EFFECT OF SINTERING TEMPERATURE AND CARBON CONTENT ON STATIC AND DYNAMIC PROPERTIES OF DIFFUSION-BONDED STEELS

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ABSTRACT

P/M parts made from diffusion-bonded powders usually exhibit high static and dynamic properties. The dynamic properties are mainly controlled by the presence of nickel-rich areas and possibly by the amount of retained austenite dispersed throughout the martensite as well as the type of martensite present in the microstructure. The presence of these microconstituents in the final microstructure primarily depends on the sintering temperature, which controls the mass transport mechanisms, as well as the carbon content and cooling rate after sintering.

The objective of this study was to evaluate the effect of nickel diffusion at 1120 and 1280°C and combined carbon contents ranging from 0.5 to 1.0 wt% on the microstructure of specimens made from a diffusion-bonded powder (*Fe-0.5Mo-4.0Ni-1.5Cu*) to optimize tensile, apparent hardness, impact and fatigue properties. To differentiate the effect of the cooling rate from that of the degree of diffusion of alloying elements, the former was closely controlled to prevent undue variation in microstructure and mechanical properties between treatments. Optical metallography and SEM-EDS were used to characterize the microstructures and the distribution of alloying elements. The proportion of microstructural constituents and pore characteristics (size and shape) were determined by image analysis, while the proportion of retained austenite was assessed by XRD examination. A sub-zero treatment was also carried out to evaluate the effect of retained austenite dispersed throughout the martensite on the fatigue strength and sintered density. Additionally, a dilatometric study was used to determine the densification process of specimens as a function of the carbon content.

Results reported in this study demonstrated that the sintering at 1280°C of the diffusion-bonded material containing 0.75 wt% combined carbon results in higher static and dynamic properties, while maintaining higher ductility and impact strength than a 0.5 wt% C material sintered at 1120°C. In particular, these conditions favored the formation of hard microconstituents such as a mixture of lath and plate martensite as well as some bainite that harden and strengthen specimens in static loading at 7.0 g/cm^3. The apparent hardness, YS and UTS achieved 41 HRC, 776 MPa and 1085 MPa respectively. Additionally, the formation of some plate martensite by raising the carbon content from 0.5 to 0.75 wt% at 1280°C was effective in improving the fatigue strength. The fatigue strength increased by 19 % to reach 282 MPa in these conditions. The retained austenite dispersed throughout martensite did not contribute to improve this property.

INTRODUCTION

P/M parts made from diffusion-bonded powders are characterized by a heterogeneous microstructure that promotes high tensile properties and fatigue strength. Several studies have shown that fatigue strength is primarily controlled by the nickel-rich regions, which limit crack propagation when P/M parts are submitted to stress cycles. In particular, several authors have demonstrated that the use of high temperature sintering (HTS) significantly deteriorates the fatigue strength of diffusion-bonded specimens containing 0.35 to 0.55 wt% combined carbon mainly due to a decrease of nickel-rich γ regions in the microstructure.(1,2,3) Pore rounding and densification resulting from this treatment were not predominant factors in affecting the fatigue strength of these materials.

However, only a few studies have evaluated the effect of HTS on tensile properties and fatigue strength of diffusion-bonded materials with carbon levels above 0.55 wt%, i.e. in conditions where the Ni-rich γ regions decrease and the formation of hard microconstituents (martensite and bainite) together with some retained austenite dispersed throughout martensite are promoted.(4) Also, as carbon content increases, the type of martensite is changed from lath below 0.6 wt% C to plate above 1.0 wt% C. Between 0.6 and 1.0 wt% C there is a mixture of both lath and plate martensite.

The presence of hard microconstituents resulting from HTS represents a good avenue to harden and strengthen P/M parts without the use of a heat treatment. However, the influence of retained austenite on the fatigue behavior of steel has been a controversial subject over the past few decades. Some authors have suggested that the transformation of retained austenite into brittle martensite under certain stress cycles accelerates crack propagation and decreases the fatigue resistance.(5) Others proposed that the strain induced by this transformation increases this property.(6,7,8) Also, a significant change in size has already been noticed for FC-0208 specimens frozen at a temperature of -40°C.(9) Because retained austenite is a metastable microconstituent that transforms into martensite within a certain range of temperatures (M_s-M_f), this transformation may create undesirable growth of parts when in service.

The purpose of the present study was to determine the influence of the carbon concentrations in diffusion-bonded materials sintered at 1120°C and 1280°C and cooled at the same rate, on microstructure and pore characteristics, in order to optimize static and dynamic properties. In addition, the effect of retained austenite on fatigue strength, sintered density and size change of tempered specimens in freezing temperatures was determined by a sub-zero cryogenic treatment.

EXPERIMENTAL PROCEDURE

Material and test specimens preparation

The test material was ATOMET DB48, a Fe-0.5Mo-4.0Ni-1.5Cu diffusion-bonded powder. This powder was mixed with 0.75 wt% zinc stearate and various graphite levels to achieve 0.5, 0.75 and 1.0 wt% of combined carbon. Tensile, Charpy and fatigue specimens were pressed to a green density of 7.0 g/cm^3. Dogbone specimens were used for tensile testing as per MPIF standard 10. Charpy and fatigue specimens were machined from sintered bars to the shape and dimensions reported in MPIF standards 40 and 56 respectively.

Sintering was conducted at 1120 and 1280°C for 45 minutes in a production size vacuum furnace (24x36x48 in) with a 6 bar overpressure cooling system to closely control the cooling rate after sintering. Pressurized nitrogen backfill gas was used to accelerate the cooling rate to 0.88°C/s. The specimens were tempered at 190°C for 60 minutes in air.

Sub-zero cryogenic treatment

A few specimens containing 0.75 and 1.0 wt% C sintered at 1280°C were also submitted to a sub-zero cryogenic treatment to determine the effect of the retained austenite dispersed throughout martensite on the fatigue strength. This freezing treatment enables a complete transformation of this microconstituent into martensite without affecting the type of martensite and the percentage of other microconstituents.

