**Evaluating the Effects of Mass and Density on the Sinterhardening Response of Different PM Steels**

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## ABSTRACT

The sinterhardening response of PM steels is affected by many factors, including the alloy system, the cooling rate, density, and component size. In this paper influence of mass and density on the response to sinter hardening has been investigated for some PM steels. Micro structural transformations, macro hardness and plane bending fatigue performance of un-notched and notched specimens have been evaluated. It is shown that the performance is highly depending on both surface hardness but also strongly on the martensite gradient in the part. Higher amount of martensite in the surface induces compressive residual stresses that are beneficial for the fatigue performance. The effect is more pronounced for notched materials compared to un-notched and this strongly compensates for the raised stress in the notch root. This information is of great value for selecting optimal sinter hardening material and processing parameters for a given application.

## INTRODUCTION

According to MPIF Standard 35 for PM Structural Components, sinterhardening is defined as "materials with sufficient hardenability to enable hardening during the cooling cycle after sintering[1]." The standard further states that the materials "exhibit a predominantly martensitic microstructure[1]." By achieving a hardened condition in the as-sintered state, a secondary heat treatment is not required. The elimination of secondary heat treatment can provide reduced processing cost, avoidance of environmentally challenging quench oil, and improved dimensional capability[2]. However, sinterhardening has disadvantages that include potentially expensive alloy systems and difficulty machining in the as hardened condition[2].

There are many factors that affect the sinterhardening response of PM materials. Some of the factors are the sintering cycle, the material composition, component density, the part mass and cross sectional area, and the furnace loading, or mass per square foot of furnace belt[3]. One of the most discussed aspects of the sintering cycle is the cooling rate. However, the time at temperature and the sintering temperature also play an important role in the final sinterhardened properties achieved[3]. Higher cooling rates may be realized by increasing the belt speed (shortening the sintering cycle). This technique may result in higher apparent hardness, but often other physical properties, such as yield strength, may be reduced[3].

The material composition is important for the final properties. In order to increase the hardenability sufficiently for sinterhardening to occur, alloys such as Mo, Ni, Cr, and Mn are pre-alloyed in the base iron[2]. Pre-alloying increases hardenability but has a negative effect on cost, particularly when Mo and Ni are utilized. Density is also an important factor. Increasing density increases thermal conductivity and

improves actual part cooling rate[1]. The actual mass through the furnace is also important. The higher the furnace load, or number of parts per square foot of belt, the lower the actual cooling rate of the parts[3].

## EXPERIMENTAL PROCEDURE

The purpose of the experiment was to evaluate the effect of cooling rate, part size (mass), and density on the sinterhardening response. In order to evaluate these parameters, the following two mix compositions based on Astaloy CrM$^{tm}$ and Astaloy CrL$^{tm}$ were utilized. Table I contains the information regarding the base iron compositions, and Table II contains the actual mix compositions.

**Table I: Base Iron Composition**

| Base Iron | Cr (%) | Mo (%) |
|---|---|---|
| Astaloy CrM$^{tm}$ | 3.0[1] | 0.5[1] |
| Astaloy CrL$^{tm}$ | 1.5[1] | 0.2[1] |

1. Pre-alloyed

**Table II: Mix Composition**

| Mix | Base Iron (Balance) | Copper[1] (%) | Graphite[2] (%) | Lubricant[3] (%) |
|---|---|---|---|---|
| FL-5305 | Astaloy CrM$^{tm}$ | n/a | 0.50 | 0.6 |
| FLC-5208 | Astaloy CrL$^{tm}$ | 2.0 | 0.75 | 0.6 |

1. ACuPowder 165
2. Asbury 1651
3. Kenolube$^{tm}$

Slugs of different sizes and densities were manufactured for evaluation of sintering parameters from each of the premixes in Table II. Table III outlines the various slugs manufactured for the test. The slugs were compacted by PowderTech. For slugs with 7.2 g/cm$^3$ green density, press – delube – repress was used.

**Table III: Slug Size and Density**

| Slug Diameter (mm) | Slug Height (mm) | 6.8 g/cm$^3$ Green Density | 7.0 g/cm$^3$ Green Density | 7.2 g/cm$^3$ Green Density |
|---|---|---|---|---|
| 25 | 25 | x | x | x |
| | 50 | x | x | x |
| 50 | 25 | x | x | x |
| | 50 | x | x | x |
| 75 | 25 | x | x | x |
| | 50 | x | x | x |

Sintering was conducted in the North American Höganäs Technology Center using an Abbott 6” Belt Furnace equipped with a Varicool cooling unit. All sintering was done for 30 minutes at 1120 °C (2050 °F) in a 90$^v/_o$ $N_2$/10$^v/_o$ $H_2$ atmosphere. Varicool settings of 0, 15, 30, and 60 Hz were used. All slugs processed using accelerated cooling were tempered at 200 °C (400 °F) for 1 hour in air.

Slugs from each size and density were evaluated for apparent hardness (top and bottom), apparent hardness through the cross section of the slug (top to bottom), and microstructure in the interior of the slug (from top to bottom).

## RESULTS AND DISCUSSION

The results and discussion section of the paper focuses on the properties of the FL-5305 material at 7.0 g/cm$^3$ sintered density. The smallest (25 mm o.d. x 25 mm height) and largest (75 mm o.d. x 50 mm height) are compared at the highest (60Hz) and lowest (0 Hz) cooling rates. The results regarding the effects of density will be reviewed in a later publication.

