Dimensional Change Comparison of Materials with Different Microstructures

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Abstract

Powder metallurgy is a near net shape technology. Demand on high performance parts increases the demand for tight tolerances to be cost effective toward competing technologies. Heat treatment is commonly used for such parts. Tolerances will be affected by how these elements are added to the powder mix in such processes. The alloying elements can be added in many ways to a mix as either a premix, diffusion or organic bonded, or as pre alloyed. They will dependent on how they are added contribute in different ways to obtained tolerances. The effect of alloying element distribution on tolerances and tolerance correlated to microstructures in the heat treated condition will be presented.

Introduction

The performance of PM components can be enhanced by increasing density, increasing sintering times and temperatures, and strengthening material structure by the use of alloying elements and secondary heat treatments [1]. Often the most convenient or cost effective methods for enhancing the performance of PM components is to manipulate the alloy system or to perform a heat treatment.

The hardenability of a material is characterized as the ability to transform austenite into martensite [2]. In PM, the hardenability of a material is dependent on the content of alloying elements, alloying method, and processing. Carbon content also plays a large role in hardenability but will not be discussed because the materials in this paper will utilize the same carbon content. Alloying increases the hardenability of a material and allows for more martensite transformation at a given cooling rate which increases the mechanical properties [3]. Elements such as nickel, copper, and molybdenum were among the first alloying elements to be used in PM to increase strength and hardenability. Although elements such as chromium and manganese increase

hardenability more than nickel and copper (Fig. 1), they were not used in PM alloys due to oxygen sensitivity. Advances in sintering & powder production technology have made it possible to successfully utilize chromium and manganese and take advantage of their attributes [4].

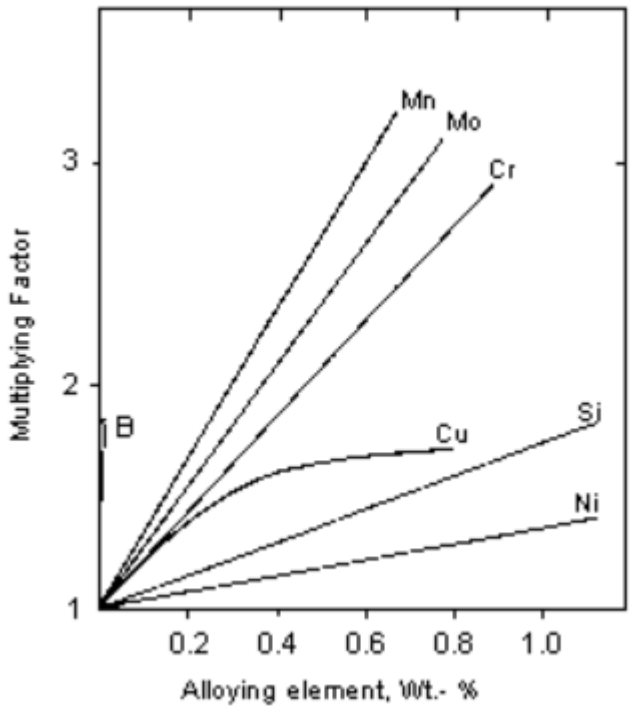


Figure 1. The effect of various alloying additions on hardenability according to Metals Handbook [5]

The method by which alloying elements are added to the material system plays a role in the strengths and tolerances achievable. Admixing of alloying elements with iron powder dates to the beginning of PM. This method allows for highly compressible mixes with flexible alloying. Although this type of alloying method is prone to segregation, it is still the most popular method used in the industry today. The sensitivity for segregation is dependent on the type and combination of powders used. Differences in size, density and morphology of the elemental powders can cause segregation [6]. Segregation of copper, for example, can increase with reduced particle size of the copper powder [7]. Variations in copper content throughout the powder mix and, in turn, the compacted components will directly affect the tolerances that can be achieved.

To reduce segregation of elemental powders, pre-alloying can be used. Pre-alloying adds the alloying elements in the melt stage before atomization. Pre-alloyed particles contain an even distribution of the alloying elements. This allows for homogeneity during sintering and increase mechanical properties and tolerances. Because the alloying elements raise the strength of the individual powder particles the compressibility of the powder is decreased [8].

In order to take advantage of the alloying elements and reduce the risk of segregation diffusion bonded iron powders are often utilized. Diffusion alloyed powders have high compressibility and consistency in alloy distribution. The production of diffusion alloyed powders involves the mixing of iron powders and alloying powders, followed by a separate annealing step where the alloying elements partially diffuse into the iron particles [9]. Once diffused into the iron, the

alloying powders cannot segregate. This allows the diffusion alloyed grades to hold very tight dimensional tolerances.

While the alloying methods reviewed above will greatly enhance the mechanical properties compared to a traditional press and sinter iron / carbon system, often a heat treatment step is needed to further enhance the mechanical properties and take full advantage of the alloying elements present. Heat treatment of PM components can be performed using a variety of methods. The traditional austenitize quench and temper method is widely used throughout the PM industry. If a component manufacturer does not want a secondary heat treatment operation, sinterhardening can be used. Sinter hardening combines sintering and heat treatment in a single step to produce high strength and wear resistance while minimizing the number of processing steps [10]. Both conventional quench and temper and sinter hardening modify the microstructure of a material system through increased cooling rates.

