COMPARISON OF FATIGUE PROPERTIES OF HEAT TREATED GEARS OBTAINED BY DOUBLE PRESSING AND SINTERING AND WARM COMPACTION

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ABSTRACT

Warm Compaction of Densmix™ powders provides means to produce P/M parts with densities in the range of 7.1 to 7.4 g/cm^3. As most properties are improved by increased density, the warm compaction method offers possibilities to increase the competitiveness of P/M compared to other manufacturing techniques.

In this paper a comparison of material properties obtained by two different manufacturing routes is presented. Heat treated properties of some P/M steels after double pressing/sintering are compared with properties obtained with sinterhardening and conventional heat treating of warm compacted Densmix™ powders. Additionally, the single tooth static rupture force and the single tooth bending fatigue strength will be presented.

INTRODUCTION

The original purpose of the work was to determine if a gear currently being manufactured by double pressing/double sintering and heat treating could be replaced by a warm compacted and sinter hardened gear. Double press/double sinter is currently used to manufacture a family of gears for an automotive application. The current producer of this component is interested in reducing the manufacturing cost of the gear without sacrificing performance. By converting to warm compaction and sinterhardening, three manufacturing processes (pre-press, pre-sinter, heat treat) would be eliminated.

The scope of manufacturing processes to be evaluated was expanded to include conventional sintering and secondary heat treating combined with warm compaction. This alternative still offers a significant cost advantage, although it only eliminates two processing steps.

The paper is divided into two parts. Part I of the paper focuses on the material properties achieved using test bars sintered and heat treated using standard production conditions. Part I was completed to

determine the material most likely to meet the goal of warm compaction – sinterhardening, or alternately warm compaction – sinter – conventional heat treat. Part II of the paper focuses on the warm compaction of actual production gears and methods of evaluating and comparing performance.

MATERIALS

Two materials were investigated based on Astaloy 85Mo and D.DC. The compositions of the base materials are shown in Table 1 and the composition of the mixes is shown in Table 2. The existing material is described below as Pre-mix and is based on Astaloy 85Mo with 0.4 $^{w}/_{o}$ Graphite and 0.6 $^{w}/_{o}$ lubricant. The warm compacted materials are referred to as WC Mixes

The Astaloy 85Mo was chosen for testing because it was the current material being tested. This material will typically not respond to sinterhardening under currently available conditions, but it was included as to use as a baseline for heat treated properties. The second material selected was D.DC. This material responds well to sinterhardening and the nickel in the material provides a density increase during sintering.

Table I: Chemical composition of Base Materials

Grade	Mo %	Cu %	Ni %
Astaloy 85 Mo	0.85*	-	-
D.DC	1.47*	-	2.10**

* Pre-Alloyed
** Diffusion Bonded

Table II: Chemical Composition of Mixes

Pre-blend Type	Description	Base Material	Graphite ($^{w}/_{o}$)	Ni ($^{w}/_{o}$)	Cu ($^{w}/_{o}$)	Lubricant ($^{w}/_{o}$)
Pre-mix	Pre-mix	Astaloy 85Mo	0.4	-	-	0.8
Densmix™ 1	WC mix 1	Astaloy 85Mo	0.4	-	-	0.6
Densmix™ 2	WC mix 2	Astaloy 85Mo	0.6	1.0	1.0	0.6
Densmix™ 3	WC mix 3	D.DC	0.6	-	-	0.6

PART I: MATERIAL PROPERTIES ACHIEVED WITH TEST SPECIMENS

PROCESSING CONDITIONS

Testing was initially completed on all the material combinations using test bars and production processing conditions. Tables III – V outline the processing conditions for the test specimens. All test specimens were manufactured in the Höganäs AB lab on the Result semi-automatic press. Sintering and tempering were carried out at the customer on production equipment. Heat treatment was performed at an outside vendor. The tensile bars were prepared to ISO 2740 and the impact energy bars to ISO 5754. Bending fatigues testing was carried out for limited sample (see Table VII).

