Influence of Sintering Conditions on Dimensional Precision for Different PM Steels

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ABSTRACT

Many new applications utilize the unique possibilities of PM to achieve high strength in combination with close dimensional tolerances and a minimum of manufacturing operations. However, there are many factors from the process, including materials, compaction and sintering, that influence the dimensional tolerances. The sintering process is one of the main factors, including sintering temperature, time, atmosphere and cooling rate. It has in many cases been overlooked or not seen as the primary focus for enabling higher quality PM component manufacturing. The need for a better understanding of the influence of sintering conditions on sinter-hardening materials is becoming more important for cost-effective manufacturing of PM components that combine high mechanical properties with high dimensional precision.

In this paper, different low alloy PM materials sintered at different temperatures and cooling rates will be described. The influence of these sintering conditions on dimensional precision of a prototype gear will also be presented.

Keywords:
Powder Metallurgy, Sintering Temperature, Sintering-Hardening, Dimensional Tolerance

1. Introduction

Powder metal technology offers the ability to manufacture near net shape components to a variety of mechanical performance levels. As the PM market grows, new applications will not only require high mechanical performance, but an increasing focus on the ability to hold tight tolerances. Sinter hardening is one example of a development combining good manufacturing economy with the ability to achieve a unique combination of mechanical properties. Due to the high apparent hardness reached after sintering, a very tight control of the final dimensions of the parts is required, since it is almost impossible to adjust the final size by secondary operations [1]. Meanwhile by increasing the sintering temperature from 1120 ℃ to 1250 ℃, the mechanical properties can be further increased. Therefore, a high temperature can have a positive effect on properties, and expensive materials that require additional processing can be replaced by less expensive alternatives. However high temperature sintering is more expensive than conventional sintering for the furnaces. The higher costs are related to capital, maintenance, and consumables [2].

A number of factors influence the component consistency, including the material, mixing, handling, compaction and sintering, which affect the dimensional change and weight scatter of the finished components[3]. Some of the key factors that affect dimensional change are related to the materials and sintering process, and these need to be better understood. Therefore, it is of great interest to know the effect of high temperature sintering in combination with rapid cooling rates on dimension precision. A newly designed sintering furnace offers the capability of achieving a sintering temperature of up to 1400 ℃ and an 8 ℃/ cooling rate. The cooling system is separately controlled to maintain an even

rate for the cooling down of parts. The goal of this study is to better understand the influence of these sintering conditions on dimensional precision for different alloy materials. Five different low alloyed materials available on the market were evaluated using a large gear component at the same density. A cooling rate from 1 ℃/s to 5 ℃/s and a sintering temperature from 1120 ℃ to 1250 ℃ were benchmarked.

2. Experimental Procedure

2.1. Materials

Five materials were investigated based on five different alloying systems: Fe-Mo-Cu, Fe-Cr-Mo, Fe-Cr-Cu, Fe-Cr-Ni and Fe-Cu. The chemical composition and identification code of the five mixes is presented in Table 1. Distaloy DH is a pre-alloyed powder with 1.5% Mo and diffusion bonded 2% Cu. Astaloy CrM is pre-alloyed with 3% Cr and 0.5% Mo. Astaloy CrA is pre-alloyed with only 1.8% Cr. AHC100.29 is water atomized iron powder. Natural graphite UF4, electrolytic copper with -200 mesh particle size, and carbonyl nickel were admixed with the base powders. Lube E was used as lubricant.

Table 1
The chemical composition and identification codes of the five mixes.

Mix No.	Identification code	Alloy system	Composition, wt.%						
			Fe	Cu	Ni	Mo	Cr	C	Lube
1	DH	Fe-Mo-Cu	Bal.	2.0	-	1.5	-	0.6	0.6
2	CrM	Fe-Cr-Mo	Bal.	-	-	0.5	3.0	0.45	0.6
3	CrA+Cu	Fe-Cr-Cu	Bal.	1.0	-	-	1.8	0.8	0.6
4	CrA+Ni	Fe-Cr-Ni	Bal.	-	2.0	-	1.8	0.8	0.6
5	FC0208	Fe-Cu	Bal.	2	-	-	-	0.8	0.6

2.2. Processing conditions

The materials in Table 1 were pressed in a hydraulic CNC press to prepare the tensile strength testing bars (ISO 2740:2009) with a green density of 7.0 g/cm^3. These tensile strength test bars were also used for the testing of dimensional change.

