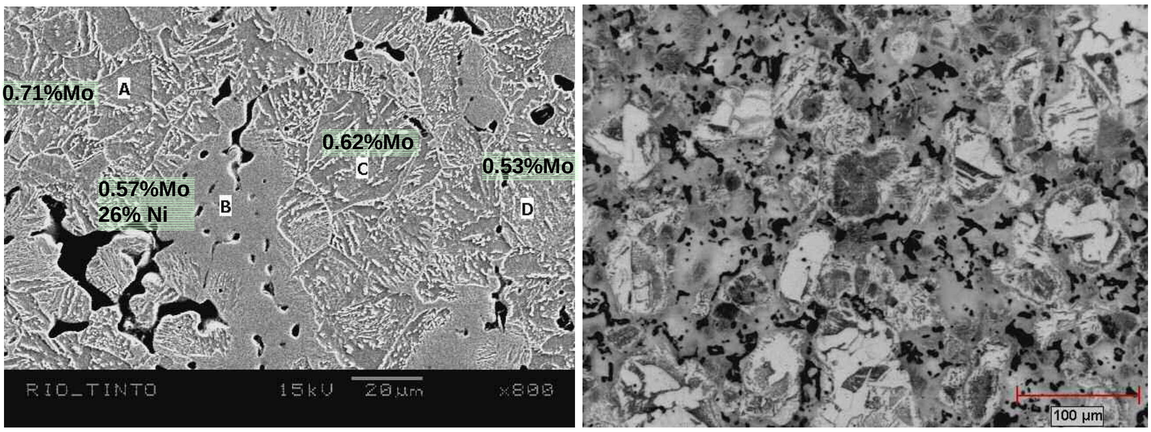
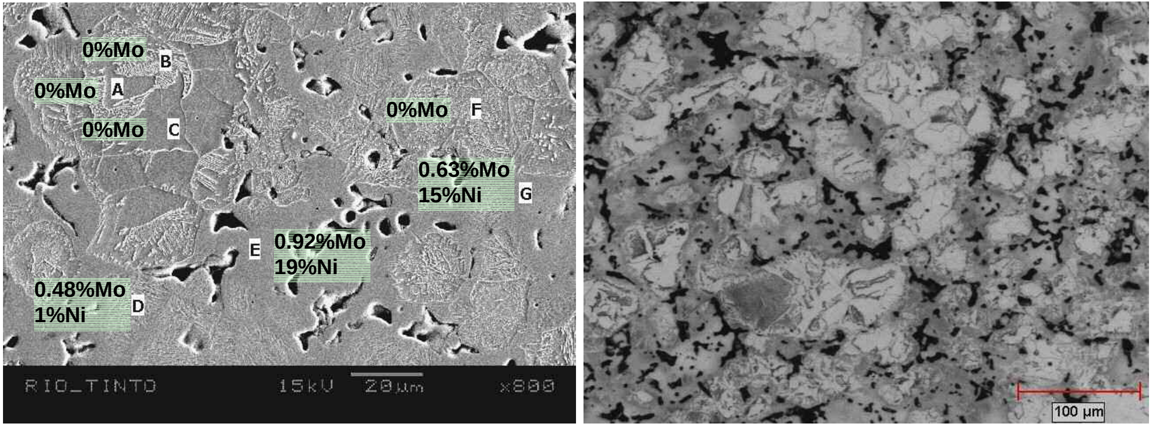


Figure 2. Effect of carbon concentration and cooling rate on tensile properties and apparent hardness of specimens pressed to 7.0 g/cm³ from powder A and B.