Table III: Current Production Processing Conditions

1. Press	2. Pre-Sinter	3. Re-press	4. Sinter	5. Heat Treat	6. Temper
700MPa	750°C	400MPa	1138°C	843°C	177°C
(50tsi)	(1382°F)	(29tsi)	(2080°F)	(1550°F)	(350°F)
	90%N_2/		38 minutes @	1 hour	1 hour
	10%H_2		Temp	0.7% C-pot	Air
				Oil Quench	

Table IV: Initial Processing Conditions for WC Mix 1 – 3

1. Warm Compact	2. Sinterharden	3. Temper
700MPa	1132°C	177°C
(50tsi)	(2070°F)	(350°F)
	26 minutes @ Temp	1 hour
	Estimated Cooling Rate:	Air
	1.5 °C/s (2.7 °F/s)	

Table V: Additional Testing for WC Mix 1 – 3

1. Warm Compact	2. Sinter	3. Heat Treat & Quench	4. Temper
700MPa	1138°C	843°C	177°C
(50tsi)	(2080°F)	(1550°F)	(350°F)
	38 minutes @ Temp	1 hour	1 hour
		0.7% C-pot	Air
		Oil Quench	

PROPERTIES

The following section contains the properties achieved with the different materials and processing methods. Testing was performed at North American Höganäs and Höganäs AB.

Table VI: Densities and Dimensional Change of Test Specimens

Mix Type	Green Density (g/cm^3)	Sintered Density (g/cm^3)	Dimensional Change – From Die (%)
Pre-mix [2]	7.33[1]	7.31	0.13[1]
WC mix 1[3]	7.35	7.34	0.06
WC mix 2[3]	7.33	7.24	0.28
WC mix 3[3]	7.33	7.32	0.04
WC mix 1[4]	7.35	7.33	0.13
WC mix 2[4]	7.32	7.26	0.18
WC mix 3[4]	7.33	7.33	0.13

1. Density and dimensional change after second pressing/second sinter.

2. Press – Pre-sinter – Re-press – Sinter – Heat Treat - Temper
3. Warm Compact – Sinterharden – Temper
4. Warm Compact – Sinter – Heat Treat - Temper

Table VII: Mechanical Properties of Test Specimens

Mix Description	UTS MPa (ksi)	Yield Strength MPa (10^3psi)	Elongation A %	Apparent Hardness HV10 (HRB, HRC)	Bending Fatigue MPa (10^3 psi)	Impact Energy J (ft-lb_f)
Pre-mix[1]	1114 (162)	1000 (145)	0.3	563 (C53)	361 (52)	15 (11)
WC mix 1[2]	568 (82)	440 (64)	2.9	175 (B85)	N/A	24 (18)
WC mix 2[2]	1062 (154)	918 (133)	0.4	332 (C34)	N/A	16 (12)
WC mix 3[2]	1100 (160)	862 (125)	0.9	344 (C35)	N/A	20 (15)
WC mix 1[3]	1170 (170)	1015 (147)	0.3	559 (C53)	375 (54)	12 (9)
WC mix 2[3]	1044 (151)	979 (142)	0.7	492 (C49)	N/A	13 (10)
WC mix 3[3]	1134 (164)	1034 (150)	0.4	522 (C51)	N/A	16 (12)

1. Double Press/Double Sinter – Heat Treat – Temper
2. Warm Compact – Sinterharden – Temper
3. Warm Compact – Sinter – Heat Treat - Temper

METALLOGRAPHY

Metallographic analysis was performed on the samples after heat treating and sinterhardening. Percentages of phases present were estimated metallographically.