A prototype gear was utilized in this investigation to evaluate dimensional precision. A picture with the dimensions of the prototype gear are shown in Figure 1. For each material, 500 pieces of this part were compacted in a hydraulic CNC press with two upper punches and two lower punches. The nominal density of the component was 7.0 g/cm^3 for all materials and the weight was around 500 g.

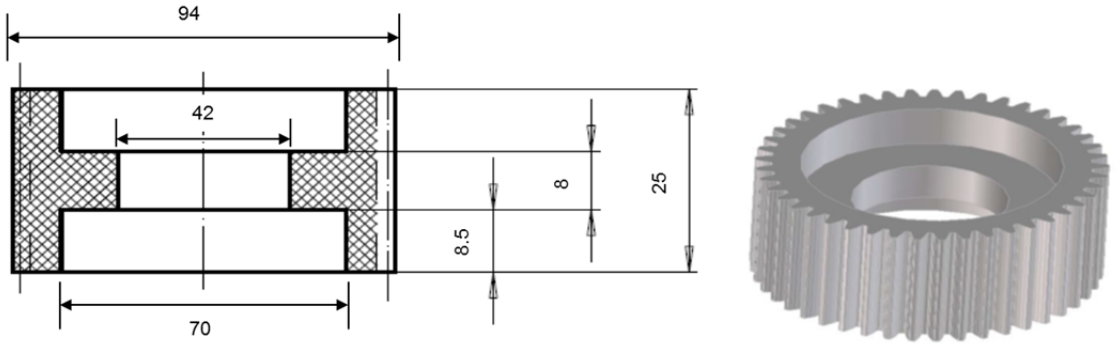


Fig.1. Picture and dimensions of prototype gear.

Sintering was carried out in a newly designed sintering furnace with the capacity to achieve a maximum sintering temperature of 1400 ℃， and equipped with a fast cooling system that is able to achieve an 8 ℃/s cooling rate. The furnace was driven by the pushing system in the dewaxing zone and a rolling system in the sintering zone and cooling zone separately. This means the cooling time for the sintering hardening can be controlled separately by the driving system. In this investigation, three different cooling rates were used: 1 ºC/s, 2.5 ºC/s and 5 ºC/s. The sintering temperature used was set to 1120 ºC, 1200 ºC and 1250 ºC. The sintering time was 30 minutes at the sintering zone. The protection atmosphere was 90% N_2 and 10% H_2 mixed gas. After sinter hardening, all parts were tempered at 200 ºC for 60 minutes in air for stress relief.

2.3.Testing

Before and after sintering, the dimensions of tensile test bars, and 10 pieces of randomly selected gear samples from each material were measured. The length of tensile test bars was measured by a SmartScope Flash 200. The dimensions of gears were measured using a Keyence XM-1000 acoordinate measuring machine. The dimensional change of height was calculated using the average of four measuring points (marked with A, B, C and D) from green to as-sintered. The roundness of tooth top, tooth root and inner diameter on both upper surface and lower surface were also measured on green and as-sintered parts using six measuring points, and by turning the part 60° between each measurement.

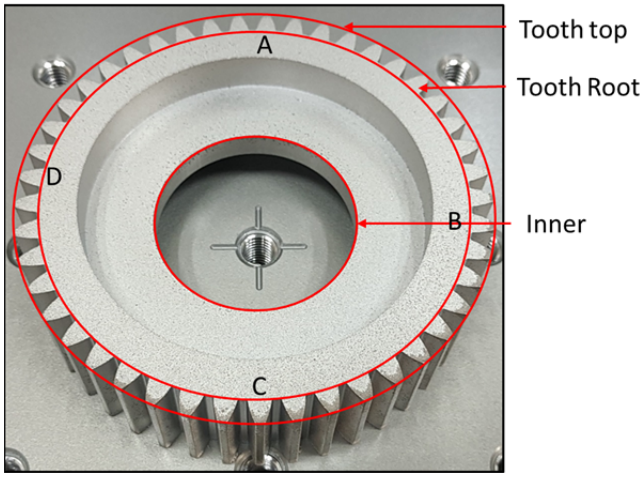


Fig.2. Measuring points of height and roundness of green and as-sintered parts.