It is well known that the level of this transformation strongly depends on the freezing temperature used and also on the composition of specimens. The retained austenite-martensite transformation starts and finishes at M_s and M_f temperatures. These temperatures essentially depend on the carbon content as well as the percentage of alloying elements such as manganese, nickel, molybdenum and copper. The M_s temperature can be estimated according to the following empirical formula: (10)

$$M_s\ (^{o}C) = 512 - (453 \times \%C) - (16.9 \times \%Ni) - (8.45 \times \%Cu) - (9.5 \times \%Mo) + (217 \times \%C^2) - (71.5 \times \%C \times \%Mn) \quad (1)$$

whereas M_f temperature, which represents 99 % retained austenite-martensite transformation, is derived from(11) :

$$f = 1 - \exp - [1.10 \times 10^{-2} (M_s - M_f)] \quad (2)$$

$$M_f\ (^{o}C) = M_s\ (^{o}C) - 419 \quad (3)$$

where f is the volume fraction of martensite. Therefore, it is assumed that about 98 to 99 % retained austenite transforms into martensite at a temperature of around -196°C for Fe-0.5Mo-4.0Ni-1.5Cu diffusion-bonded materials containing 0.75 and 1.0 wt% C. Hence, in order to ensure a complete transformation of retained austenite into martensite of these specimens, a sub-zero cryogenic treatment was performed within 4 days following the sintering cycle using a one hour exposure to liquid nitrogen in order to attain -196°C. The specimens were also tempered at 190°C for 60 minutes in air to stress relief the martensite.

The effect of retained austenite on fatigue strength and sintered density was determined by comparing specimens submitted to the sub-zero cryogenic treatment and tempered specimens. The influence of this microconstituent on sintered density at a freezing temperature of -40°C was also estimated based on results obtained at -196°C.

Dilatometric study

The dimensional change of 15x4x4 mm specimens containing 0.5 and 1.0 wt% C at 1280°C was investigated using a Linseis L-75 absolute-differential dilatometer. This study was carried out under a $95N_2$-$5H_2$ atmosphere. The sintering cycle was the same as that used to sinter specimens in the vacuum furnace.

Tensile, hardness, impact and fatigue testing

Tensile, impact and fatigue properties were performed using an Instron, Charpy and four R.R. Moore style Rotating Bending Fatigue (RBF) machines respectively. Tensile properties, apparent hardness, impact energy and sintered density were determined according to MPIF standards 10, 43, 40, 42 respectively. The fatigue tests were conducted at room temperature according to the procedure described in MPIF Standard 56 and ASTM E 468. The fatigue machine was set to apply a high cycle fatigue loading using a constant force sinusoidal waveform at 10,000 cycles per minute, fully reversed. A run out test was established to be at 10 million cycles. Testing was performed on 12 test specimens for each condition. The data analysis was completed following the statistical method described in MPIF standard 56 to determine the 90 % fatigue survival strength.

Microstructural characterization

The microstructure was characterized using an optical microscope and a Scanning Electron Microscope (SEM / JEOL JSM-5800) coupled with an Energy Dispersive Spectroscopy analyzer (EDS) after etching specimens in a solution containing 2 % Nital. The SEM analysis was used to determine the distribution of alloying elements (Ni/Cu) in the microstructure, to reveal the type of martensite (lath, plate) and also to differentiate bainite and pearlite.

The percentage of microstructural constituents and pore characteristics (shape and size) were also estimated by using a Clemex 640 image analyzer. The magnification was kept constant at 200X for these analyses. The amount of microconstituents was determined by analyzing an average of 15 fields of $1.66x10^5$ µm^2 chosen randomly in such a way as to cover (1x1) cm^2 of the surface area. The main microconstituents were regrouped based on their optical white and gray color tones in order to accurately measure their percentage (Table 1).

TABLE 1
Group of Main Phases Characterizing the Microstructure of Fe-0.5Mo-4.0Ni-1.5Cu Diffusion-Bonded Materials

Group	Color	Phase
I	Dark	Pore, Nodular pearlite*, Bainite
II	Light and dark gray	Martensite
III	White	Ni-rich γ, Retained γ**

* dispersed throughout martensite
** fine pearlite in formation

The percentage of bainite was estimated based on an SEM analysis, while the amount of nodular pearlite was determined by subtracting the percentage of pores and bainite. The nodular pearlite refers to fine pearlite in formation. The amount of Ni-rich γ and retained γ dispersed throughout martensite was also measured by using the image analyzer. These microconstituents were qualitatively differentiated by measuring their percentage in nickel using an SEM analysis. Also, the amount of retained γ dispersed throughout the martensite was assessed by performing an X-ray diffraction analysis.

The pore characteristics were determined by scanning 150 field areas ($1.66x10^5$ µm^2) of a polished specimen for a total of $2.49x10^8$ µm^2. The pore size was evaluated according to the

$$\text{P.S.F.} = \frac{4p\ \text{A}}{\text{P}^2} \tag{4}$$

length of pores. The pore shape was assessed according to the following Pore Shape Factor (P.S.F.) formula:

where A is the area of pores and P, the perimeter. A perfect circular pore has a shape factor of one. The P.S.F. did not consider pores smaller than 5 μm since they were mostly round.

RESULTS AND DISCUSSION

STATIC AND DYNAMIC PROPERTIES

Effect of carbon content and sintering temperature

The yield strength (YS) and ultimate tensile strength (UTS) of diffusion-bonded materials sintered at 1120 and 1280^{o}C are illustrated in Figures 1 and 2 as a function of the carbon content.

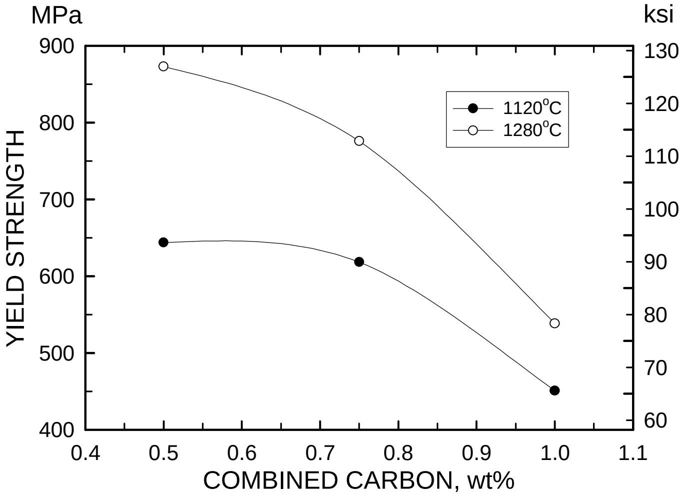


Figure 1. Effect of Carbon Content and Sintering Temperature on Yield Strength.

