The Effect of Surface Treatments on the Brazing of Iron-Based Powder Metal Compacts

Surface condition proves a very important factor in attaining sound brazements with powder metallurgy parts

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ABSTRACT. Powder metallurgy (P/M) parts may be difficult to braze because molten filler metal may infiltrate porous compacts resulting in voids in the joint area. The influence of base material composition and brazing parameters on infiltration and joint filling have been studied on compacts of a pure iron powder and an alloyed powder (Fe-1.75Ni-1.5Cu-0.5Mo-0.5C). The filler metal was AWS/ANSI BNi-8. The effect of brazing temperature, filler metal amount, and compact density has been established on as-sintered compacts, as well as on compacts that were surface modified by coining, lapping and grit-blasting. Lapping and grit-blasting resulted in fully closed surface pores, making the brazing operation comparable to that of brazing fully dense parts. Coined and as-sintered compacts, with open pores, resulted in increased infiltration, but by using compacts with higher densities and a brazing temperature just above the liquidus temperature of the filler metal, the infiltration was reduced due to isothermal solidification. In this way, good-to-acceptable joints can be obtained. The results were the same with either of the base metals studied.

Introduction

The use of powder metallurgical (P/M) products is increasing throughout industry. Existing and many new industries are taking advantage of P/M-processing for new parts and by replacing existing parts made by other methods and materials. The same or better parts can often be produced at the same or lower cost, especially when manufacturing complex parts in large quantities (Ref. 1).

Unfortunately, there are certain restrictions in form and size of the P/M parts due to the rigid P/M tooling and limitations to the pressing force available, *e.g.*, it is impossible to press undercuts, hollow grooves and holes transverse to the pressing direction. However, there would be a much wider market, if reliable and competitive joining processes, e.g., brazing, were available to join P/M parts to bigger components and/or components with a high complexity.

Brazing is recognized as a reliable and competitive process for the joining of many materials and components. But when brazing P/M materials, it is often seen that much of the brazing filler metal infiltrates the porous compacts instead of filling the joint. As the strength and quality of the joint are drastically affected by the presence of voids, it is important to control and limit the infiltration of the compacts.

The infiltration of a porous P/M component by a filler metal is closely related to a series of parameters, such as the size and amount of porosity, whether it is open or closed internally, as well as to the faying surface, the viscosity and amount of the melted filler metal, together with its ability to wet and its possibility to solidify isothermally by reactions with the P/M material. In this study we used a particular joint design with a "planar" geometry and the filler metal preplaced in the joint, so as to closely control the degree of infiltration by varying the above-mentioned parameters, especially the effect from a possible reduction in amount and size of the surface pores by means of coining, lapping or grit-blasting.

KEY WORDS

Surface Treatment
Brazing
Powder Metallurgy
P/M Parts
Fe-Based Powder
As-Sintered Compacts
Coined Compacts
Grit-Blasted Parts
Brazing Parameters

Background

During the brazing process the brazing filler metal, normally placed at the edge of the joint, becomes molten and if the surfaces in the joint are wettable, the capillary forces will continue to pull molten filler metal into the joint clearance until it is filled. The open porosities in the P/M compacts now have access to the molten filler metal in the joint, and the capillary forces in the pores can draw molten filler metal from the gap into the pores and start infiltration followed by possible isothermal solidification and other reactions with the P/M material.

From Ref. 2 we have the theoretical distance x travelled by the liquid along the capillary after a time t due to the capillary forces

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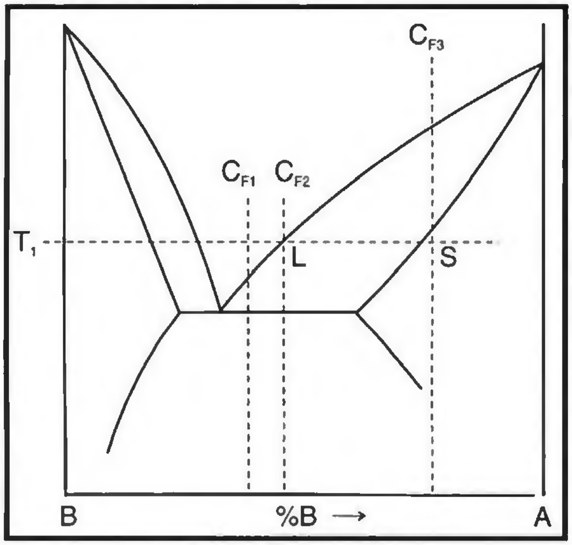

Fig. 1 — Model binary phase diagram with solid solubility.