A Linseis RITA L78 Quench Dilatometer was used for the dimensional change measurement at different cooling rates. A cross section of the test bars was prepared for metallographic investigation. As-polished samples were analyzed using electron dispersive spectroscopy (EDS) in the SEM, and line profiles were used to measure the alloy element distribution.

3. Results and discussion

3.1.Microstructure analysis

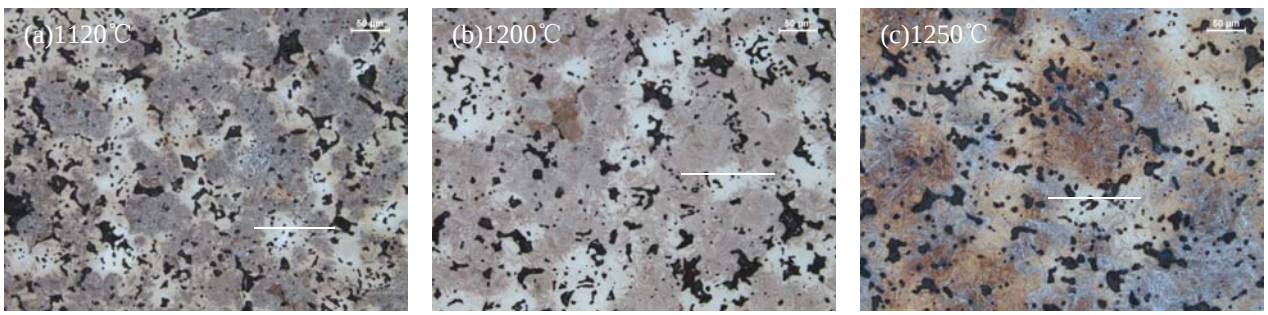
The different crystal structures have different sizes, which could result in different dimensions on the part. Therefore, the microstructure obtained using the sintering conditions described above need to be investigated. The overall alloy elements of steels, and the processing conditions are key factors in delaying the transformation of austenite, thus forming martensite at lower cooling rates. Some

commercial powder grades currently used lead to microstructures with large proportions of martensite after accelerated cooling, but at a high cost due to the high quantities required and the price of alloying additions. Therefore, further research to design lean alloying systems has been undertaken in pursuit of a more cost-effective use of raw materials while still meeting the requirements imposed by demanding applications. Some recently reported[4-7] powder materials based on Astaloy CrM and Astaloy CrA groups have been shown to fulfill these requirements.

As shown in Table 2, by changing the type and amount of alloying elements, the post-sintering cooling rate and the sintering temperature, can vary the quantity of martensite and bainite in the microstructure. By accelerating the post sintering cooling rate, the quantity of martensite can be increased. A fully martensite structure was achieved for the Astaloy CrM at 2℃/s, and for Distaloy DH, and Astaloy CrA+Ni/Cu at 5 ℃/s. However, FC0208 is not sensitive to the cooling rate in the microstructure. As shown in figure 3, raising the sintering temperature from 1120 ℃ to 1250 ℃ can result in a more even element diffusion, a more even microstructure, as well as rounder pores for all materials.

Table 2
A metallographic analysis for the five materials.