In this paper, different alloying methods are subjected to different cooling rates ranging from conventional to oil quench. The dimensional change observed with these processing steps is then measured and related to the microstructure that is produced. The relationship between microstructure and dimensional change can be useful in helping to select the appropriate alloying system for the desired performance and tolerance level.

Experimental Method

Materials

The chemical composition of the FD-0205 material system (iron, 1.75% nickel, 1.50% copper and 0.50% molybdenum) was chosen for investigation. A diffusion alloyed material, an admixed version and a pre-alloyed powder with similar chemistry were chosen. The chemical composition of the base irons used is listed in Table I.

Table I. Chemical Composition of Base Irons

Base Iron	Ni (%)	Mo (%)	Cu (%)	Mn (%)
D.AB	1.75[D]	0.50[D]	1.50[D]	-
Astaloy 45Mo	-	0.45[P]	-	-
Astaloy A	1.90[P]	0.55[P]	-	0.20[P]

D = Diffusion alloyed, P = Pre-alloyed

The chemical compositions of the mixes investigated are shown in Table II. The nickel and copper numbers indicated are admixed values. The total alloying for the system is also listed.

Table II. Chemical Composition of Mixes

Mix #	MPIF Designation	Base Iron	Ni (wt %)	Cu (wt%)	Graphite (wt %)	Lubricant (wt %)	Total Alloying (%)
1	FD-0208	D.AB	-	-	0.80	0.75	3.75
2	-	45Mo	1.75	1.5[A]	0.80	0.75	3.70
3		45Mo	1.75	1.5[B]	0.80	0.75	3.70
4	FLC-4608	A	-	1.5[A]	0.80	0.75	4.15

A = Cu-165, B = Cu-268

Graphite Asbury 1651, Inco Ni123 and coppers Cu-165 (50 – 65% -45µm, ACu Powder) and Cu-268 (80 – 90% -45µm, ACu Powder) were admixed with the base irons. Acrawax C (Lonza) was used as the lubricant.

Components and Processing

For each mix, one thousand 55 mm diameter rings by 35mm inner diameter were compacted to a height of 20mm and green density of 6.80 g/cm^3 using a Gasbarre 100 ton mechanical press. The rings were numbered in the sequence in which they were compacted and marked with an X for orientation purposes (Fig. 2). Every tenth ring was measured for weight and density. The rings for each mix were separated into four (4) groups for sintering and heat treatment. Sintering was performed on a 152 mm (6 inch) Abbott mesh belt furnace equipped with a Varicool unit. The rings were sintered for 30 minutes at 1121°C (2050°F) in a 90 v/o 10 v/o nitrogen / hydrogen atmosphere. Different cooling rates were achieved by altering the frequency on the Varicool unit and a secondary heat treatment. The processing conditions are listed below in Table III.

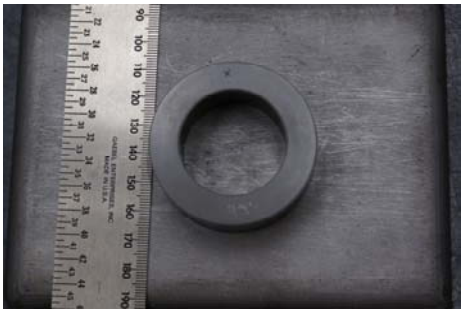


Figure 2. Ring used in Study

Table III. Processing Conditions

Designation	Sintering Temp. °C (°F)	Time at Temp. Minutes	Varicool Setting Hz	Approximate Cooling Rate °C/s (°F/s)
0	1120 (2050)	30	0	0.5 (1.0)
30	1120 (2050)	30	30	1.0 (2.0)
60	1120 (2050)	30	60	2.0 (4.0)
HT	1120 (2050)	30	N/A	~ 50 (~ 100)

The heat treated rings were heat treated by Pennsylvania Industrial Heat Treaters LLC using the parameters listed in Table IV.

Table IV. Heat Treat Conditions

Austenizing Temp °C (°F)	Time Hours	Carbon Potential %C
900 (1652)	1	0.5

Even though the mixes contained a graphite addition of 0.80%, a carbon potential of 0.5% was used. The purpose of the heat treatment was to utilize the fast cooling rate. No decarburization was observed on the rings. All rings were tempered at 204°C (400°F) for 1 hour in air. After processing, the rings were measured for dimensional change on the outer diameter. Two (2) measurements were made 90° to one another as shown in Figure 3. The two (2) measurements were then averaged to determine an overall dimensional change. The apparent hardness, microstructure and microhardness were analyzed for each set of rings.