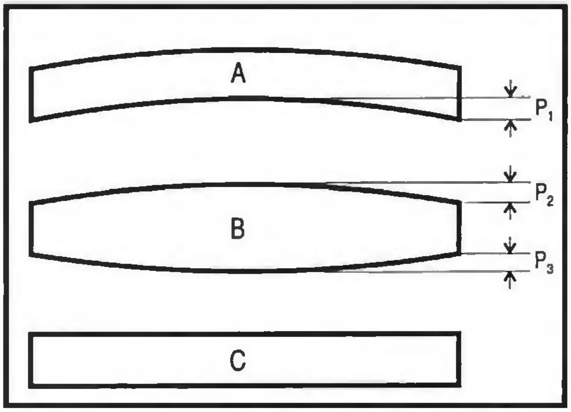

Fig. 2 — Geometry of sectioned plates. A — As-sintered; B — coined; C — lapped.

$$x = [rt\gamma_{lv}\cos\theta/2\eta]^{1/2}$$

where r is the radius of a cylindrical capillary, t the time, γ_{lv} the liquid-vapor surface energy, θ the contact angle and η is the viscosity of the liquid. Although the penetration depth for the same infiltration time increases with the radius of the capillary, it can be calculated from the equation that the rate of penetration in the compacts is orders of magnitudes higher than the joint filling rate, supposing perfect wetting ~$\cos\theta = 1$ and that the 10–15% porosity in the compacts is cylindrical with a radius of 5 µm and perpendicular to a 100-µm-wide joint. Besides, the gravity has only a negligible effect on the infiltration depth, due to the high capillary forces under good wetting conditions.

The infiltration depth of open porosity can be limited by a reduced wettability of the internal porosity surfaces compared to a good wettability of the surfaces in the joint (heavy oxidation of all internal and external surfaces followed by either a controlled heat treatment in a reducing atmosphere, which mainly reduces the external oxides, or by a mechanical cleaning, leaving an external surface with a good wettability and oxidized internal surfaces (Ref. 3)). Another method is to close the very narrow bottlenecks between the pores near the surface in the brazed joint by local isothermal solidification of the filler metal.

Isothermal solidification of a molten brazing filler metal of composition C_{F1} in contact with a solid base metal A at the brazing temperature T_1 can be explained by a model binary phase diagram with high solid solubility — Fig. 1 (e.g., brazing of pure iron with cast iron as the filler metal). From Fig. 1, it can be seen that there is no equilibrium condition between the molten filler metal of composition C_{F1} and the metal A. By dissolution of metal A into the melt and diffusion of B to the solid interface, equilibrium is obtained between the liquid phase C_{F2} in L and the solid phase C_{F3} in S. The solid phase C_{F3} having some of the component B in solid solution is now in contact with the pure metal A at the solid interface. The component B will therefore diffuse into the base metal A and the solid phase C_{F3} will compensate this loss by taking more component B from the restmelt. Supposing the mass of the liquid is small compared to the mass of the solid metal A, component B will continue to diffuse into metal A from the melt via the solid phase C_{F3} until all the liquid has solidified isothermally at the temperature T_1 with the composition C_{F3}.

When P/M compacts produced from metal A are brazed with a filler metal of composition C_{F1} or C_{F2}, a major part of the unwanted infiltration of the pores can be limited by plugging the pores or the bottlenecks between them by isothermal solidification of the filler metal. In addition, it can also be seen from Fig. 1 that isothermal solidification will be enhanced if brazing is carried out as close to the liquidus temperature as possible. This will minimize the dissolution of the base metal and thereby decrease the time to plug the very narrow bottlenecks.