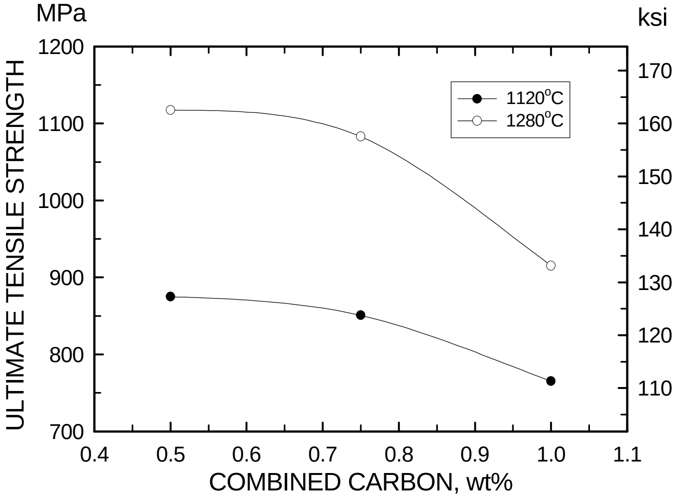


Figure 2. Effect of Carbon Content and Sintering Temperature on Ultimate Tensile Strength.

It is seen that YS and UTS significantly decline by raising the carbon content from 0.5 to 1.0 wt% for both sintering temperatures. At 1120^{o}C, this deterioration is mainly due to a decrease in the amount of martensite to the benefit of retained austenite and coarse pearlite (Figures 3 and 4). An increase of the amount of carbon dissolved in iron particles increases the shear resistance of austenite, which limits its transformation into martensite when cooled to room temperature. The percentage of martensite significantly decreases from 78 to 44 % by raising the carbon content from 0.5 to 1.0 wt% C (Figure 3). Also, it is likely that the use of a high carbon level limits the diffusion of the alloying elements and this favors, as shown in Figure 4, the formation of coarse nodular pearlitic regions rich in carbon and surrounded by a few nickel and copper austenitic regions dispersed throughout the martensite. A SEM-EDS mapping revealed that the nickel rich regions are also rich in copper.

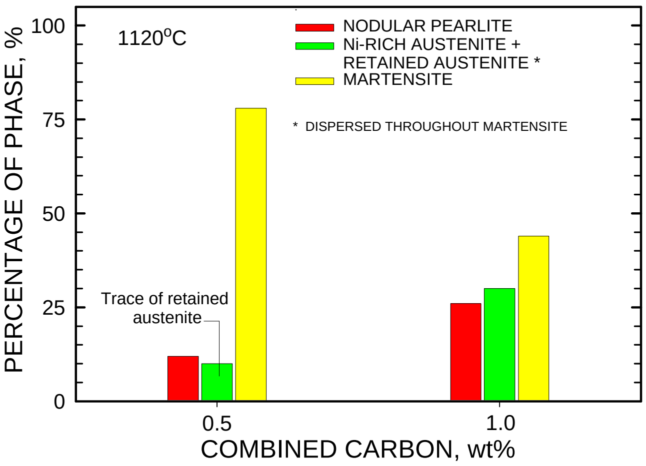
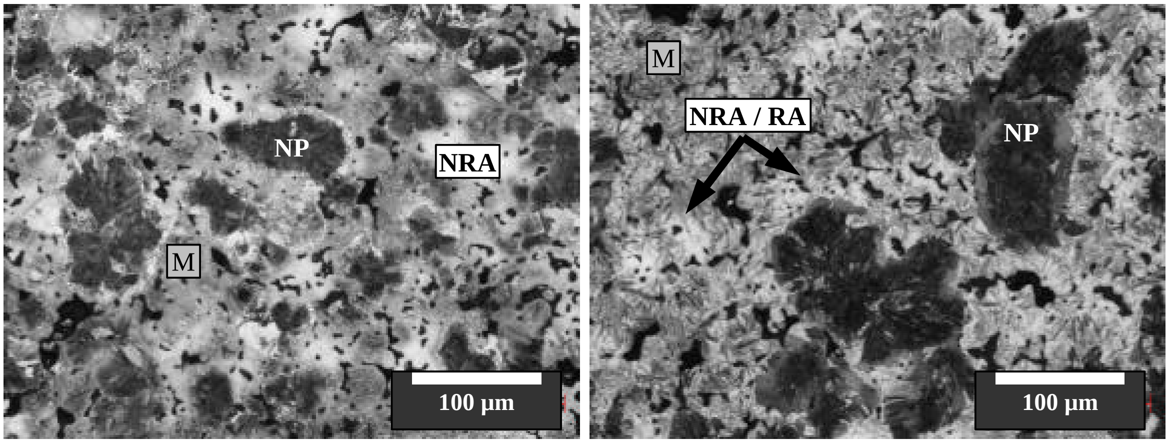


Figure 3. Percentage of Phases as a Function of Carbon Content for Specimens Sintered at 1120 °C.



0.5 wt% C

1.0 wt% C

Figure 4. Microstructure as a Function of the Carbon Content for Specimens Sintered at 1120 °C. (NP: nodular pearlite, NRA: Ni-rich γ, RA: retained γ, M: martensite)

A significant decrease in the amount of martensite is also noticed in specimens sintered at 1280°C, when raising the carbon content (Figures 5 and 6). The percentage of martensite decreases from 98 to 87 % by raising the carbon content from 0.5 to 1.0 wt% C. However, it is seen that the martensite only decreases to the benefit of retained austenite. It is believed that the diffusion of carbon and alloying elements was sufficiently high to