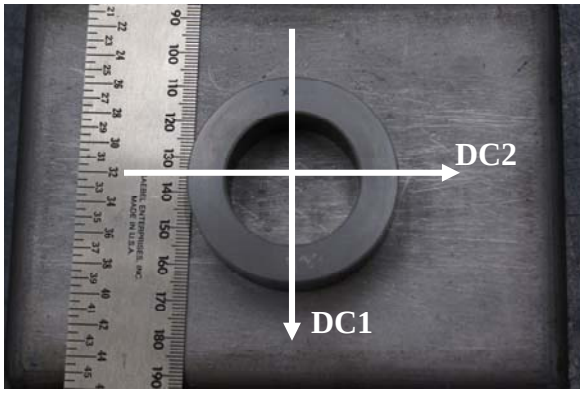


Figure 3. Direction of Measurement

Results and Discussion

Microstructure and Microhardness – Mix 1

The microstructures obtained for Mix 1 are shown in Figures 4 through 7.

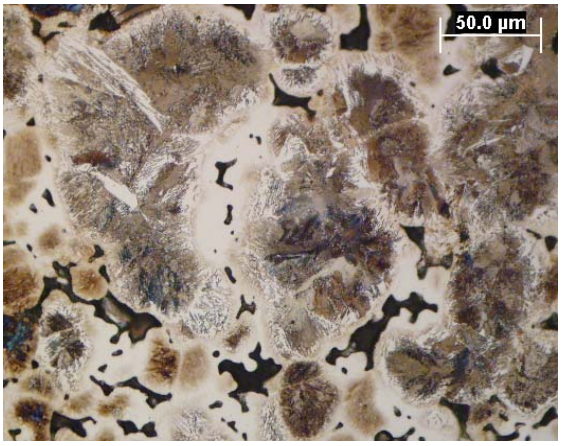


Figure 4. Mix 1-0, FD-0208 0Hz

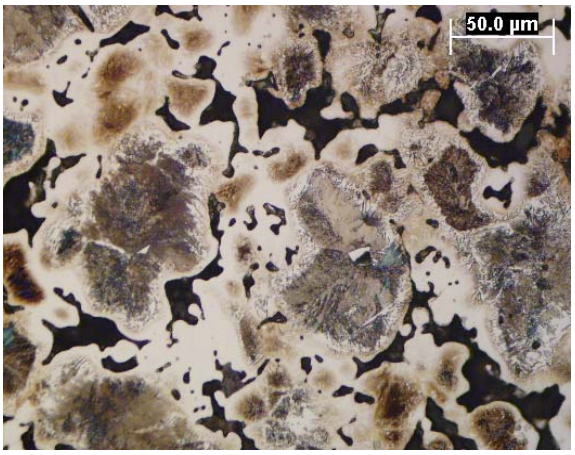


Figure 5. Mix 1-30, FD-0208 30Hz

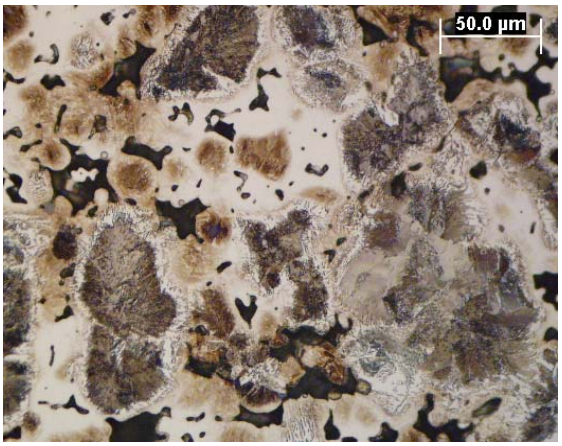


Figure 6. Mix 1-60, FD-0208 60Hz

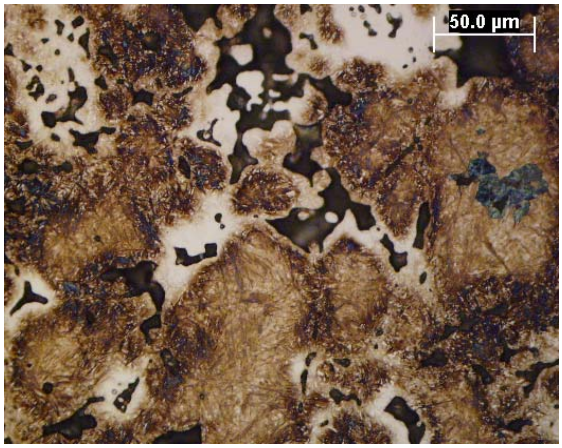


Figure 7. Mix 1-HT, FD-0208 Heat Treated

The microstructure for Mix 1-0 consisted of ferrite, pearlite, bainite, nickel rich austenite and a small amount of martensite. A slight change in microstructure was observed by increasing the cooling rate using the Varicool. The structure of Mix 1-60 was almost identical to Mix 1-0 except that little to no ferrite was observed. The structure of Mix-HT was drastically different than at other processing conditions. The structure was predominately martensite. Nickel rich austenite and small amounts of bainite and retained austenite were observed. The same trend was observed in the microhardness measurements. For Mixes 1-0, 1-30, and 1-60 the measurements were taken in the bainite regions. The microhardness measurements are shown in Figure 8.