Materials code	Cooling rate	1.0 ℃/s				2.5 ℃/s				5.0 ℃/s			
	Sintering Temp.	M,%	B,%	P,%	Ni-rich A,%	M,%	B,%	P,%	Ni-rich A,%	M,%	B,%	P,%	Ni-rich A,%
DH	1120 ℃	25	75	-	-	82.5	17.5	-	-	99.5	0.5	-	-
	1200 ℃	22.5	77.5	-	-	75	25	-	-	98.5	1.5	-	-
	1250 ℃	12.5	87.5	-	-	77.5	25	-	-	98.5	1.5	-	-
CrM	1120 ℃	10	90	-	-	99	1	-	-	100	-	-	-
	1200 ℃	10	90	-	-	98.5	1.5	-	-	100	-	-	-
	1250 ℃	10	90	-	-	99	1	-	-	100	-	-	-
CrA+2Ni	1120 ℃	44.5	51.5	2	2	78	20	-	2	98	-	-	2
	1200 ℃	48	50	1	1	79	20	-	1	99	-	-	1
	1250 ℃	43.5	56	1	0.5	89.5	10	-	0.5	99.5	-	-	0.5
CrA+1Cu	1120 ℃	32.5	65	3	-	82.5	17.5	-	-	98	2	-	-
	1200 ℃	28.5	70	1.5	-	82.5	17.5	-	-	99	1	-	-
	1250 ℃	30	70	-	-	62.5	27.5	-	-	98	2	-	-
FC0208	1120 ℃	-	-	100	-	-	-	100	-	-	-	100	-
	1200 ℃	-	-	100	-	-	-	100	-	-	-	100	-
	1250 ℃	-	-	100	-	-	-	100	-	-	-	100	-



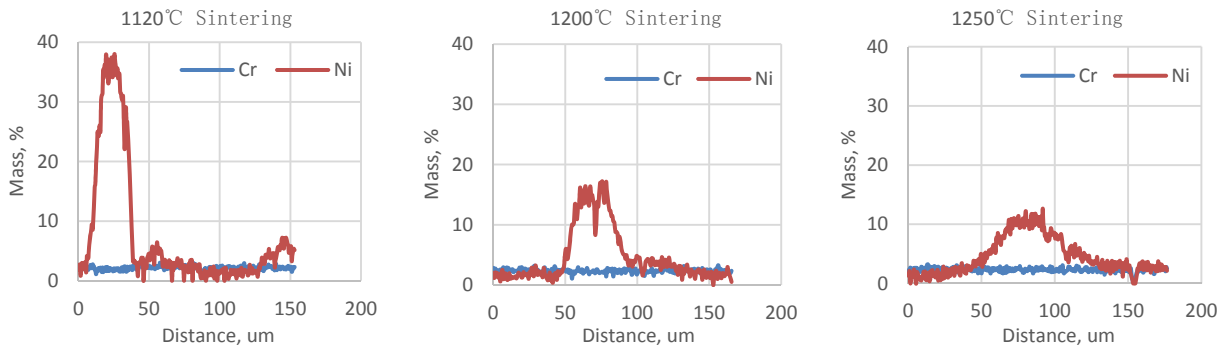


Fig.3. Microstructure and line scan profile of elements of Astaloy CrA+2%Ni+0.8%C sintered at different temperatures.

3.2.Dimensional change

Figure 4 shows the dimensional change from green to as-sintered, obtained for the five materials during sintering at three different temperatures, and at three cooling rates. As can be seen, dimensional change achieved when sintering at 1120 ℃ and 1200 ℃ showed a swelling for Distaloy DH and Fe-Cu-C, whereas the Astaloy CrM, Astaloy CrA+Ni/Cu showed a shrinkage when sintering at all three sintering temperatures. When the sintering temperature was increased from 1120 ℃ to 1250 ℃, shrinkage increased for all five materials. The Astaloy CrA+2%Ni showed the greatest shrinkage (0.75 %) compared to the other materials at a 1250 ℃ sintering temperature. This increased shrinkage is due to more active sintering, a more even element distribution, and smaller, rounder pores observed in the microstructure.

It is also observed that no obvious difference in final dimensional change among these cooling rates for Fe-Cu-C. However, other alloy materials like Distaloy DH, Astaloy CrM and Astaloy CrA showed slightly larger swelling or smaller shrinkage at a higher cooling rate. This was expected because the higher amount of martensite observed at a higher cooling rate results in slightly increased dimensions.