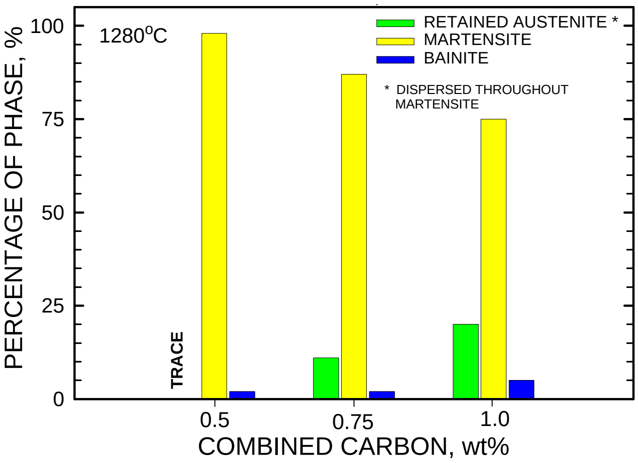
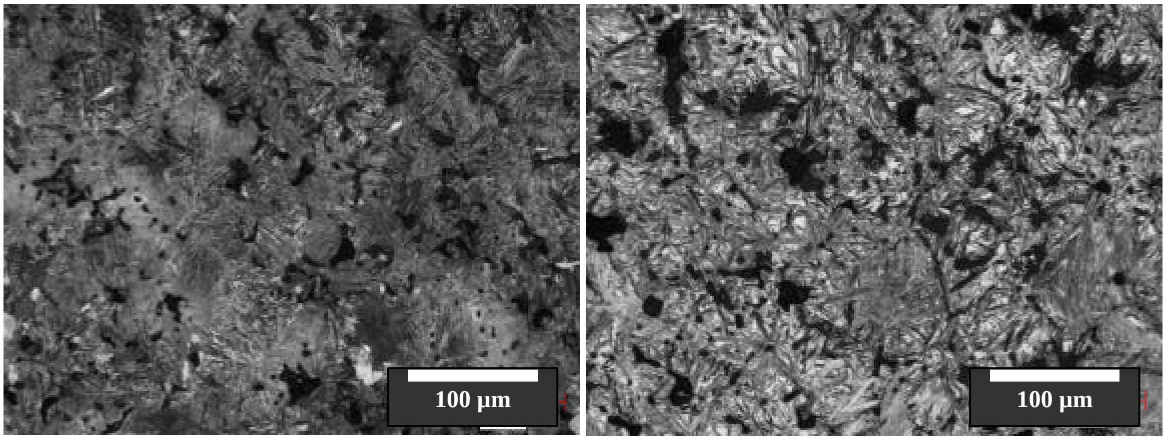


Figure 5. Percentage of Phases as a Function of Carbon Content for Specimens Sintered at 1280 °C.

prevent the formation of nodular pearlite at this sintering temperature.



0.5 wt% C 1.0 wt% C

Figure 6. Microstructure as a Function of Carbon Content for Specimens Sintered at 1280^{o}C.

However, it should be emphasized that YS and UTS achieved at high temperature is still noticeably higher than that obtained at 1120^{o}C whatever the carbon content in diffusion-bonded materials. In particular, it can be seen that relatively high YS and UTS are achieved even for materials containing a high carbon level of 0.75 wt% at 1280^{o}C. Indeed, these properties reach 776 MPa and 1085 MPa respectively, which is about 20 and 24 % higher than those attained at 0.5 wt% C and 1120^{o}C. As shown in Figures 3 and 5, this is mainly due to a more active diffusion of carbon and alloying elements (Cu/Ni) at 1280^{o}C leading to the formation of a larger amount of martensite than in specimens sintered at 1120^{o}C. This hard microconstituent was mainly formed at the expense of softer microconstituents such as nodular pearlite and Ni-rich γ regions.

Therefore, the use of high carbon levels can still achieve high YS and UTS when sintering diffusion-bonded materials at high temperature. This presents a real advantage for improving properties such as the apparent hardness, sintered density and fatigue resistance. In particular, the apparent hardness increases from 17 to 41 HRC by raising the carbon content from 0.5 to 0.75 wt% and the sintering temperature from 1120 to 1280^{o}C (Figure 7). A further rise in carbon content to 1.0 wt% does not significantly improve apparent hardness.

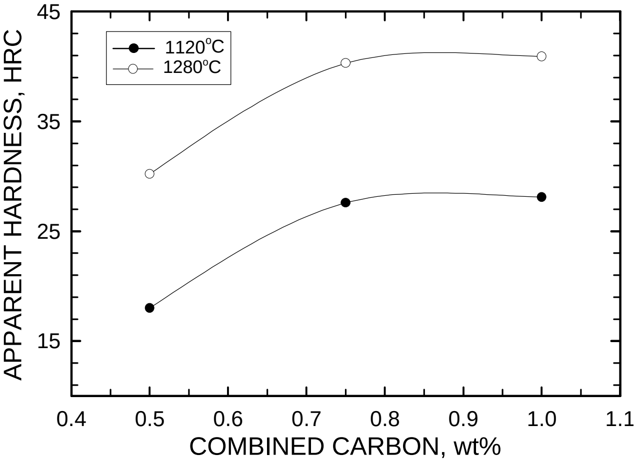
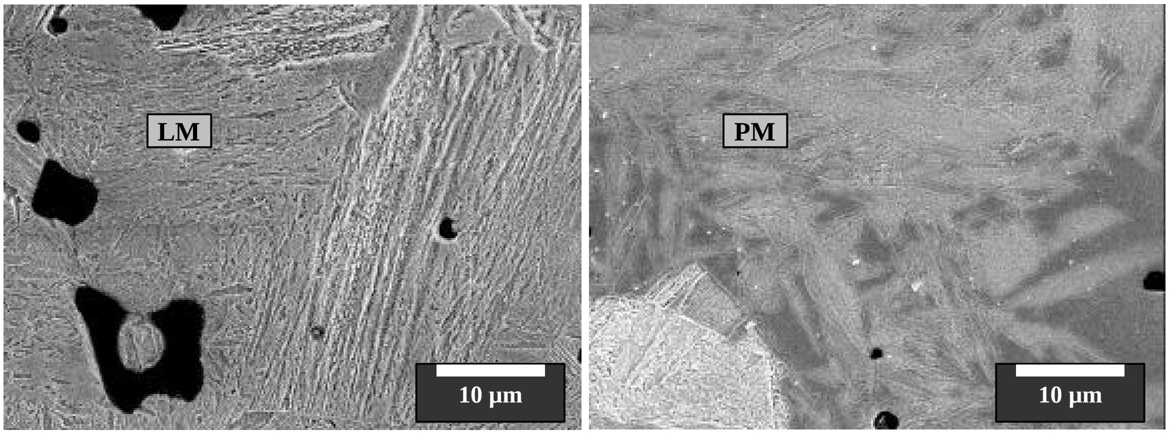