Experimental Procedures

Materials

Powder metallurgical compacts were produced from two commercial powders having the composition shown in Table 1. Both powders were produced by atomization. The brazed specimens were made from a standard production of plates having dimensions of 43 x 43 x 4 mm^3. The green plates were pressed to densities, which after sintering in a continuous hydrogen furnace at 1120°C, gave a final density of 6.7 g/cm^3 (relative density: RD 0.85) for the lower density compacts and 7.1 g/cm^3 (RD 0.90) for the higher density compacts. The sintered plates were then processed according to the routes indicated in Table 2, resulting in plates with four different surface conditions: as-sintered, coined, lapped and grit-blasted. Coining was done in a press between two plane-parallel, heavy steel plates, while lapping was carried out in a SiC-kerosene slurry on a rotating wheel, and grit-blasting using a grit made from a nickel-chromium stainless steel, which will not reduce the very good wettability of the as-sintered surfaces.

The different steps in the processing of the plates gave rise to very different geometries of the plates — Fig. 2. The measurements were done on the different plates with a three-axis measuring system to an accuracy better than 4 µm. The as-sintered plates (Fig. 2A) showed a constant thickness but were arched to a maximum height p_1 of 40 µm in the center, whereas, the as-sintered and coined plates (Fig. 2B) were barrel shaped with maximum arch heights of $p_2 = p_3 = 40$ µm in the centers. The lapped plates (Fig. 2C) were plane parallel within the measuring accuracy, while the geometry of the grit-blasted as-sintered plates is comparable to that of the as-sintered plates.

One commercial filler metal, BNi-8 (Table 1), was used for producing brazed joints. The filler metal was chosen for the investigation on the basis of experience gained earlier by the industrial partner in the project. The liquidus and solidus temperature of the filler metal has been determined by differential thermal analysis. The solidus temperature was found to be 1005°C, and the liquidus temperature to be 1040°C.

Experimental Procedure

All P/M plates used for brazed specimens were, with their as-received, coined, lapped or grit-blasted surfaces, carefully degreased in an ultrasonically agitated bath, dried and kept in sealed boxes until further processing.

Table 1 — Base Materials and Filler Metal

	Composition (wt-%)							Melting Range
	Fe	Ni	Mo	Cu	C	Si	Mn	T_{sol}-T_{liq}
P/M materials								
Type A	100	–	–	–	–	–	–	–
Type B	bal	1.75	0.5	1.5	0.5	–	–	–
Filler metal								
BNi-8	–	bal	–	5	–	2	23	1005–1040°C

Table 2 — Processing of Compacts

Surface	Processing route
As-sintered	pressing – sintering
Coined	pressing – sintering – coining
Lapped	pressing – sintering – coining – lapping
Grit-blasted	pressing – sintering–grit-blasting

The filler metal powder was applied to the tops of the plates by using a Nicrocoat[1] spray gun. An appropriate amount of organic binder was mixed with the filler metal powder during the spraying process to ensure adherence. Various filler metal layer thicknesses were deposited to explore the effect of that parameter. The amount of filler metal is given as a nominal thickness of a solid layer, calculated as

$$t = m/A\rho$$

where t is the nominal thickness, m the mass of the applied powder, A the sprayed area and ρ is the specific gravity of the applied powder. The amount of applied filler metal was controlled by weighing during the application. The mass of the organic binder is negligible.

Three thicknesses of the sprayed filler metal layer were used, corresponding to a solid layer of 50 μm, 100 μm and 200 μm for all four different surface conditions. Plates with the same thickness of the sprayed filler metal layer and a top plate without filler metal were stacked and vacuum brazed. During brazing the stacked plates were kept in a horizontal position in ceramic jigs, which only allowed a vertical movement of the plates in a stack. Brazed stacks of three-coated plates and a top plate were sectioned and used for investigations of infiltration and joint filling, while specimens for tensile testing with a 6-mm OD cylindrical shaft (DIN 50125) were machined from approximately 10 x 10 x 81 mm³ rods cut from brazed stacks of 19 coated plates and a top plate.