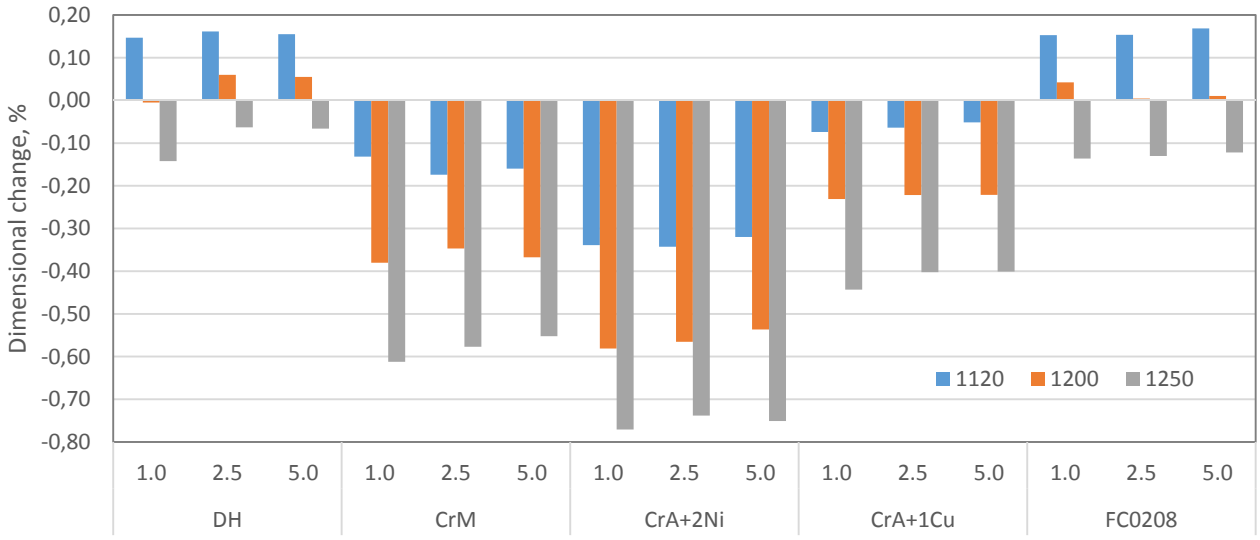


Fig.4. Dimensional change of the test bars from green to as-sintered.

In order to examine the influence of the sintering furnace on cooling rate and dimensional change, further investigations were conducted using a dilatometer on typical sinter-hardened materials. These results are shown in Figure 5. It can be seen that dimensional change behavior was slightly different across these cooling rates as different phases were formed during cooling. These include more bainite for Distaloy DH, and more pearlite for Astaloy CrA+Ni at 1 ℃/s, but the final dimensional change after complete cooling was similar across different cooling rates. Therefore, no obvious difference in dimensional change across cooling rates was observed for any of the alloyed materials.