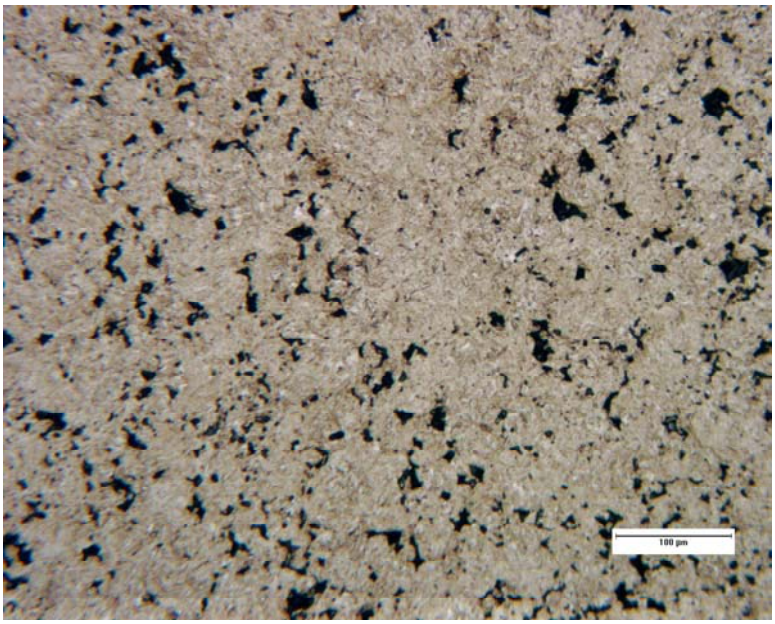


Figure 1 : Pre-mix 1, heat treated, 100% Martensite

Pre-mix exhibits complete martensite transformation due to secondary heat treat and quench. Pore distribution is good, with the presence of some large pores.

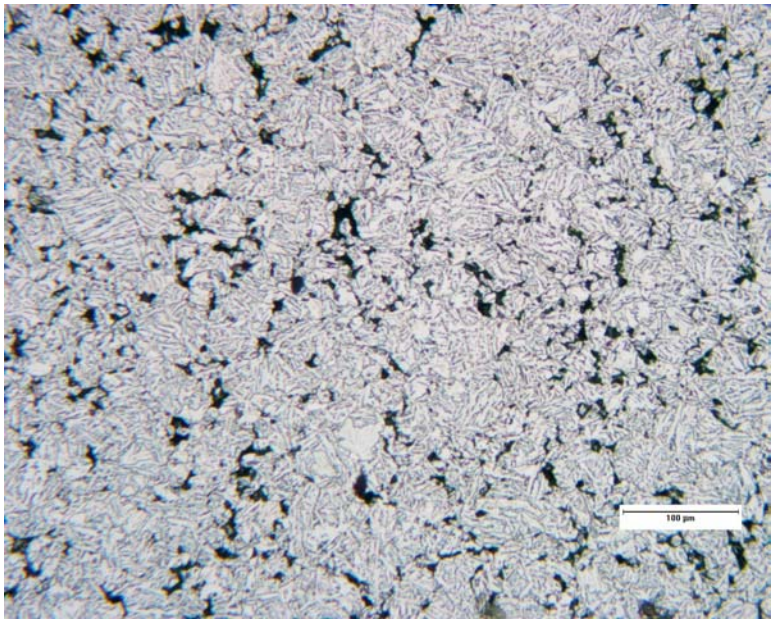


Figure 2: WC Mix 1, sinterhardened, 100% Bainite

WC Mix 1 exhibits limited response to sinterhardening at available cooling rate. Microstructure is Bainitic with good pore distribution.

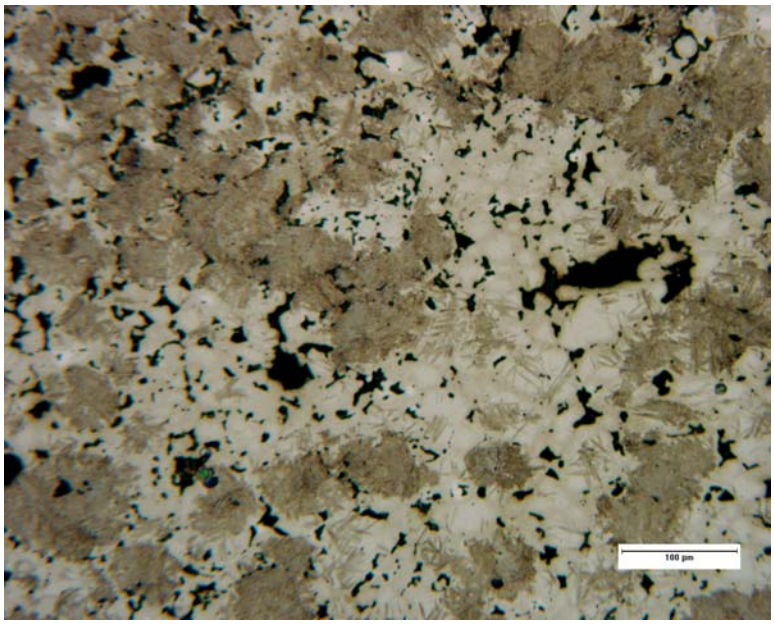


Figure 3: WC Mix 2, sinterhardened 55 – 60% Martensite + Bainite + Ni-rich Austenite

