EFFECT OF CARBON CONTENT AND POST-SINTERING COOLING RATE ON MECHANICAL PROPERTIES OF HIGH DENSITY SINTERED MATERIALS MADE FROM DIFFUSION-BONDED POWDERS

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ABSTRACT

Diffusion-bonded powders based on the Fe-Cu-Ni-Mo system are well known in the P/M industry for combining good compressibility and dimensional stability with a potential for high strength. The typical heterogeneous microstructure of these materials has proven to provide favourable mechanical properties. However, in applications where strength and hardness become critical variables, faster cooling rates after sintering are required to meet application requirements.

Test specimens containing various graphite contents to achieve 0.20, 0.35 and 0.55 % combined carbon were pressed to 7.0 and 7.2 g/cm^3, sintered in a production belt furnace at 1120^{o}C and cooled directly from sintering temperature with either normal or rapid cooling. Test results are discussed in terms of tensile properties, apparent hardness and microstructure.

The formation of bainite and martensite by raising carbon content and cooling rate increased tensile strength and apparent hardness, while a higher green density maintained satisfactory ductility. It was possible to achieve ultimate tensile and yield strengths as high as 915 and 665 MPa respectively with apparent hardness of 30 HRC.

INTRODUCTION

Diffusion alloy steels generally develop a complex microstructure during sintering due to Ni-rich phases. By selecting good combinations of carbon content, cooling rate and green density, it is possible to obtain mixtures of constituents that yield desirable mechanical properties.

Increasing the carbon content and the cooling rate may significantly enhance tensile strength and apparent hardness by the formation of hard microconstituents such as martensite and bainite [1-3]. The bainitic structure also becomes finer as the cooling rate increases [3]. However, it was admitted that the improvement in tensile strength mostly occurs in a certain range of carbon and the optimal concentration of this element strongly depends on the type of treatment applied (as-sintered, heat-treated with tempering or not, etc.) [2,4-6]. Khaleghi and Bertilsson also found that an increase of density significantly raises both, tensile strength and ductility [7,8]. Bertilsson reported that the strength increases almost linearly with density, whereas the relative gain in elongation is more pronounced at higher densities (7.4-7.8 g/cm^3). Chagnon also demonstrated that the sintered density primarily affects fatigue resistance and elongation with a lesser effect on tensile strength [9]. Most studies reported in the literature relate the increase of strength with density to the reduction of porosity rather than a change of microstructure. However, according to Tunstall, reducing the porosity promotes the heterogeneity of chemical composition, which represents unfavourable conditions for enhancing the tensile strength [10]. A possible explanation of this behavior is that the solute elements will disperse more rapidly via the pore surfaces during sintering since the kinetic of surface diffusion is much higher than that of volume diffusion.

The objective of this study is to evaluate the effect of carbon content (0.20, 0.35 and 0.55 %) and cooling rate on tensile and apparent hardness properties of a diffusion-bonded powder (Fe-4.0Ni-1.5Cu-0.5Mo) at 7.0 and 7.2 g/cm^3 sintered under industrial conditions. The microstructure and pore characteristics (porosity, shape, size) were examined and related to these mechanical properties. The formation mechanism of microstructural features (microconstituents and pores) will be discussed in terms of mechanical properties of the diffusion-bonded material.

EXPERIMENTAL PROCEDURE

The test material was ATOMET DB48, a Fe-4.0Ni-1.5Cu-0.5Mo diffusion-bonded powder. This powder was mixed with 0.75 % zinc stearate and various graphite contents to achieve 0.20, 0.35 and 0.55 % combined carbon. Regular “dog-bone” specimens were pressed to green densities of 7.0 and 7.2 g/cm^3. Sintering was carried out in a production belt furnace kept under a $95N_2$-$5H_2$ atmosphere at 1120^{o}C for 30 minutes. The specimens were cooled at either normal (1.0^{o}C/s) or fast (3.5^{o}C/s) cooling rate from 900 to 400^{o}C.

Tensile properties and apparent hardness were determined according to MPIF standards 10 and 43 respectively. The microstructure of specimens, previously etched with a solution containing 4 % Picral and 2 % Nital, was analyzed using an optical microscope and a Scanning Electron Microscope (JEOL JSM-5800) coupled with an Energy Dispersive Spectroscopy analyzer (EDS). The pore characteristics (porosity, shape and size) and the percentage of microstructural constituents were determined using a Clemex 640 image analyzer according to a procedure described elsewhere [11]. The pore shape was evaluated by eliminating pores smaller than 10 μm in length since these were mostly round. The magnification was kept constant at 200X for all analyses.