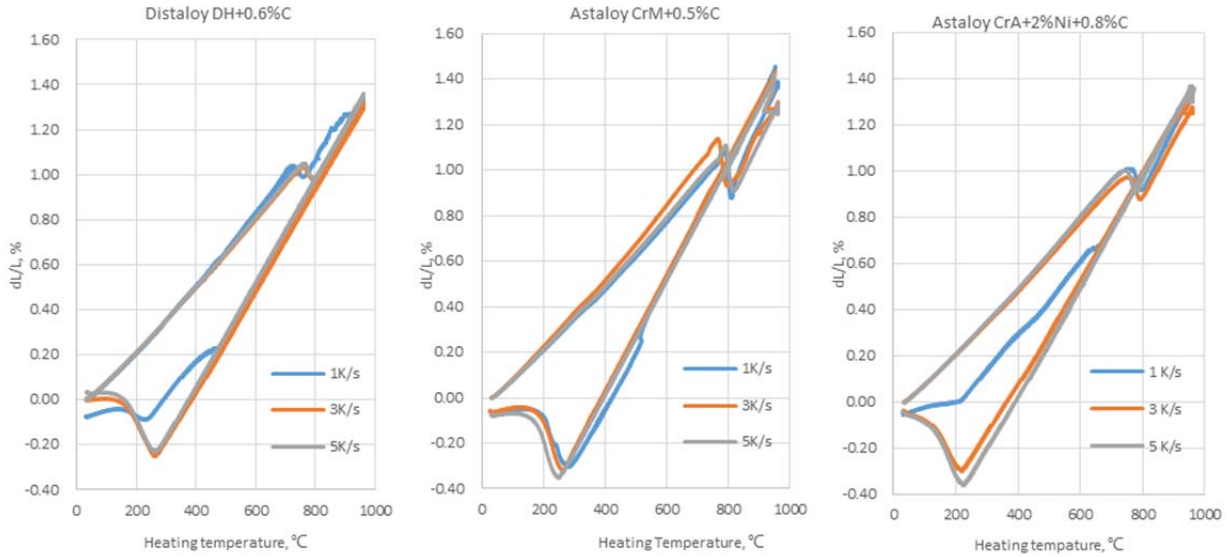


Fig. 5. Dilatometry profile of Distaloy DH, Astaloy CrM and Astaloy CrM+Ni.

3.3.Dimensional precision on the prototype gear

Dimensional precision was evaluated using the height and diameter roundness of sampled gear parts. Figure 6 shows the standard deviation and average value of four measuring points on the height of parts described above. A slightly larger variation was shown by the FC0208 when sintering at 1120 ℃, compared to other alloyed materials. This is because the FC0208 material was admixed with 2 % copper powder and CrA+Cu was admixed with 1 % copper powder, whereas other alloyed materials were diffusion bonded or pre-alloyed.

When the sintering temperature was increased to 1200 ℃ and 1250 ℃, the variation in all materials was similar and decreased considerably when compared to 1120 ℃. Astaloy CrM and Astaloy CrA+2%Ni showed more reduction at a sintering temperature of 1250 ℃. However, no obvious differences in height variation were observed across cooling rates. Figure 7 presents the average roundness difference on the tooth top, tooth root and inner diameter.

The change from green to as-sintered showed how much deformation the roundness occurred during sintering. A higher roundness difference means more deformation. A smaller roundness difference was observed at a higher sintering temperature, in a similar way to the height results. The smaller variation in height and diameter obtained with a high sintering temperature supported more active sintering and more element diffusion. In addition, a more even microstructure, despite a higher

dimensional change at a 1200 ℃ and 1250 ℃ sintering temperature. Most of the results showed that a higher cooling rate could result in a slightly larger roundness difference.

The reasons for this could be that a higher cooling rate leads to higher distortion and hence more martensite, with tempering sensitivity promoting more dimension fluctuation. Meanwhile, two other factors influencing dimensional precision of the gear parts cannot be ignored. The first is that a furnace with capability to provide even heat distribution in the sintering zone, and even gas speed leads to less deformation in the cooling zone. The second reason is the geometry of the gear part used in this investigation is symmetrical and large so is therefore less sensitive to dimensional fluctuation at a high sintering temperature.