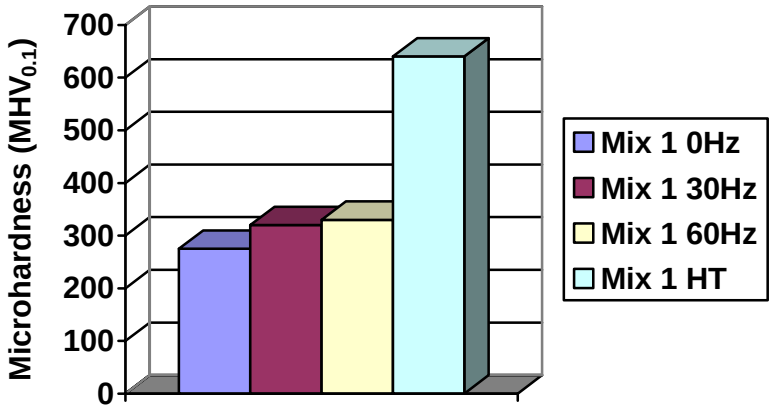


Figure 8. Microhardness of Mix 1 through Processing

Microstructure and Microhardness – Mix 2
The microstructures obtained for Mix 2 are shown in Figures 9 through 12.

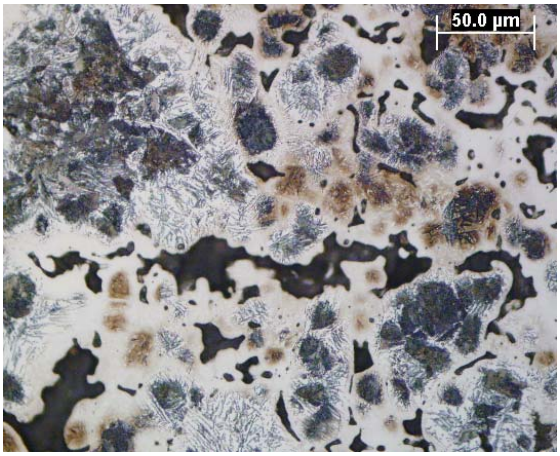


Figure 9. Mix 2-0, FD-0208 Admixed Cu-165 0Hz

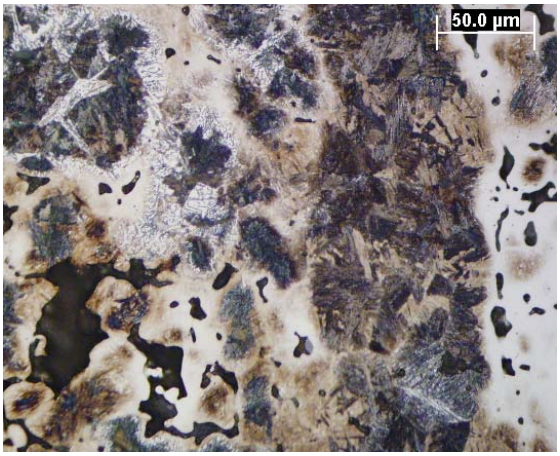


Figure 10. Mix 2-30, FD-0208 Admixed Cu-165 30Hz

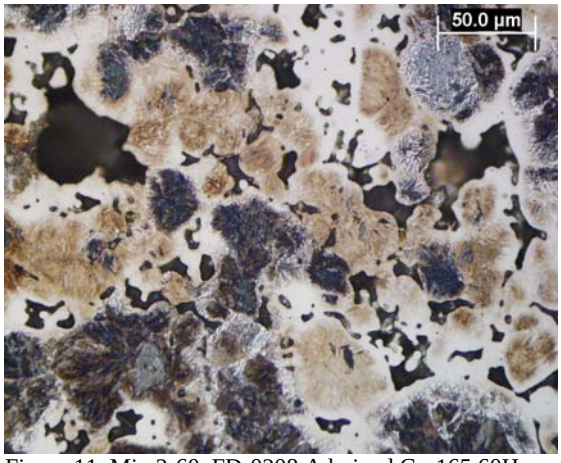


Figure 11. Mix 2-60, FD-0208 Admixed Cu-165 60Hz

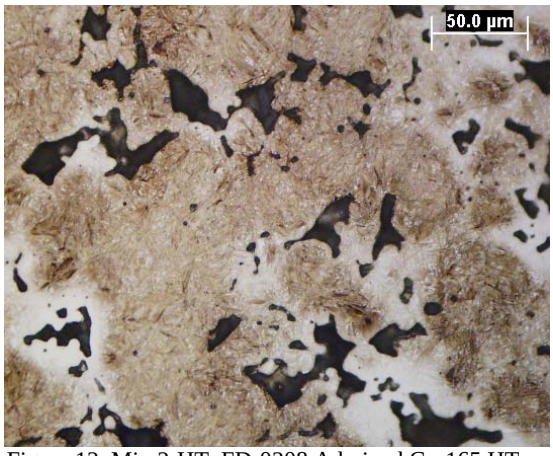


Figure 12. Mix 2-HT, FD-0208 Admixed Cu-165 HT

The microstructure for Mix 2-0 consisted of pearlite, bainite, nickel rich austenite and martensite. This differs slightly from the structure of Mix 1. Since a pre-alloyed base iron was used in Mix 2 there is no tendency for ferrite to form. A larger change was observed when the cooling rate was increased. More bainite and martensite were formed as the cooling rate increased. Once again, the pre-alloyed base iron promotes this. The structure of Mix 2-HT was predominately martensite. Nickel rich austenite and small amounts of retained austenite were observed. The microhardness measurements for each processing condition are shown in Figure 13.