Brazing experiments were carried out at temperatures between 990° and 1115°C. Brazing in the melting range of the preplaced filler metal was included to investigate the possibility that the viscosity of the melted fraction might be so high that only the surfaces in the joint would be wetted, leaving the compacts without infiltration.

Brazing was performed in a vacuum furnace with graphite heating elements and insulation, a vacuum better than 10^{-5} torr and a heating rate of 25°C/min. The furnace was heated to 800°C with a soak for 30 min, and then to the brazing temperature with a soak for 10 min. After brazing, the stacks were cooled at a rate of 40°C/min down to 800°C, followed by a decreasing cooling rate to room temperature.

Examination of joints

The flexible joint geometry in the stacks induces a varying joint clearance, depending on the filler metal available in the joint just before the filler metal solidifies and on the state of the filler metal. During brazing at or above the liquidus temperature, the stacks will contract due to gravity and capillary forces as the filler metal melts, and in this way, compensate for the clearance induced by the loose packing in the filler metal coating. The melted filler metal will keep the plates floating on top of each other, and the width of the joint, or the film thickness of melted filler metal, will be fixed as a function of the capillary forces in the melt, the extent to which the filler metal infiltrates the compact, and the weight of the top pieces.

The brazed joints created in the stacks were evaluated by light optical and electron microscopy to determine the depth of infiltration, degree of joint filling, joint clearance and the metallurgical structure.

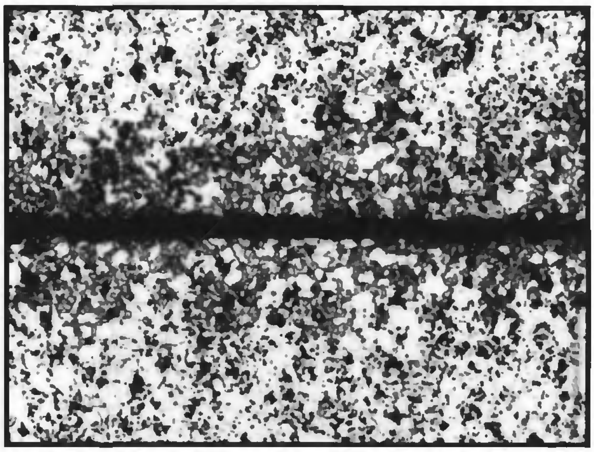

Fig. 3 — Brazed joint of Type A, high-density, as-sintered compacts brazed at 1065°C with 50-μm filler metal applied. (50X)

Results and Discussion

Infiltration

Due to the characteristic porosity of the P/M compacts, the molten filler metal will not only wet the surfaces in the joint but also infiltrate the compacts. Figure 3 shows how the applied 50-μm filler metal has infiltrated the type A high-density, as-sintered compacts at 1065°C and left a completely drained joint. It is also observed that the surfaces of the compacts in the joint have been perfectly wetted by the filler metal. The infiltration depth is found as the mean depth to which the filler metal has infiltrated. The depth of infiltration is shown in Fig. 4 as a function of brazing temperature, compact surface and density and the amount of filler metal. It is noted that infiltration has occurred at a brazing temperature of 990°C, 15°C below the solidus of the filler metal; apparently as the result of the formation of a low melting phase from the reaction of the filler metal and base metal. The composition of the two investigated compacts was found to have no effect on the resulting infiltration depth. The infiltration of the compacts by the filler metal is heavily affected by the surface quality resulting from the processing of the compacts, and this is most strongly recognized for the lapped plates where the penetration is zero. Apparently in the lapping process the material at the surface is smeared, and, thereby, the pores adjacent to the surface are closed. Also, the grit-blasted compacts had zero infiltration due to closed surface pores. For the coined and as-sintered compacts, the infiltration is pronounced, especially for the as-sintered compacts, where in most cases all available filler metal had infiltrated.