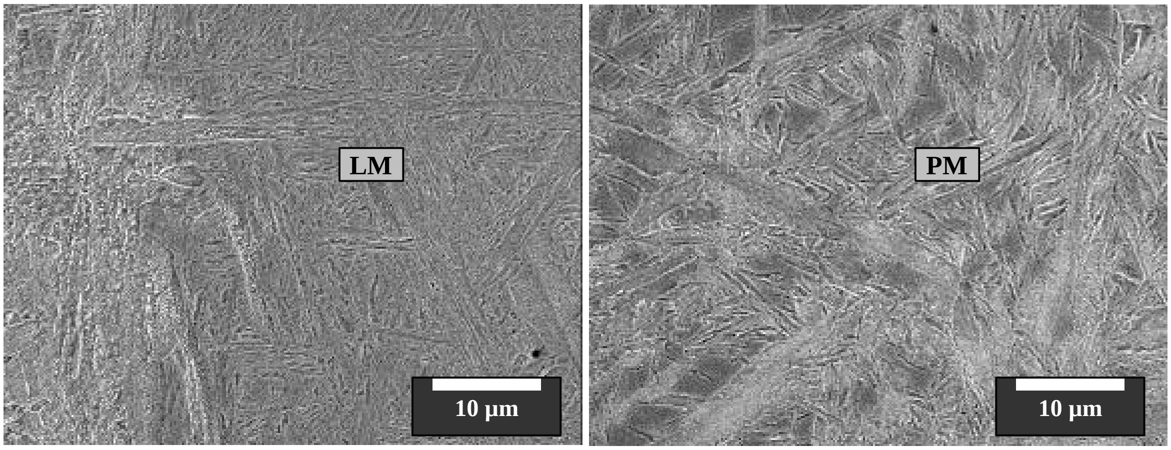
Figure 7. Effect of Carbon Content and Sintering Temperature on Apparent Hardness.

Thus, it is likely that a decrease in the amount of martensite by raising the carbon content did not negatively affect the apparent hardness. In contrast, this property significantly improves at both sintering temperatures. This is mainly due to a change in the type of martensite as a function of the carbon content. Lath and plate type structures are predominately formed at 0.5 and 1.0 wt% C respectively (Figures 8 and 9). The plate martensite formed at 1.0 wt% C contains a higher carbon content and is much harder than the lath martensite formed at 0.5 wt% C.



0.5 wt% C 1.0 wt% C

Figure 8. SEM Analysis Revealing the Type of Martensite as a Function of Carbon Content for Specimens Sintered at 1120 °C. (LM: lath martensite, PM: plate martensite)

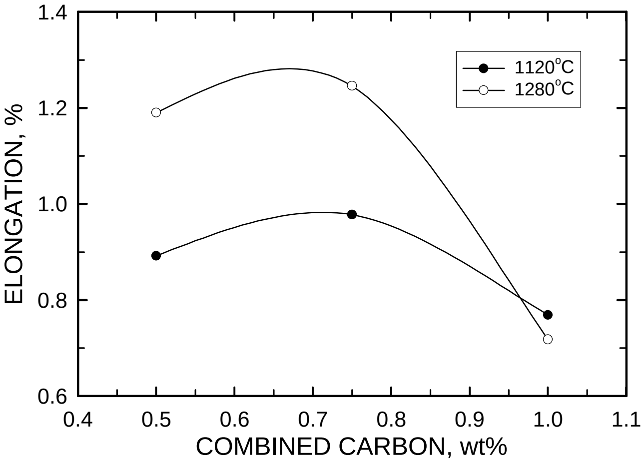


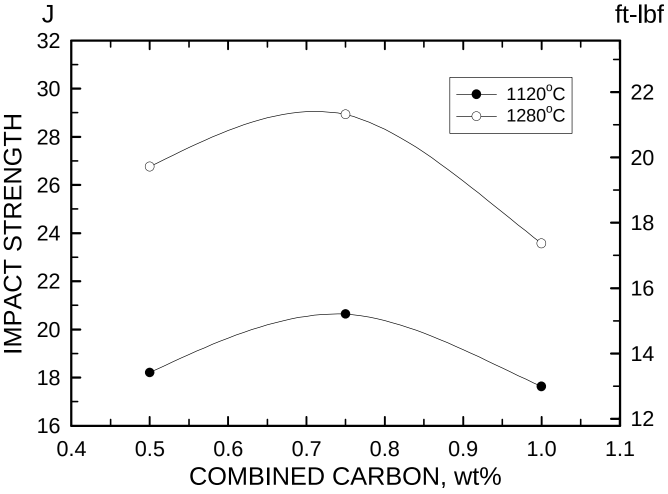
0.5 wt% C 1.0 wt% C

Figure 9. SEM Analysis Revealing the Type of Martensite as a Function of Carbon Content for Specimens Sintered at 1280°C. (LM: lath martensite, PM: plate martensite)

It is worth mentioning that the increase in apparent hardness achieved by raising the carbon content also leads to a significant decrease in elongation and impact strength and this is even more pronounced at 1280°C (Figures 10 and 11). Hence, the plate martensite formed at 1.0 wt% C contributes to enhance the apparent hardness, but also significantly reduces ductility and toughness of specimens. However, it appears that the elongation of specimens containing 0.75 wt% C at 1280°C is still significantly higher than that obtained at 0.5 wt% C and 1120°C. The impact strength at 1280°C is also noticeably higher whatever the carbon content added in diffusion-bonded materials. For instance, elongation and impact strength reach 1.25 % and 29 J respectively at 0.75 wt% C and 1280°C, which is about 40 and 50 % higher than those obtained at 0.5 wt% C and 1120°C.

A large densification of diffusion-bonded specimens also occurs by raising the carbon content from 0.5 to 1.0 wt% C at 1280°C. The sintered density increases from 7.0 to attain 7.25 g/cm^3, which represents a significant gain of 0.31 g/cm^3 as compared to specimens containing 0.5 wt% C sintered at 1120°C (Figure 12).





Temperature on Elongation.

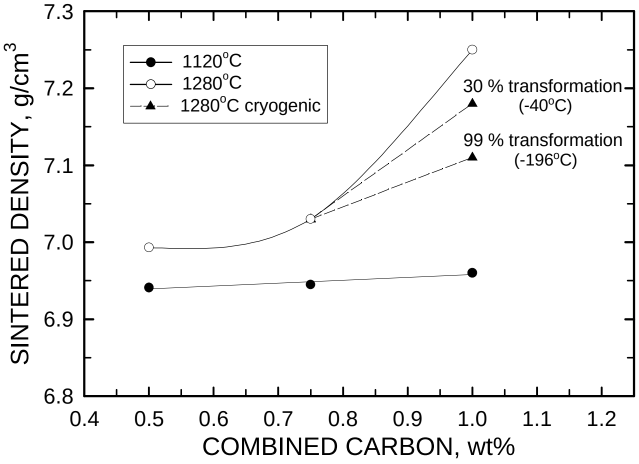


Figure 12. Effect of Carbon Content, Sintering Temperature and the Sub-zero Cryogenic Treatment

This is directly related to the formation of retained austenite at the expense of martensite and also to a rise of the self-diffusion rate of the iron atoms as the carbon content increases. It is well known that the volume occupied by the retained austenite is significantly lower than that of martensite. In particular, it can be seen in Figure 12 that if 99 % of the retained austenite formed in specimens containing 1.0 wt% C is transformed into martensite with the use of a sub-zero cryogenic treatment, the sintered density noticeably decreases from 7.25 to 7.1 g/cm^3. Additionally, the dilatometric curves reported in Figure 13 clearly show that the densification rate of specimens in the gamma phase is significantly increased by raising the carbon content from 0.5 to 1.0 wt% at 1280°C. The self-diffusion rate of the γ-Fe atoms probably increases as the carbon content increases, which leads to a better densification of specimens.