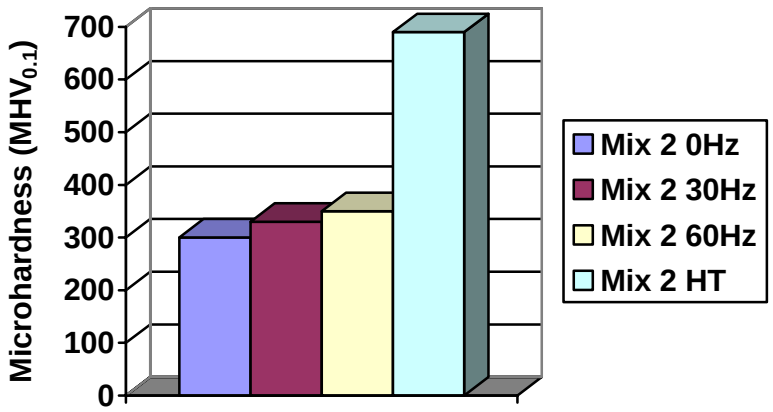


Figure 13. Microhardness of Mix 2 through Processing

Microstructure and Microhardness – Mix 3
The microstructures obtained for Mix 3 are shown in Figures 14 through 17.

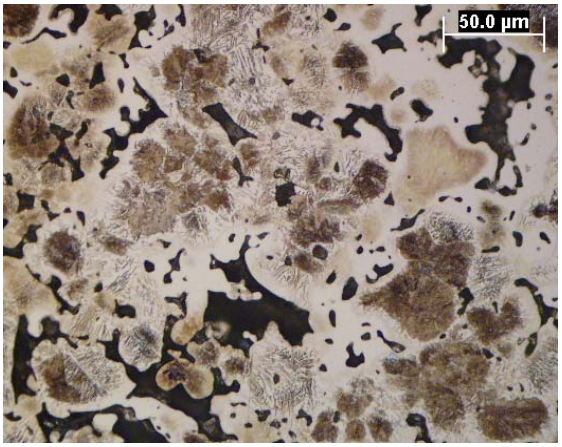


Figure 14. Mix 3-0, FD-0208 Admixed Cu-268 0Hz

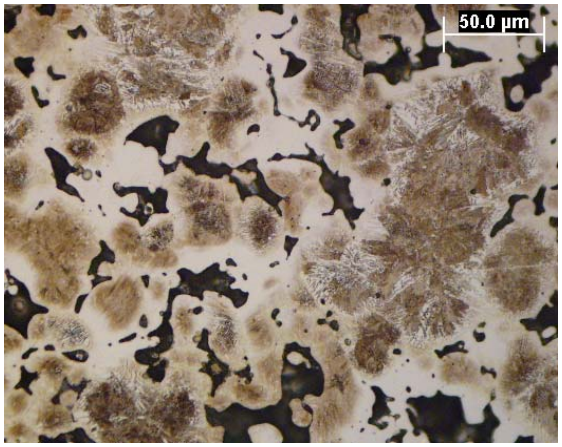


Figure 15. Mix 3-30, FD-0208 Admixed Cu-268 30Hz

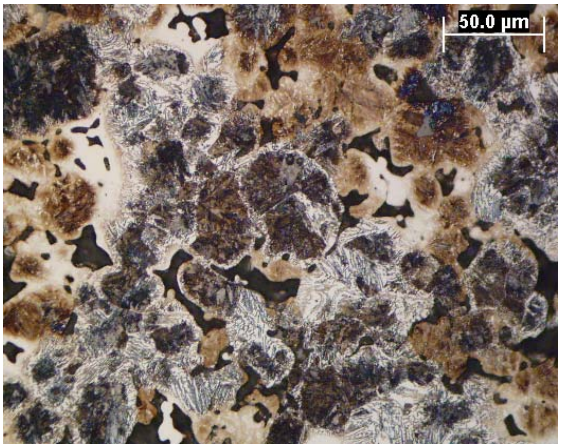


Figure 16. Mix 3-60, FD-0208 Admixed Cu-268 60Hz

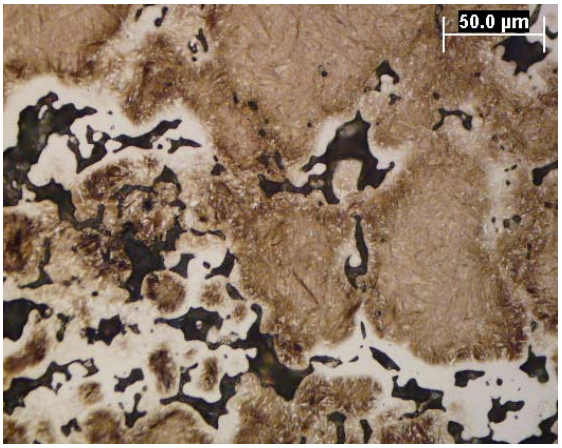


Figure 17. Mix 3-HT, FD-0208 Admixed Cu-268 HT

The microstructure for Mix 3-0 consisted of pearlite, bainite, nickel rich austenite and martensite. The structure is comparable to Mix 2. Slightly more martensite was formed due to the more complete diffusion of the fine copper. Bainite and martensite were formed as the cooling rate increased. The structure of Mix 3-HT was predominately martensite. Nickel rich austenite and small amounts of retained austenite were observed. The microhardness measurements for each processing condition are shown in Figure 18.

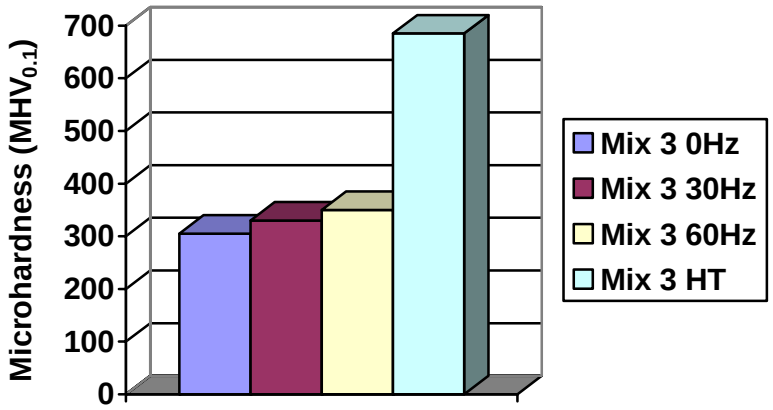


Figure 18. Microhardness of Mix 3 through processing

Microstructure and Microhardness – Mix 4

The microstructures obtained for Mix 4 are shown in Figures 19 through 22.