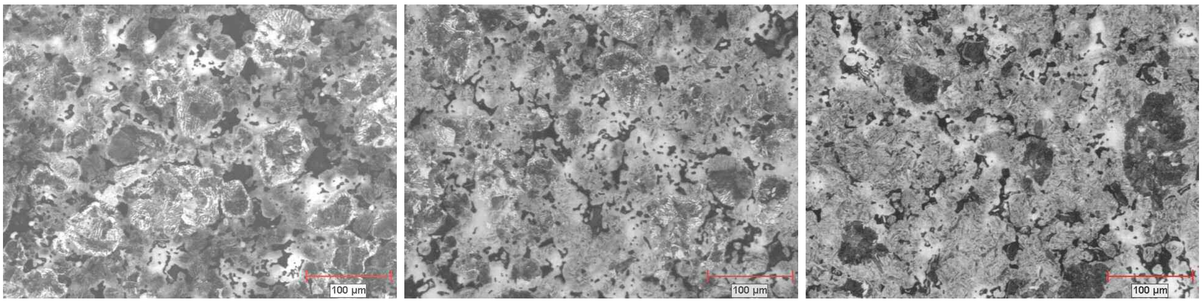
Material A, 0.30%C; 0.6°C/s **Material B, 0.30%C; 0.6°C/s**



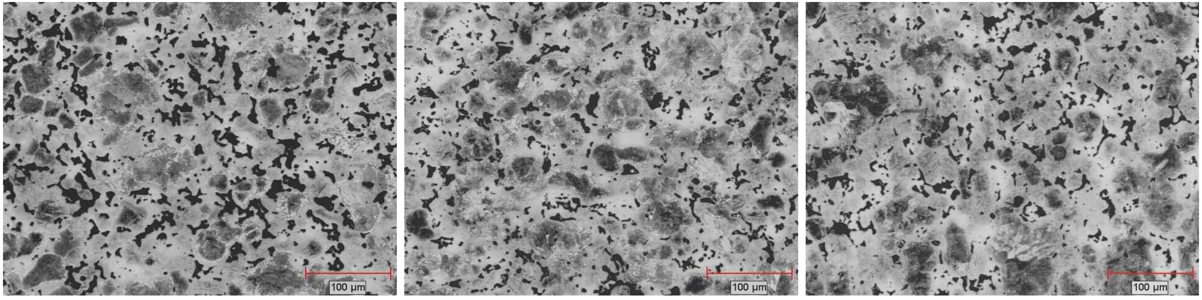
Material A, 0.30%C; 1.0°C/s **Material B, 0.30%C; 1.0°C/s**

Figure 3. Microstructure of materials A and B containing 0.30%C and cooled at 0.6 and 1.0°C/s (Nital etched, 200X).

Figure 4 shows the microstructures observed for both materials containing 0.55%C, cooled at either 0.6, 1.0 or 5.0°C/s. For material A, as the cooling rate increases, the microstructure changes from bainite/pearlite/Ni-rich phases/martensite to martensite/bainite/Ni-rich phases. This explains the increase of UTS as the cooling rate rises. Similar observation can be made with material B with the exception of lower amount of martensite at 5.0°C/s. This is also confirmed by the larger difference in hardness results between material A and B.



Material A, 0.55%C; 0.6°C/s **Material A, 0.55%C; 1.0°C/s** **Material A, 0.55%C; 5.0°C/s**



Material B, 0.55%C; 0.6°C/s **Material B, 0.55%C; 1.0°C/s** **Material B, 0.55%C; 5.0°C/s**

Figure 4. Microstructure of materials A and B containing 0.55%C and cooled at 0.6 and 1.0 and 5.0°C/s (Nital etched, 200X).

Figure 5 shows the microstructures observed for both materials containing 0.75%C cooled at either 0.6, 1.0 or 5.0°C/s. For material A, as the cooling rate increases, the microstructure changes from bainite/martensite/pearlite/Ni-rich phases to martensite/Ni-rich phases. Similar observation can be made with material B, with the exception of lower amount of martensite and larger amount of bainite, particularly at 1.0 and 5.0°C/s. This difference is confirmed by the hardness results, where a difference of about 60 HV or 7 HRC is observed between both materials.