RESULTS

Tensile Strength

Figures 1 and 2 illustrate the effect of carbon content and cooling rate on ultimate tensile strength (UTS) and yield strength (YS) of as-sintered specimens pressed to 7.0 and 7.2 g/cm^3. As shown in Figure 1, UTS significantly increases by raising the carbon content and green density to reach a maximum at 0.35 % C at either 7.0 or 7.2 g/cm^3. Beyond 0.35 % C, UTS tends to decrease and this is even more evident when using a fast cooling rate. Consequently the gain in UTS by raising the cooling rate is much more pronounced with specimens containing a moderate carbon content of 0.35 %. This property significantly increases to reach 795 and 920 MPa for fast cooled specimens pressed to 7.0 and 7.2 g/cm^3 respectively, while it changes only slightly at 0.55 % C because of the presence of untempered martensite.

As illustrated in Figure 2, YS significantly increases with the carbon content from 0.20 to 0.55 %. YS also increases with cooling rate and green density. Also, this property tends to reach a plateau as a function of the carbon content with a fast cooling rate, but it is still likely that an increase of the cooling rate more positively affects this property as the carbon content increases, particularly at 7.2 g/cm^3. The YS improves by 70 MPa to attain 700 MPa by raising the cooling rate for specimens containing 0.55 % C at 7.2 g/cm^3, while it only slightly increases by 24 MPa at 0.20 % C.

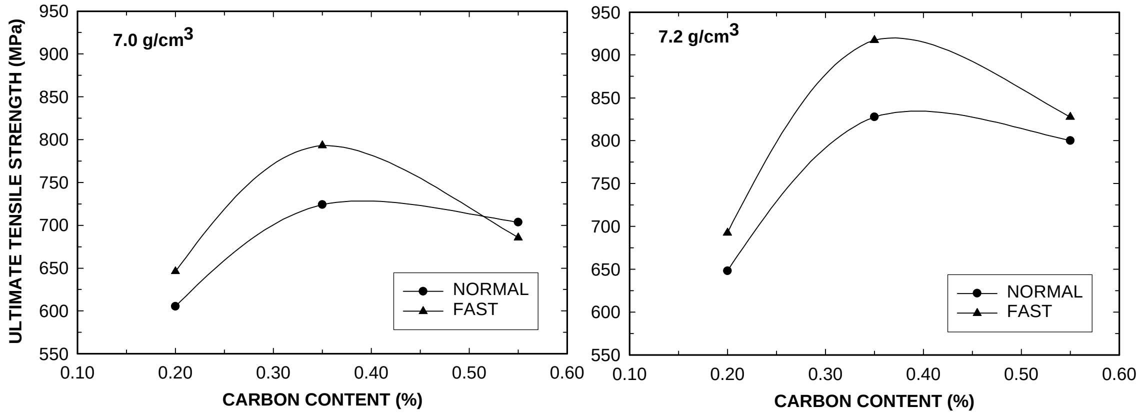


Figure 1. Effect of Carbon Content and Cooling Rate on UTS of As-Sintered Specimens Pressed to 7.0 and 7.2 g/cm^3.

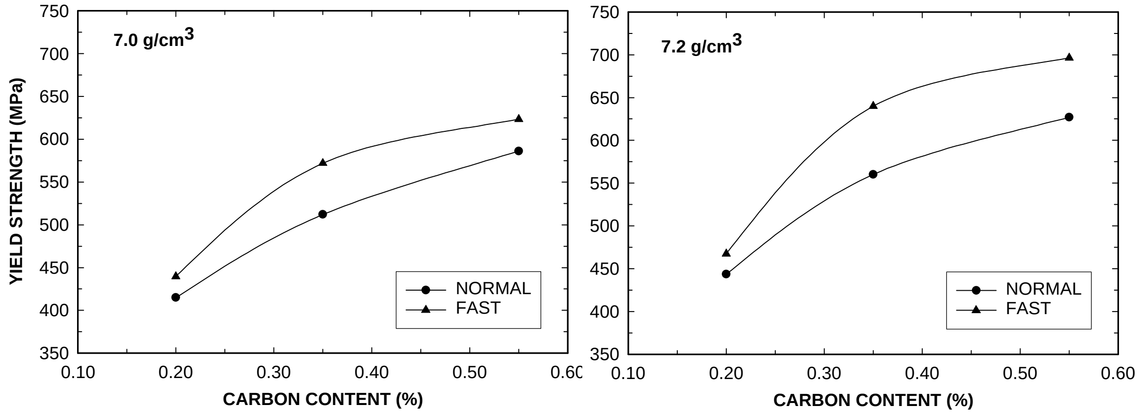


Figure 2. Effect of Carbon Content and Cooling Rate on Yield Strength of As-Sintered Specimens Pressed to 7.0 and 7.2 g/cm^3.