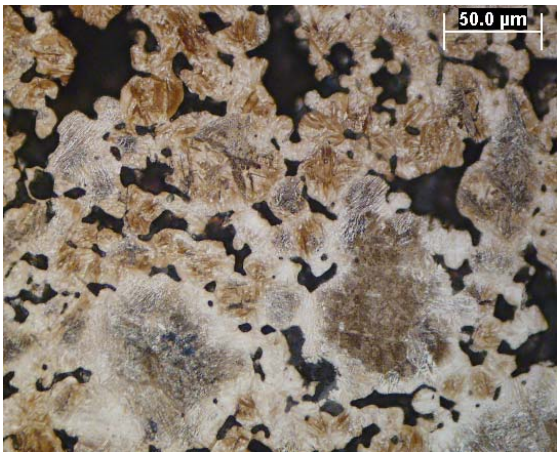


Figure 19. Mix 4-0, FLC-4608 0Hz

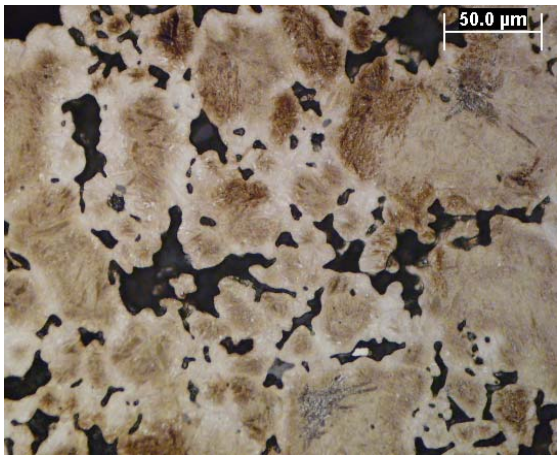


Figure 20. Mix 4-30, FLC-4608 30Hz

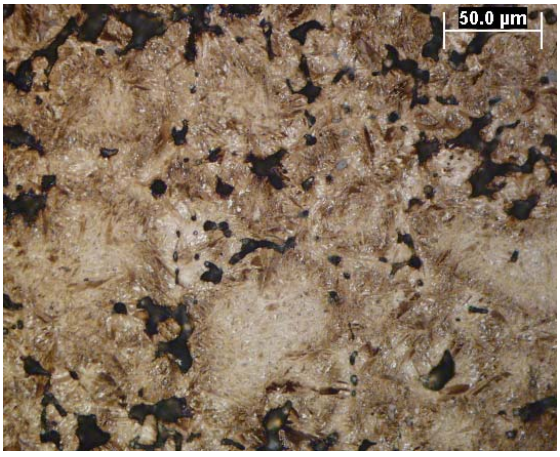


Figure 21. Mix 4-60, FLC-4608 60Hz

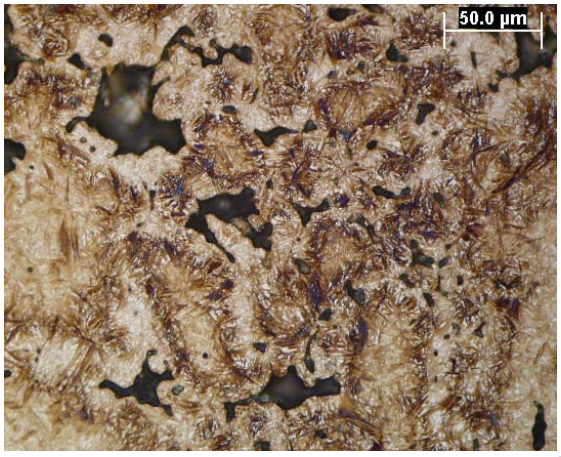


Figure 22. Mix 4-HT, FLC-4608 Heat Treated

The microstructure for Mix 4-0 consisted of bainite, martensite, and a small amount of pearlite. Due to the higher alloying content and the pre-alloying of the base iron, martensite and bainite transformation occur more readily than the diffusion bonded mix or premix. Increasing the cooling rate transformed the structure to martensite. Mix 4-60 and 4-HT were both completely martensitic. The microhardness measurements for Mix 4 can be viewed in Figure 23.

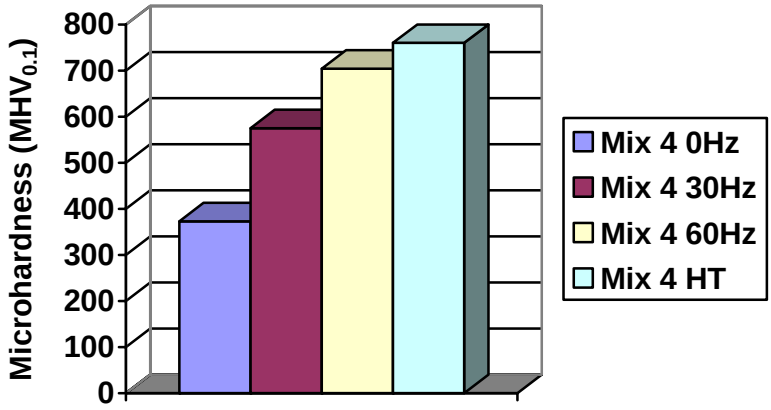


Figure 23. Microhardness of Mix 4 through Processing