However, it is worth mentioning that there is a maximum carbon content required in order to prevent any size change of parts exposed to cold weather. Indeed, it is seen in Figure 12 that the level of transformation of retained austenite into martensite at -40°C is sufficiently high to create a decrease in sintered density of diffusion-bonded specimens, and this is even more pronounced as the carbon content increases from 0.75 to 1.0 wt%. For instance, it can be seen that the sintered density of specimens containing 1.0 wt% C significantly decreases, by around 0.07 g/cm^3, when they are frozen to a temperature of -40^{o}C.

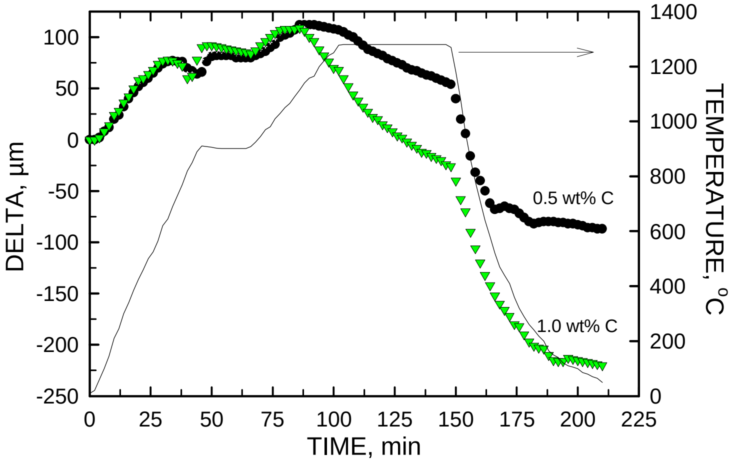


Figure 13. Dilatometric Curves as a Function of the Carbon Content for Specimens Sintered at 1280^{o}C.

The fatigue strength is also significantly affected by raising the carbon content at both sintering temperatures and the sintering temperature above a certain carbon level (Figure 14). This property noticeably increases from 235 MPa at 0.5 wt% C to reach a maximum of 282 MPa at 0.75 wt% C. Further increasing the carbon content has little effect on the fatigue strength of specimens sintered at 1280^{o}C but results in a sharp decrease of the fatigue resistance of specimens sintered at 1120^{o}C. The significant improvement in fatigue strength by raising the sintering temperature above 0.75 wt% C is mainly due to a large densification of materials as discussed previously and a significant change in pore shape and size.

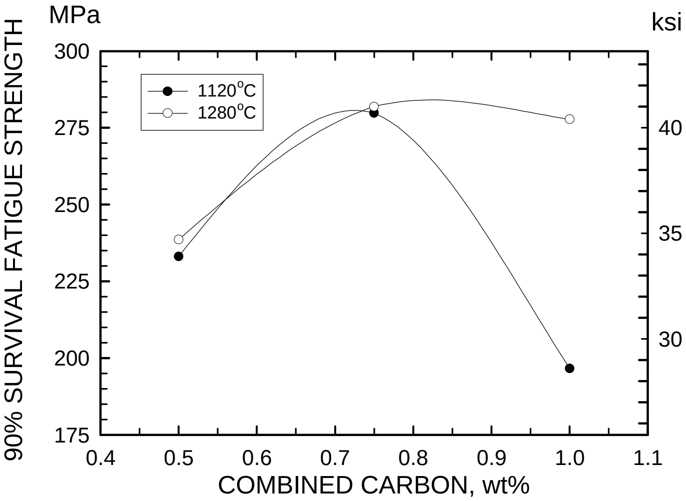


Figure 14. Effect of Carbon Content and Sintering Temperature on Fatigue Strength.

Hence, these results lead to the conclusion that the optimum carbon content required to improve the fatigue strength and also avoid any size change of parts exposed to cold weather is about 0.75 wt% C for diffusion-bonded specimens sintered at 1280^{o}C.

Effect of microstructural characteristics on fatigue strength

It is believed that the microstructure and pore characteristics (porosity, size and shape) are critical parameters in affecting the fatigue strength. Indeed, the presence of retained austenite dispersed throughout martensite, a change in the type of martensite as well as the formation of coarser and rounder pores together with a decrease in porosity may be favorable to improve the fatigue strength.

Microstructure

As discussed previously, an increase of the carbon content from 0.5 to 1.0 wt% favors the formation of 20 % retained austenite at the expense of martensite at both sintering temperatures, 1120°C and 1280°C (Figures 3 and 5). In order to determine the effect of this microconstituent on the fatigue strength, a sub-zero cryogenic treatment was performed on specimens containing 0.75 and 1.0 wt% C previously sintered at 1280°C. This treatment enables a complete transformation of the retained austenite into martensite (Figures 15 and 16). The specimens were also submitted to a tempering treatment in order to stress relief the martensite.

As illustrated in Figure 15a, the retained austenite in the 0.75 wt% C material is not effective in improving the fatigue strength of the diffusion-bonded material. Indeed, this property significantly increases although the amount of retained austenite is almost completely transformed into a mixture of lath/plate martensite with the use of a sub-zero cryogenic treatment.