Apparent Hardness and Elongation

Figure 3 shows the effect of carbon content and cooling rate on apparent hardness of as-sintered specimens pressed to 7.0 and 7.2 g/cm^3. As for strength, apparent hardness noticeably increases with carbon content,

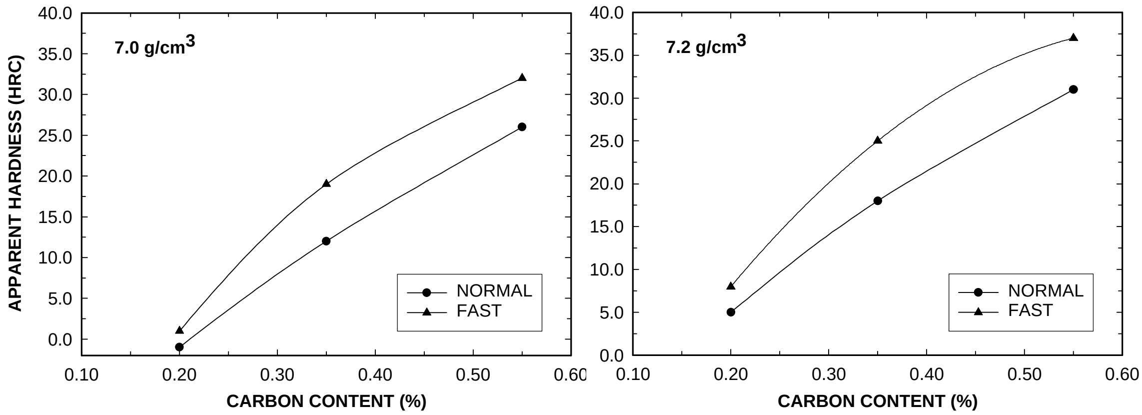


Figure 3. Effect of Carbon Content and Cooling Rate on Apparent Hardness of As-Sintered Specimens Pressed to 7.0 and 7.2 g/cm^3.

cooling rate and green density. Also, it is noteworthy the more pronounced effect of the cooling rate as the carbon content increases for both green densities. For instance, the apparent hardness only slightly increases by 3 HRC at 0.20 % C and 7.2 g/cm^3, while it increases by 6 HRC to reach 37 HRC at 0.55 % C, making this material suitable for sinter hardening applications.

On the other hand, it was observed that increasing the apparent hardness by raising the carbon content and cooling rate also tends to reduce the elongation (Figure 4). The detrimental effect of the cooling rate on elongation is even more pronounced at higher carbon contents. However, it is worth noting that the higher apparent hardness obtained by raising the green density only slightly affects the ductility. This property is still increased with the green density, particularly at 0.20 % C. The more beneficial effect of density at 0.20 % C is probably due to a lower amount of untempered martensite at this relatively low carbon content.