Dimensional Change

A comparison of the average dimensional change measurements for all mixes and processing conditions is shown in Figure 24. Scatter bars have been added to show the scatter associated with each mix and processing condition. Two interesting trends were observed. For the admixed material systems, increasing the cooling rate of the sintering furnace improved the scatter in the dimensional change measurements. The opposite trend was observed for the diffusion bonded material system. By increasing the cooling rate, the admixed systems were able to achieve the same scatter as the diffusion bonded system. Large amounts of scatter were observed for the heat treated condition.

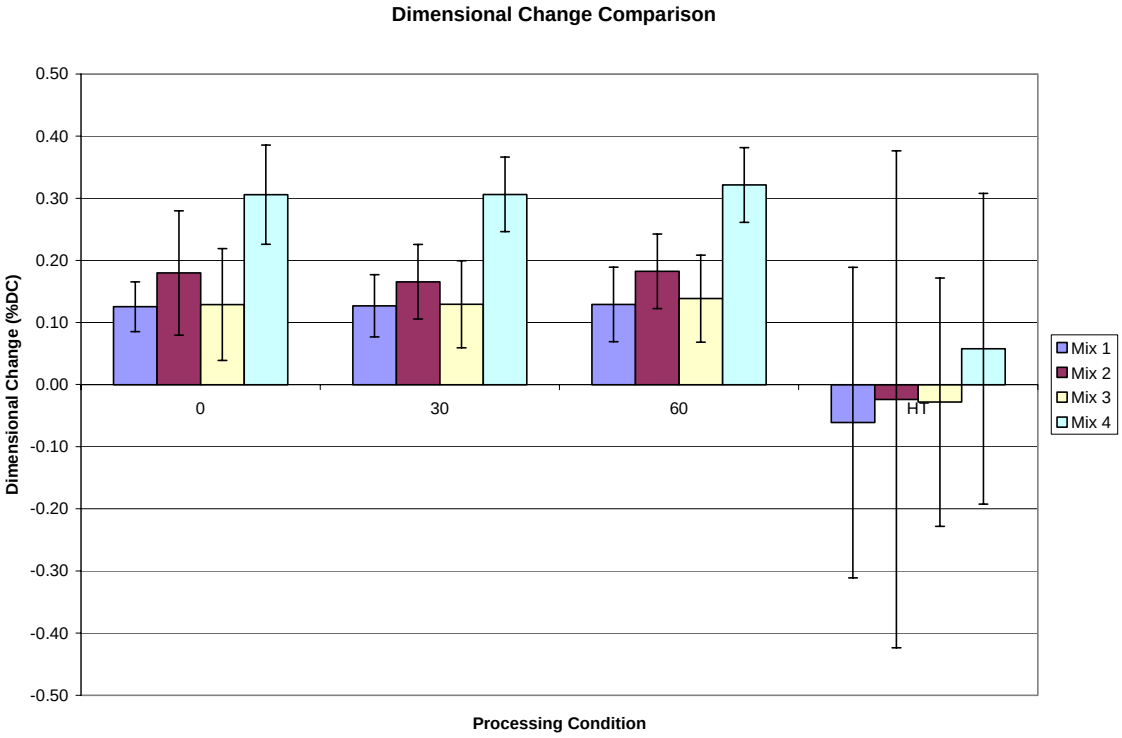


Figure 24. OD Dimensional Change Comparison

The apparent hardness values for each material and processing condition are shown in Figure 25.