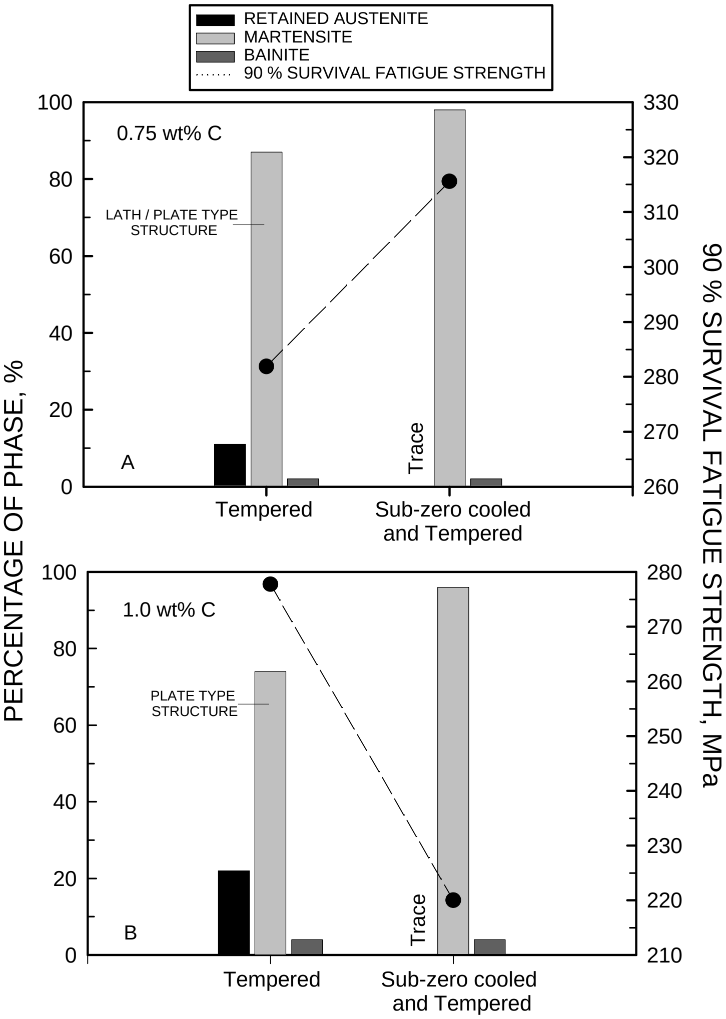
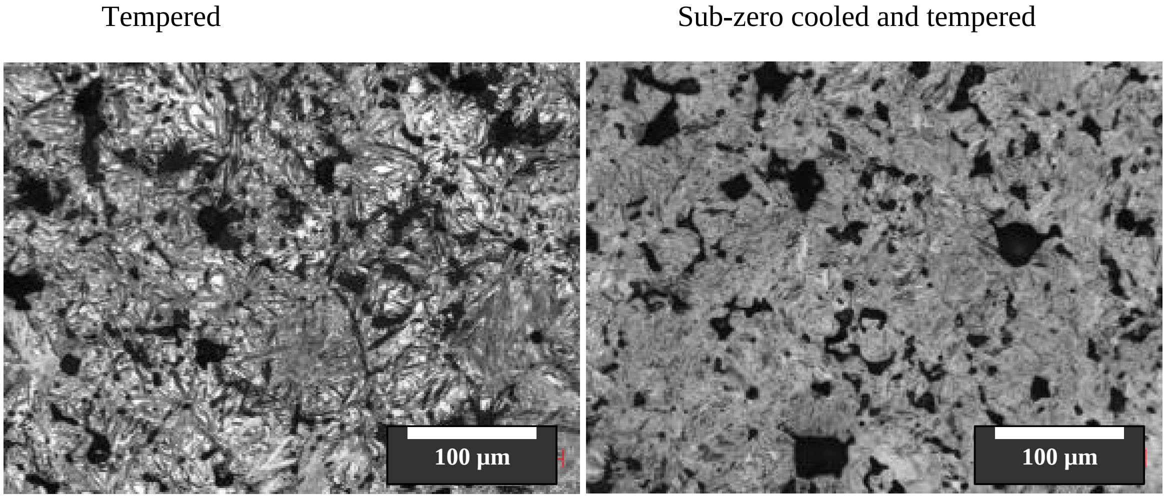


Figure 15. Effect of the Cryogenic Treatment on Microstructure and Fatigue Strength for Specimens Containing 0.75 and 1.0 wt% C at 1280°C.

Hence, the improvement in fatigue strength derived by raising the carbon content from 0.5 to 0.75 wt% at 1280°C is not related to the formation of retained austenite in the microstructure. Instead, it is believed that this improvement is attributed to the formation of some plate martensite which strengthens the specimens. The lath type martensite is predominant at 0.5 wt% C, whereas a combination of plate and lath type martensite is formed for specimens containing 0.75 wt% C at both sintering temperatures.



Tempered

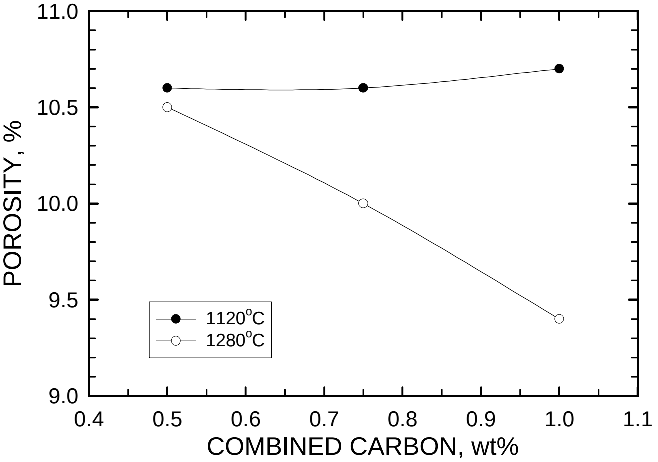
Sub-zero cooled and tempered

Figure 16. Microstructure before and after the Sub-zero Cryogenic Treatment for Specimens Containing 1.0 wt% C at 1280°C.

Nevertheless, it is worth mentioning that a certain amount of retained austenite is still effective in improving the fatigue strength of materials containing 1.0 wt% C sintered at 1280°C. In fact, Figure 15b reveals that this property significantly decreases when the retained austenite is completely transformed into plate martensite with the use of a sub-zero cryogenic treatment. Therefore, it is strongly believed that the presence of some retained austenite has a beneficial effect on the fatigue strength when there is formation of hard microconstituents such as in specimens containing 1.0 wt% C sintered at 1280°C.

However, it is seen in Figure 14 that an increase of the amount of retained austenite by raising the carbon content from 0.75 to 1.0 wt% C is not the main controlling factor in affecting the fatigue strength. In fact, this property respectively decreases and remains almost unchanged at 1120 and 1280°C within this range of carbon content. One possible explanation of this behavior is the formation of an excess plate martensite and possibly the precipitation of some fine carbide particles (Fe_3C) at the grain boundaries that weakens the specimens and overcomes the beneficial effect of the retained austenite formed at 1.0 wt% C.