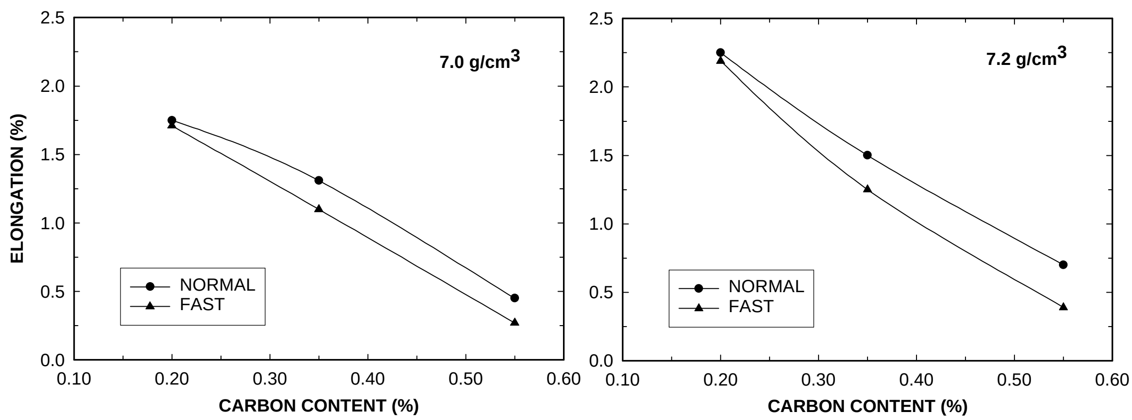


Figure 4. Effect of Carbon Content and Cooling Rate on Elongation of As-Sintered Specimens Pressed to 7.0 and 7.2 g/cm^3.

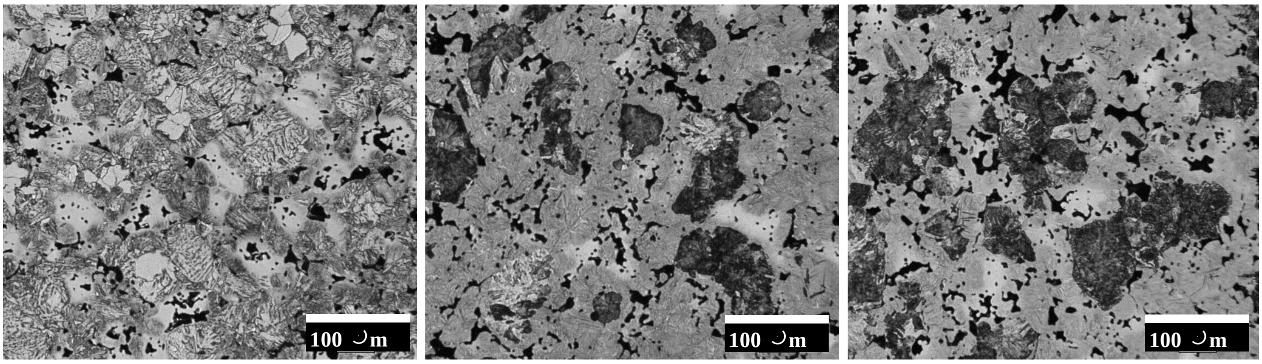
DISCUSSION

Applications requiring high strength and apparent hardness but where elongation is not a requirement, can be met by controlling the carbon content, cooling rate and green density of parts made from a diffusion-bonded powder (Fe-4.0Ni-1.5Cu-0.5Mo). These parameters are critical to reach desired microstructures and pore characteristics to optimize these properties. Indeed, the diffusion-bonded material is generally characterized by a very heterogeneous microstructure (ferrite, Ni-rich γ, nodular/divorced/fine pearlite, bainite, martensite), which strongly depends on the carbon content, the distribution of nickel and cooling rate [1-3].

This study demonstrated that tensile strength and apparent hardness of as-sintered specimens are significantly improved with carbon content, cooling rate and green density, while the ductility increases by raising green density. For instance, at a green density of 7.2 g/cm^3, UTS,YS and apparent hardness as high as 920 MPa, 650 MPa and 25 HRC respectively combined with an elongation value of more than 1.0 % can be achieved with specimens containing 0.35 % C fast cooled after sintering.

The increase in tensile strength and apparent hardness by raising the carbon content and increasing the cooling rate at a density of 7.2 g/cm^3 is directly related to the formation of hard microconstituents including martensite and bainite since the pore characteristics (porosity, shape and size) remained the same, which is consistent with a previous study [2]. As illustrated in Figures 5a and 5b, the proportion of martensite and bainite significantly increases by raising the carbon content from 0.20 to 0.55 %. Only a few islands of pearlite appear in specimens containing 0.55 % C. These hard phases are mainly formed at the expense of softer microconstituents such as ferrite, Ni-rich regions and divorced pearlite. The CT-diagram strongly suggests that these phases can be formed in typical regions containing 0.55 % C and 2.0 % Ni whatever the cooling rate used (Figure 6). Also, it can be seen that the amount of martensite noticeably increases to the detriment of bainite by raising the cooling rate (Figures 5b, 5c and 6). The Ni-rich regions remained the same (7 %) whatever the cooling rate, which is in agreement with a previous study [3]. The percentage of martensite increased from 50 to 65 % by using a fast cooling rate at 0.55 % C, while the bainite decreased from 32 to 17 %.