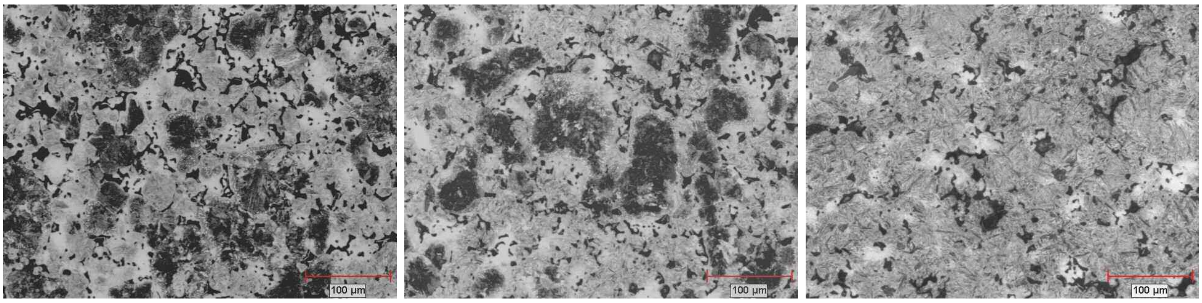
Conclusions

The effect of carbon content and cooling rate on tensile properties and apparent hardness of specimens made with two different diffusion bonded powders containing 4.0%Ni, 1.5% Cu and 0.5%Mo, the latter being pre-alloyed in the melt prior to atomization or diffusion bonded, were investigated. Results showed:

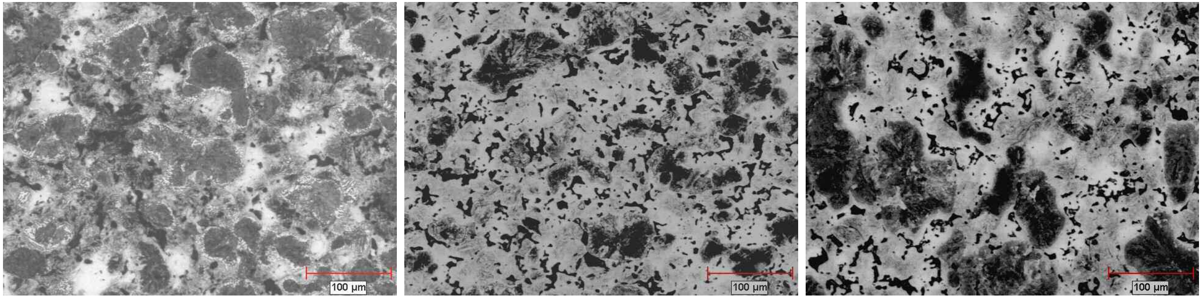
1. Diffusion bonded powder with pre-alloyed molybdenum displayed a homogeneous distribution of this element in the steel particles compared to those where Mo was diffusion bonded. As a result, in the former, Mo was evenly distributed in the steel matrix after sintering, while in the latter, because of the poor diffusion of Mo, many areas without Mo were found.
2. The distribution of Cu and Ni in the steel matrix was similar for both materials.
3. Higher apparent hardness, particularly at higher carbon content and faster cooling rate was observed in specimens made with diffusion-bonded powder containing pre-alloyed Mo. This was related to a larger quantity of martensite in this material compared to the material

with diffusion bonded Mo. This would make the former material more appropriate for sinter hardening applications.

4. For cooling rates of 0.6 and 1.0°C/s, specimens pressed with both types of diffusion-bonded powders showed similar UTS, with maximum values achieved at about 0.55%C.
5. Prealloyed Mo achieved higher yield strength than diffusion alloyed Mo for carbon content and cooling rate up to 0.55% and 1.0°C/s, respectively. For carbon concentration of 0.75% and cooling rate of either 1.0 or 5.0°C/s, diffusion alloying Mo showed better yield strength.
6. Diffusion alloying of Mo achieved better elongation values than pre-alloyed Mo because of the larger quantity of soft phases in the former material.



Material A, 0.75%C; 0.6°C/s **Material A, 0.75%C; 1.0°C/s** **Material A, 0.75%C; 5.0°C/s**



Material B, 0.75%C; 0.6°C/s **Material B, 0.75%C; 1.0°C/s** **Material B, 0.75%C; 5.0°C/s**

Figure 5. Microstructure of materials A and B containing 0.75%C and cooled at 0.6 and 1.0 and 5.0°C/s (Nital etched, 200X).

References

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