Hence, all these results lead to the conclusion that the formation of a few plate martensite at 0.75 wt% C has a beneficial effect on the fatigue strength of diffusion-bonded materials sintered at 1280°C. However, excessive amounts of this microconstituent together with the precipitation of some fine Fe_3C particles by raising the carbon content from 0.75 to 1.0 wt% C also significantly reduces ductility, toughness as well as the fatigue strength of these specimens.



Pore characteristics

Figure 17 shows the effect of sintering temperature on the percentage of porosity as a function of the carbon content. Increasing the sintering temperature reduces the porosity of specimens and this is even more pronounced as the carbon content increases. In fact, the percentage of porosity significantly decreases by raising the carbon content at 1280°C. As discussed earlier, the self-diffusion of the γ-Fe atoms at 1280°C probably increases by raising the carbon content, which leads to a larger densification of specimens and a decrease in porosity.

Figures 18 and 19 also illustrate the effect of the sintering temperature on shape and size of pores as a function of the carbon content. The pore shape was assessed by considering a pore shape factor (P.S.F.). Pores having factors higher than 0.75 are considered spherical.

It is seen that the P.S.F. and mean pore size area noticeably increase by raising the sintering temperature from 1120 to 1280°C and this is even more pronounced as the carbon content increases. At 1280°C, there is an important coalescence of large pores and small voids left by the graphite and alloying elements (Ni/Cu), which results in rounder and larger pores than specimens sintered at 1120°C. This behavior is even more pronounced as the carbon content rises due to an increase of the amount of small voids.

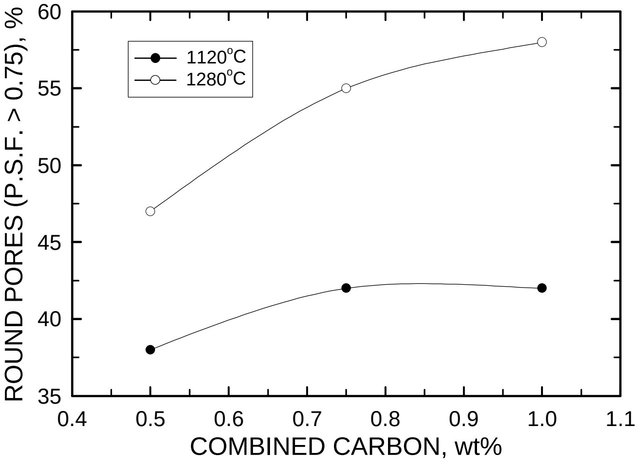


Figure 18. Effect of Sintering Temperature on Pore Shape Factor as a Function of the Carbon Content.

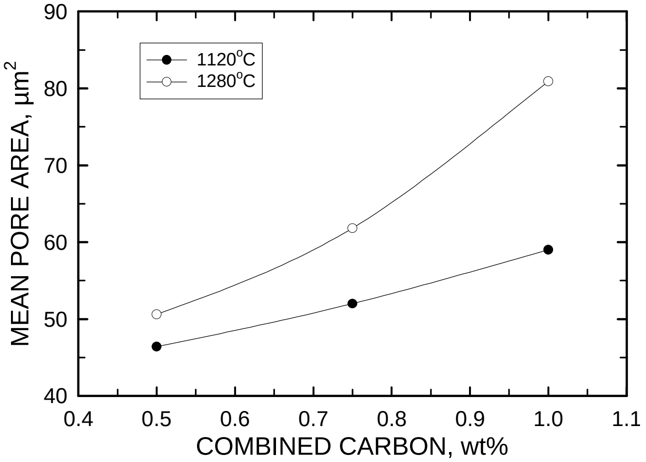


Figure 19. Effect of Sintering Temperature on Mean Pore Size Area as a Function of the Carbon Content.

It is likely that the coalescence of pores by raising the sintering temperature only has a minor effect on the fatigue strength within 0.5 to 0.75 wt% C (Figure 14). However, the formation of much rounder and larger pores by raising the sintering temperature at 1.0 wt% C together with a significant decrease in porosity certainly contributed to enhance the fatigue strength and inhibit the detrimental effect of hard microconstituents (plate martensite, fine Fe_3C particles) formed at this high carbon content. As shown above, the fatigue strength achieved at 1280°C is about 40 % higher than that obtained at 1120°C for specimens containing 1.0 wt% C.

CONCLUSIONS

The influence of carbon content in diffusion-bonded materials sintered at 1120 and 1280°C was investigated to optimize tensile, apparent hardness, impact and fatigue properties.

YS and UTS significantly decreased when raising the combined carbon content from 0.5 to 1.0 wt% C at 1120 and 1280°C. This was mainly due to a decrease in the amount of martensite to the benefit of retained austenite dispersed throughout martensite. Some nodular pearlite was also formed at the expense of martensite at 1120°C. However, YS and UTS achieved at 1280°C were significantly higher than those obtained at 1120°C whatever the carbon content, while maintaining higher ductility and impact strength. In particular, the use of 0.75 wt% C at 1280°C achieved YS and UTS of 776 MPa and 1085 MPa respectively. This corresponds to an improvement of 20 and 24 % as compared to specimens with 0.5 wt% C sintered at 1120°C. These conditions favored the formation of hard microconstituents such as a mixture of lath and plate martensite as well as some bainite in the microstructure.

Therefore, the use of high carbon levels can still achieve high YS and UTS when sintering specimens at 1280°C. This represented a real advantage for improving sintered density, apparent hardness and fatigue strength of diffusion-bonded materials pressed to 7.0 g/cm^3. For instance, these properties respectively achieved 7.03 g/cm^3, 41 HRC, and 282 MPa for specimens containing 0.75 wt% C, which was an improvement of 0.04 g/cm^3, 37 % and 19 % as compared to specimens containing 0.5 wt% C sintered at 1280°C. The apparent hardness was also more than twice as high as that obtained at 0.5 wt% C and 1120°C, while the sintered density was 0.09 g/cm^3 higher. The improvement in apparent hardness and fatigue strength by raising the carbon content from 0.5 to 0.75 wt% was directly related to the formation of some plate martensite in the microstructure. The plate martensite formed at 0.75 wt% C contains a higher carbon content and was much harder and stronger than the lath martensite formed at 0.5 wt% C. The retained austenite dispersed throughout martensite at 0.75 wt% C did not improve the fatigue strength.

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