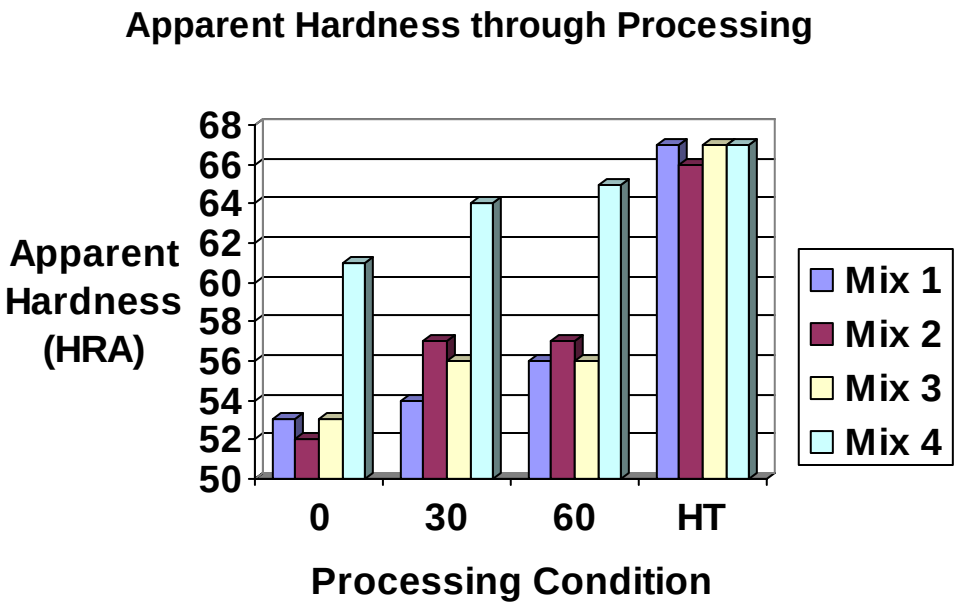


Figure 25. Apparent Hardness Measurements

The apparent hardness measurements of the rings followed the trend observed in the microstructures. Increasing martensite formation led to increased hardness levels. Increasing the rapid cooling from the 30Hz condition to 60Hz did not affect the apparent hardness of the Mixes 2 & 3. Mix 1 improved throughout the processing because of the elimination of ferrite as the cooling rate increased.

Conclusions

1. The microstructure of Mix 1 contained ferrite, pearlite, bainite and nickel rich austenite at 0Hz. The ferrite was formed because the material system is based on a pure iron particle. Increasing the cooling rate decreased the amount of ferrite formed; however, the microstructure did not change drastically when processed at 30 and 60 Hz. The slight change in microstructure had a slight affect on the scatter found in dimensions. When Mix 1 was subjected to an oil quench the microstructure changed to predominately martensitic. No ferrite was observed in the heat treated condition.

2. The microstructure of Mix 2 contained pearlite, bainite, nickel rich austenite and martensite at 0Hz. Since the base iron was pre-alloyed with molybdenum, no ferrite was formed. Increasing the cooling rate increased the amount of martensite formed. At the 30 and 60 Hz conditions the majority of the microstructure was martensite and bainite. By increasing the cooling rate the amount of scatter decreased compared to the 0Hz condition. The amount of scatter at 30 and 60Hz was comparable to the scatter found for Mix 1. In the heat treated condition, the microstructure was almost entirely martensitic. Mix 2 had the largest amount of scatter in the heat treated condition.

3. The structure of Mix 3 was similar to Mix 2. The difference in copper sieve size did not have an effect on the microstructure formed. The dimensional scatter improved at the 30 and 60Hz conditions in the same manner as Mix 2. The amount of improvement observed was better than Mix 2. After heat treatment, Mix 3 exhibited a completely martensitic microstructure. Mix 3 had the least amount of dimensional scatter after heat treatment.

4. The microstructure of Mix 4 consisted of martensite and bainite after normal sintering. The higher alloying content of Mix 4 provided for an easier transformation to martensite. At 30Hz an almost entirely martensitic structure was generated. Increases in cooling rate generated a harder martensitic structure. Sinterhardening improved the dimensional scatter compared to normal cooling.

5. Sinterhardening Mix 2 and Mix 3 improved the scatter in the dimensions while the dimensional scatter for Mix 1 decreased compared to a normal cooling rate. Increasing the cooling rate moderately may help to increase the achievable tolerances. This may allow for admixed material systems to compete with diffusion bonded systems on tolerance demands.

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