The brazing temperature has a great influence when brazing as-sintered and coined low-density compacts. It is clear that brazing at a higher temperature promotes infiltration and that the filler metal

1. *Product of Wall Colmonoy, Detroit, Mich.*

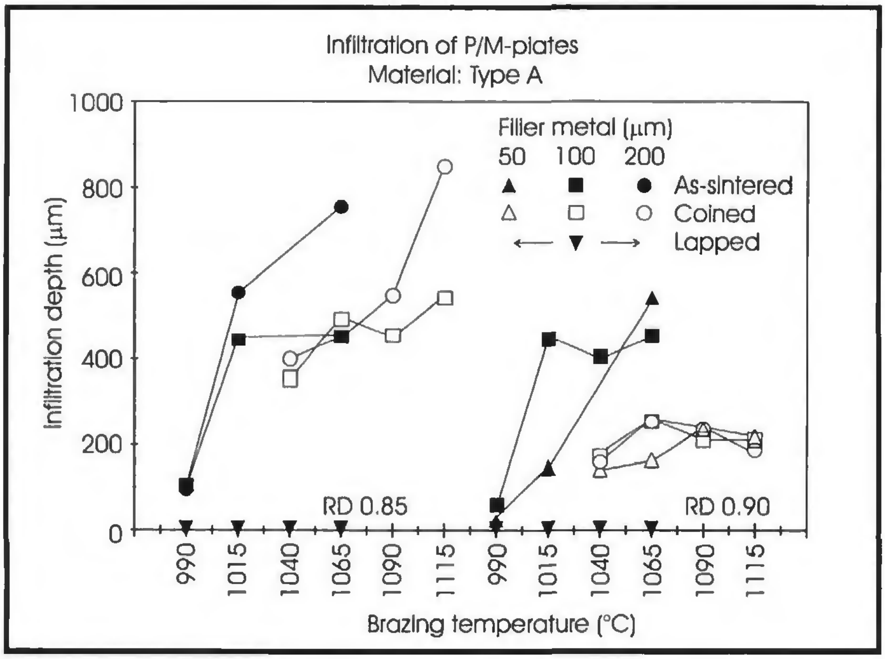

Fig. 4 — Infiltration of compacts as a function of filler metal amount, surface, compact density and brazing temperature.

infiltrates deeper into the compacts. This is explained by the reduced viscosity of the melted filler metal as the temperature exceeds the liquidus temperature. Furthermore, brazing at higher temperatures retards isothermal solidification; a higher degree of interaction is necessary as mentioned above. Little or no temperature effect was observed in the higher density coined compacts. An explanation could be that the pores, especially those open to the faying surfaces, have been partly closed during coining, and therefore easier to plug by isothermal solidification after the filler metal has infiltrated to a certain limit. Therefore, isothermal solidification alone does not control the degree of infiltration, as higher temperatures should give rise to deeper infiltration.

Figure 4 also shows that the density of the compacts has a noticeable effect on the coined plates. Plates of the higher density had a limit of infiltration of around 200 μm independent of temperature, while plates of the lower density showed for increasing temperature an increasing infiltration depth varying between 350 and 900 μm. The penetration depth of all low-density plates, except the coined ones brazed below 1100°C, was even deeper than that needed to fill all the 15% pore volume closest to the joint. This means that the bigger pores nearer to the joint are not fully filled. During the coining process, only the bottlenecks near the surface in the high density compacts were reduced to a degree where they could be closed by isothermal solidification of the infiltrating filler metal. All available filler metal infiltrated the as-sintered compacts, so no limit was observed regarding density. No density effect was, of course, observed in the well wetted lapped or grit-blasted plates due to closure of the surface porosities.

Table 3 — Composition of Stuctural Phases in Brazed Joint

	Composition (wt-%)				
	Ni	Cu	Si	Mn	Fe
Lighter phase	55.3	7.3	2.5	23.5	11.5
Darker phase	62.8	1.5	10.4	23.4	1.7

Joint Filling

Different degrees of joint filling were achieved depending on the investigated parameters: surface quality, compact density, filler metal amount and brazing temperature. No effect of compact composition was observed. The joint filling is, of course, dependent on the available amount of filler metal, and thus strongly affected by the degree of infiltration as discussed above.