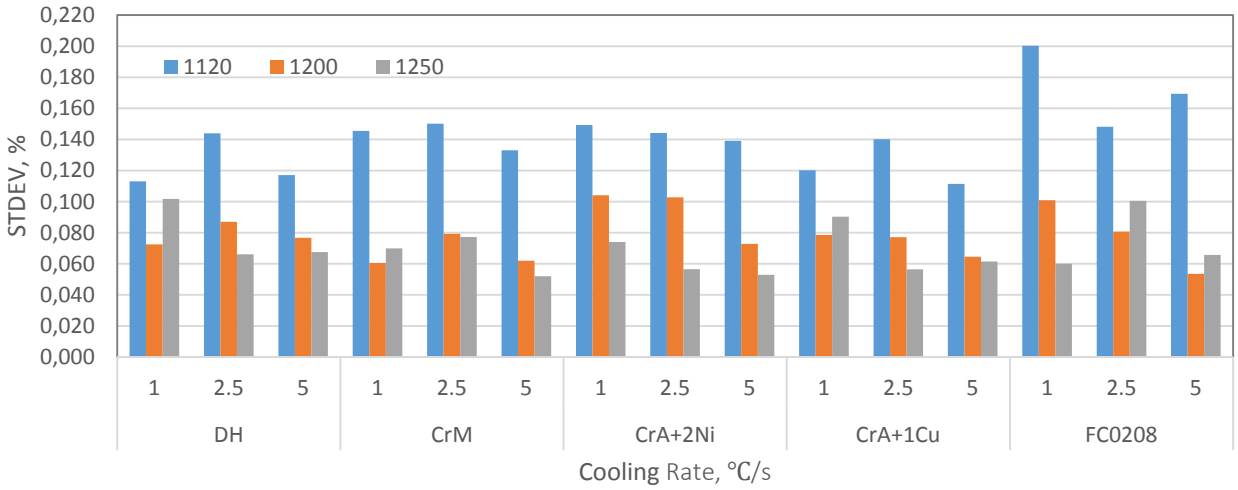


Fig.6. Dimension variations in height of the prototype gear from green to as-sintered.

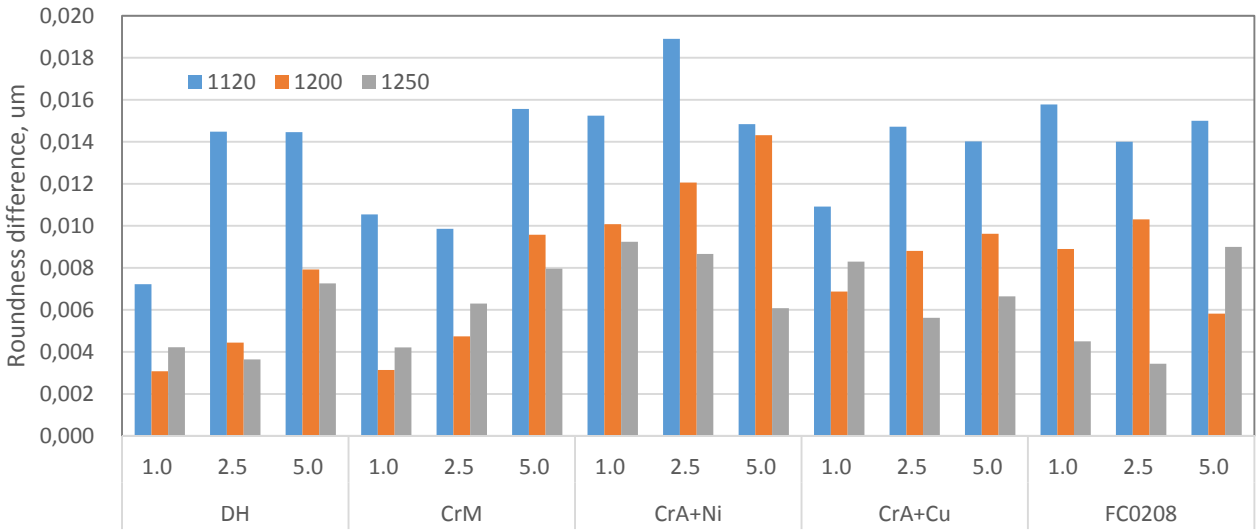


Fig.7. Average roundness difference from green to as-sintered.

4. Conclusions

In this paper, different low alloy PM materials sintered at different temperatures and cooling rates were examined to better understand the influence of sintering conditions on the dimensional precision of a large prototype gear. The main conclusions that can be drawn are:

(1) Sintering at a high temperature promotes shrinkage in dimensional change green to as-sintered materials, and even including FC0208 at a 1250 ℃ sintering temperature, and there is no obvious effect of cooling rate on dimensional change.

(2) Sintering at a high temperature can improve dimensional precision as it increases diffusion which results in a more even microstructure and rounder pores, while a higher cooling rate provides a slightly greater variation in roundness.

(3) Better variation was shown by the pre alloy and diffusion bonded alloy materials when compared to the FC0208 admixed with elementary Cu when sintering at 1120 ℃. A similar variation was shown for all investigated materials when sintering at 1200 ℃ and 1250 ℃.

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