Table I compares the difference in mass and the mass to surface area ratio of the largest and smallest slugs. At 7.0 g/cm$^3$, the 75 mm x 50 mm slug weighs 1470 g more than the smallest slug. The largest slug also has a mass to surface area ratio approximately 2.5x less than the smaller 25 x 25 mm slug. By comparing the mass and surface area to mass ratio, it can be hypothesized that the larger slug will not achieve the same effective cooling rate as the smaller slug, even at the same varicool setting.

**Table IV: Mass and Surface Area to Mass Ratio of Different Size Slugs**

| Slug Size (o.d. x height) | Mass @ 7.0 g/cm$^3$ (g) | Surface Area to Mass @ 7.0 g/cm$^3$ (mm$^2$/g) |
|---|---|---|
| **25 mm x 25 mm** | 86 | 34.3 |
| **75 mm x 50 mm** | 1545 | 13.3 |

Table II shows the microstructures and effective cooling rate for the FL-5305 materials at 7.0 g/cm$^3$ and highest and lowest varicool settings. For the 25 mm x 25 mm slug at 0 Hz, a bainitic/martensitic microstructure is achieved[4]. Based on dilatomer studies, this bainitic/martensitic microstructure corresponds to an effective cooling rate of approximately 0.5 °C/s. When the varicool speed is increased to the maximum, 60 Hz, a 100% martensitic microstructure is achieved. This 100% martensitic microstructure corresponds to an effective cooling rate of approximately 2.0 °C/s.

When the size of the slug is increased to 75 mm x 50 mm, the same varicool settings do not achieve the same microstructure. When the larger slug is processed at 0 Hz, a 100% upper bainitic microstructure is achieved. This 100% upper bainite structure corresponds to an effective cooling rate of approximately 0.25 °C/s. When the varicool is set at the maximum of 60 Hz, a bainitic/martensitic microstructure is achieved, very similar to the microstructure with the smaller slug at 0 Hz.

The difference in microstructure between the largest and smallest slugs illustrates the importance of testing cooling rate with an appropriately sized component. The difference in effective cooling shows that the setting of the varicool is not necessarily an appropriate indicator of final microstructure. The mass and surface area can influence the effective cooling rate of the components. In the example used here, there is a reduction in effective cooling rate of approximately 1.5 °C/s, resulting in significantly different microstructures at the same furnace setting.

**Table V: Microstructure and Effective Cooling Rate on FL-5305 Material at two Different Varicool Settings**

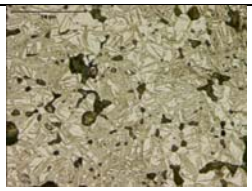
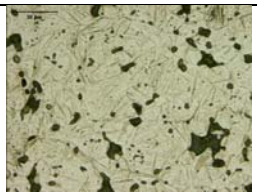
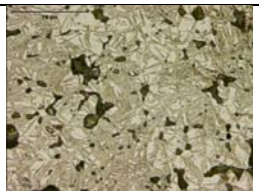
| Slug Size (o.d. x height) | Varicool = 0 Hz | Varicool = 60 Hz |
|---|---|---|
| **25 mm x 25 mm** |  |  |
| | **Bainite/Martensite Effective Cooling Rate ~ 0.5° C/s** | **Martensite Effective Cooling Rate ~ 2.0° C/s** |
| **75 mm x 50 mm** |  |  |
| | **Bainite Effective Cooling Rate ~ 0.25° C/s** | **Bainite/Martensite Effective Cooling Rate ~ 0.5° C/s** |

Table III compares the difference in apparent hardness between the top of each slug and bottom of each slug (belt side). As can be seen, although each material sees a different effective cooling rate at the same furnace settings, the apparent hardness achieved is virtually identical between the top and bottom of the slugs, regardless of size. This consistency was also seen throughout each different size slug. Although the effective cooling rate may change depending on the mass and surface area, the effective cooling rate is consistent regardless of mass and surface area for the FL-5305 material system.

**Table VI: Comparison of Top and Bottom Apparent Hardness of FL-5305 Slugs at two Different Cooling Rates and two Different Sizes**

| Varicool Setting | Slug (o.d. x height) | Apparent Hardness – Top (HRC) | Apparent Hardness – Bottom (HRC) |
|---|---|---|---|
| **0 Hz** | **25 mm x 25 mm** | 23 | 23 |
| **0 Hz** | **75 mm x 50 mm** | 98 (HRB) | 97 (HRB) |
| **60 Hz** | **25 mm x 25 mm** | 36 | 35 |
| **60 Hz** | **75 mm x 50 mm** | 22 | 21 |

## CONCLUSIONS

Based on the evaluation, the following conclusions can be made:

1. For the material system investigated, the mass and surface area of the part affected the sinterhardened properties achieved.

2. The effective cooling rate achieved on actual parts varied by up to 1.5°C/s between the largest and smallest slugs

3. The apparent hardness and microstructure of each slug was consistent throughout the cross section.

## ACKNOWLEDGMENTS

The authors would like to acknowledge Mary Schmidt from the West Virginia University. Mary's help in generating the data for this paper was invaluable.

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