Even though the brazing filler metal is preplaced in the joint clearance, it is necessary to secure a brazing temperature right at or above the liquidus temperature of the filler metal. When brazing at temperatures below the liquidus tempera-

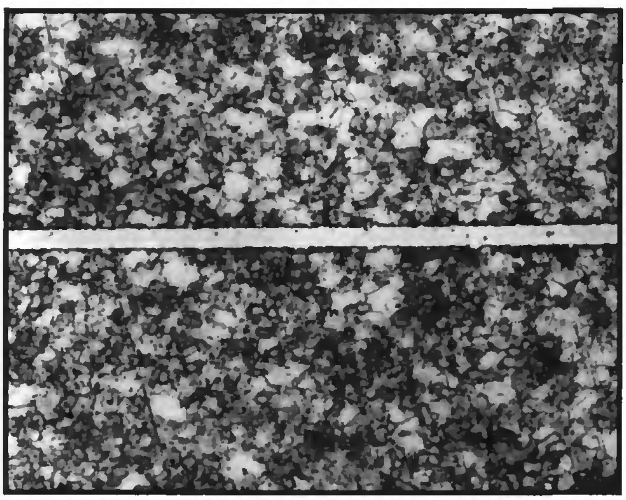

Fig. 5 — Brazed joint Type B, high-density, lapped compacts brazed at 1065°C with 100-μm filler metal applied. (50X)

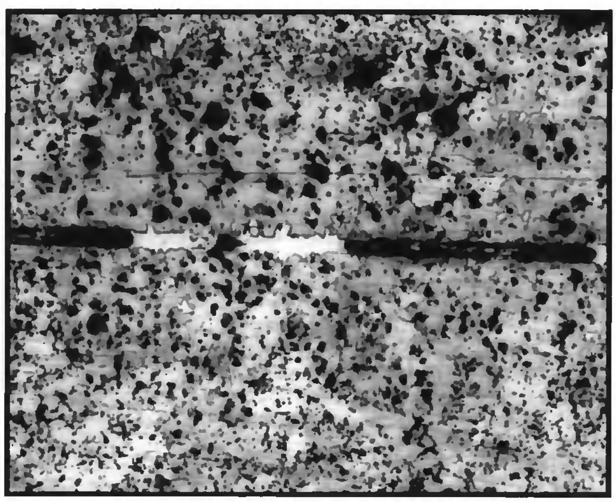

Fig. 6 — Brazed joint Type A, high-density, as-sintered compacts brazed at 1065°C with 100-μm filler metal applied. (50X)

ture, a nonmelted fraction of the filler metal is still present in the joints acting as spacers between the parts. This obstructs the contraction of the parts by capillary forces and gravity, and in this way keeps the joint volume too high to be filled with the part from the melted fraction, which has not infiltrated the compact. Only when the filler metal is fully melted are the parts able to contract, and the filler metal can fully fill the joint clearance.

The most pronounced effect from the surface variations is seen on the lapped or grit-blasted compacts as they all demonstrate a 100% filling of the joint clearance — Fig. 5. This is, of course, related to the total closure of the surface pores, giving no effect from the compact density and filler metal amount.

The degree of infiltration of the as-sintered compacts, and thus the amount of filler metal left in the joint, was essentially independent of compact density; nearly all available filler metal was lost by infiltration using preplaced filler metal thicknesses up to 200 μm. Only when larger amounts of filler metal was applied and when brazing was right at the liquidus temperature, was it possible to establish a full joint in some areas, but it was not possible to create a consistent joint in these compacts. An example of a joint between as-sintered compacts is given in Fig. 6. Note the voids along with the areas where the joint is filled.

The joint filling behavior of the coined compacts is also influenced by the barrel-shaped geometry of the plates (Fig. 2B), resulting in a joint width variation from the center toward the edge of up to 100 μm, and therefore the joint clearance filling becomes very inconsistent throughout the joint. The results are therefore based only on observations at or near the center of the plates. For the high density compacts, the joint was filled 100% with any combination of filler metal amount and brazing temperatures above the liquidus temperature, but for the lower density compacts, variations in joint filling were found, depending on filler metal amount and brazing temperature. The fraction of the joint filled has been measured and is given as a function of filler metal amount and brazing temperature in Fig. 7. The positive effect of larger amounts of filler metal and a brazing temperature closer to the liquidus temperature can be seen. For compacts of both densities, it was found that the joined area stretches out from the center of the plates toward the edge, only limited by the available filler metal. The final amount of filler metal in a solidified joint is thus a function of the applied amount, the infiltration of the compacts, and the overall geometry of the plates. Compared to Fig. 4, it is seen that a fully filled joint requires that serious measures must be taken to restrict the strong capillary forces in the as-sintered compacts.