On the other hand, the elongation is also reduced with the formation of martensite and bainite as a function of carbon content and cooling rate. Moreover, UTS reached an optimum at 0.35 % C for the same reason, regardless the cooling rate and green density used. Surprisingly, the formation of these phases only had a slight negative effect on YS. Indeed, YS increases by raising the carbon content up to 0.55 % with a normal cooling rate, while it only tends to reach a plateau from 0.35 to 0.55 % C when using a faster cooling rate. It is worth mentioning that the improvement in tensile properties at high carbon contents would still be possible by releasing stress in martensite with a tempering treatment [2].



a) 0.20%C - fast cooling rate **b) 0.55%C - fast cooling rate** **c) 0.55%C - normal cooling rate**

Figure 5. Microstructure Obtained as a Function of the Carbon Content and Cooling Rate at 7.2 g/cm^3.

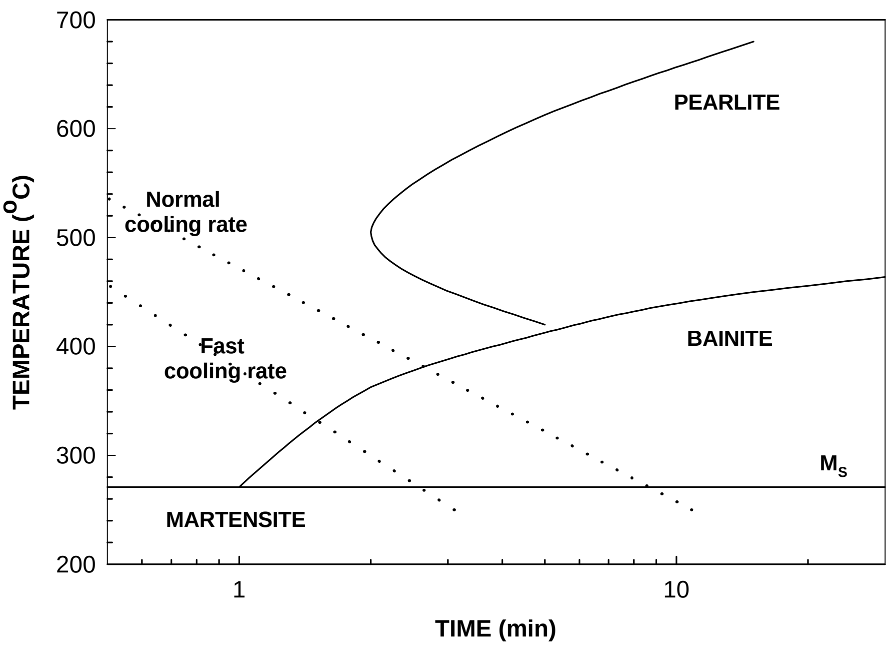


Figure 6. CT-Diagram of Typical Regions Containing 0.55 % C, 2.0 % Ni, 1.5 % Cu and 0.5 % Mo.

<u>CONCLUSIONS</u>

The effect of carbon content and cooling rate on tensile properties and apparent hardness was investigated for as-sintered specimens made from diffusion-bonded powder pressed to 7.0 and 7.2 g/cm^3. The results of the investigations suggest the following conclusions:

- Tensile strength and apparent hardness increased with carbon content, cooling rate and green density. The effect of cooling rate on YS and apparent hardness was even more pronounced as the carbon content increases. These improvements were directly related to the formation of hard microconstituents (martensite, bainite) along with carbon content and cooling rate and also to densification by raising the green density.

- The formation of a martensitic rich microstructure also reduced tensile strength within a given range of carbon content. The UTS reached an optimum at 0.35 % C, while YS tended to reach a plateau, particularly with a fast cooling rate. The elongation also decreased with martensite as a function of carbon and cooling rate. However, an increase in densification by raising the green density did not attenuate the detrimental effect of this microconstituent on ductility. A tempering treatment would probably improve tensile properties at high carbon contents by releasing stress in martensite.

- If the tempering treatment is avoided, the optimum carbon content required to balance tensile strength, apparent hardness and ductility would be in the range of 0.35 to 0.45 % C. For mixes pressed to 7.2 g/cm^3, UTS, YS and apparent hardness as high as 915 MPa, 665 MPa and 30 HRC respectively would be attained for specimens rapidly cooled after sintering.

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