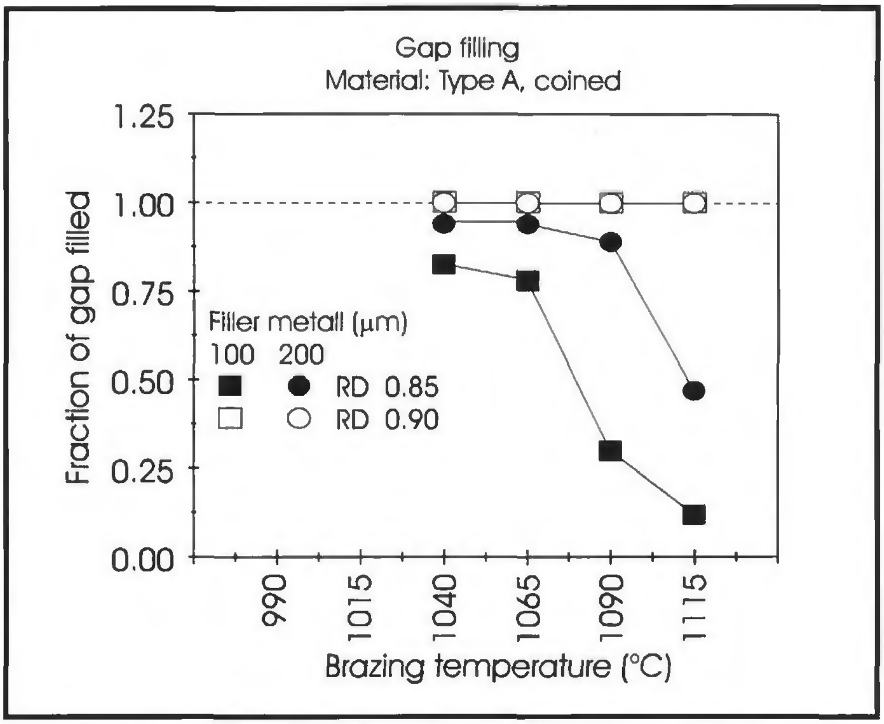

Fig. 7 — Joint clearance filling for Type A, coined compacts as a function of filler metal amount, compact density and brazing temperature.

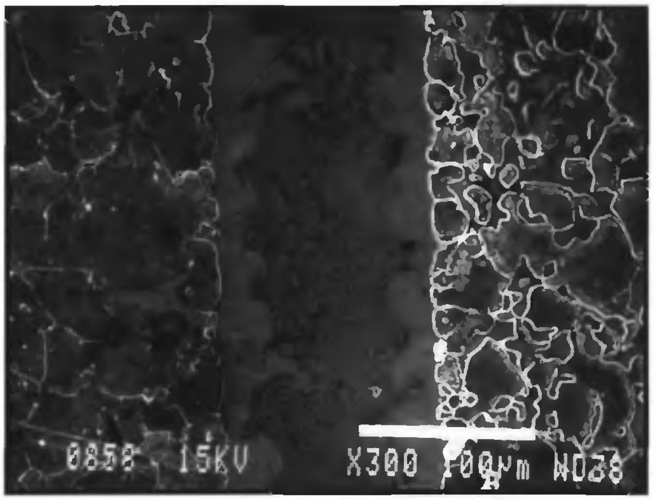

Fig. 8 — SEM image of brazed joint Type A, high-density, lapped compacts brazed at 1065°C with 200-μm filler metal. (300X)

Joint Width

When a brazement is made, the resulting thickness of the joint is determined by the available filler metal; less material in the joint leads to a thin joint. The thickness of the joint is also determined by the capillary forces between the compacts and the molten filler metal, which will try to pull the parts close together. The resulting joint thickness is established by the equilibrium state of these capillary forces, and it may give rise to voids alongside joined areas.

For the lapped and grit-blasted compacts, where all the available filler metal is maintained in the joint area, relatively thick joints have been achieved. The thickness of the joint is on the order of 70–80 μm when 100 μm filler metal was applied, and 110–120 μm when 200-μm filler metal was applied. The excess amounts of filler metal are accounted for by the wetting and infiltration of external surfaces on the sides of the compacts. When only 50 μm, or less, filler metal was applied, narrow joints were not achieved, a phenomenon that is explained by the wetting of external surfaces and the flexible joint design used. External wetting and infiltration drains filler metal from the joint clearance, and the capillary forces apparently find an equilibrium at joint thicknesses of 60–70 μm, resulting in joined areas with some voids.

There was insufficient filler metal to fill the joints between the coined compacts, apparently due to infiltration and geometric effects. Here the capillary forces pulled the barrel-shaped compacts together to establish a joint clearance of 20 µm at the center of the plates and 100–120 µm at the edges, regardless of the brazing temperature, filler metal amount and compact density.

In the as-sintered compacts, the width of the joints, in areas where a joint has been established, is somewhat higher (around 40–60 µm), as shown in Fig. 6. This width is believed to be partly determined by the capillary forces, but also by the double-curve surface geometry of the plates — Fig. 2A.

Metallurgical Structure

For any established joint observed in these experiments, the metallurgical structure is basically the eutectic structure shown in Fig. 8. This structure consists of two phases, one rich in Si and Ni (darker phase), the other rich in Fe and Cu (lighter phase). The composition of the phases found through EDX is given in Table 3.

This eutectic structure is only found when the joint thickness exceeds 30–40 µm. With joints thinner than this, the Si-Ni-rich phase is not present and only one phase, close to the lighter phase in composition, is found.

The eutectic structure results in joints with limited mechanical properties, especially regarding tensile strength. The tensile strength of a series of five machined specimens, each with 70-µm-thick joints in lapped compacts, was found to be 89 ±11 MPa. All specimens failed in the joint. This value is comparable to the yield strength of Type A compacts 85 ±5 MPa, while the higher-alloyed Type B compacts have a yield strength of 210 ±10 MPa. SEM investigations have shown that the fracture is located in the Si-Ni-rich phase, and never in the Fe-Cu-rich phase or the interface between base material and filler metal.

Attempts to establish eutectic-free joints suitable for testing were not succesful. Heat treatment of thick joints only results in a coarsening of the eutectic structure, and the use of smaller amounts of filler metal only creates voids along the joined areas and 60–70 µm wide joints.

Conclusion

When one is going to braze compacts produced by a powder metallurgical route, the processing of the compacts is of the highest importance. The resulting surface quality has a great influence on the degree of infiltration by the filler metal, and, therefore, the amount of filler metal left in the joint. Lapping and grit-blasting closed surface pores, so no infiltration occurred, and brazing of the compacts was similar to brazing fully dense parts.

When brazing as-sintered and coined compacts, close attention should be given to parameters such as brazing temperature, amount of filler metal and compact density. By varying these parameters, it is possible to create joints between these porous parts.

It is noted that the brazing temperature should be kept right at or slightly above the liquidus temperature. In this way, isothermal solidification is enhanced and the degree of infiltration limited.

It is easier to control infiltration for higher density compacts relative to lower density compacts, thereby giving a more consistent joint quality.

Coined compacts require approximately 50 µm of filler metal for the higher density compacts (7.1 g/cm^3) and 100 µm of filler metal for the lower density compacts (6.7 g/cm^3).

As-sintered compacts require at least 100 µm of filler metal for the higher density compacts (7.1 g/cm^3) and 200 µm of filler metal for the lower density compacts (6.7 g/cm^3). It might be necessary to use even higher amounts of filler metal, as infiltration is very hard to control for these compacts.

The composition of the investigated compacts did not have an effect when brazing with filler metal BNi-8. However, strong effects can be expected in other material and filler metal combinations, especially where the effect of isothermal solidification is high (Ref. 3).

Acknowledgment

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