WC Mix 2 exhibits higher level of martensite transformation. This can be attributed to the addition of elemental nickel and copper[2]. The addition of elemental copper also leaves large pores from the prior copper locations.

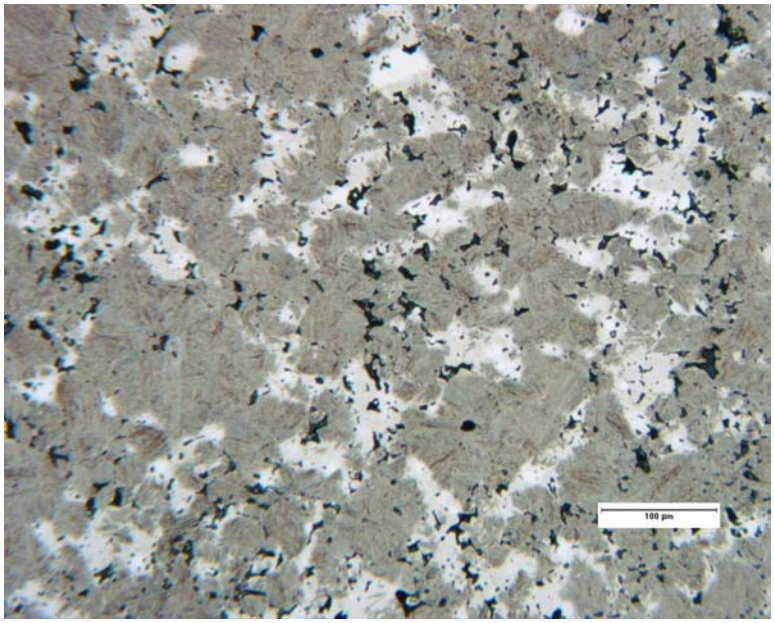


Figure 4: WC Mix 3, sinterhardened, 25% Martensite + Ni-rich Austenite + Bainite

WC Mix 3 shows higher martensite transformation than WC Mix 1. WC Mix 3 has higher Molybdenum content (1.5% vs. 0.85%) and diffusion bonded nickel (2%), which contributes to better hardening response[2]. There is good pore distribution and an absence of large pores.

PART II: PRODUCTION GEARS

PROCESSING CONDITIONS

Based on the results attained by the test specimens, it was determined that the existing sintering equipment did not have the required cooling capacity to achieve the required martensite transformation. Therefore, production of warm compacted gears focused on two of the material combinations that were warm compacted and heat treated, WC1 and WC3.

Production gears were warm compacted at Brockway Pressed Metal using a production press and a mobile warm compaction unit. A controller and heater were temporarily set up on the production press for the purpose of the warm compaction trials.

PROPERTIES

The gears were then tested to determine the static tooth rupture force and the single tooth bending fatigue strength. The results of the testing were compared to the results of the current process. The density variation in the components was also calculated.

Table VIII shows a comparison of the density in the actual production gears.

Table VIII: Sintered Gear Density

	Sintered Density (g/cm^3)
Pre-mix[1]	7.40
Warm Compacted	7.35

The static tooth rupture force cannot be evaluated on the gears in the as manufactured condition due to the limitations of the fixture. The length and geometry of the teeth would likely require a break force higher than the fixture is capable of withstanding without deformation. Since this deformation could invalidate the results, sections of the gear are used to determine the static tooth rupture strength. The gears are cut into three 8mm sections. The mid-sections are used since the chamfers on the end sections may lead to biased results.

The single tooth rupture strength is performed on an Amsler 10SZD tensile testing machine. Figure 5 describes the type of setup used to test the pinions. The testing was performed over four teeth. Spacers were used during setup to ensure correct location of test jaws.

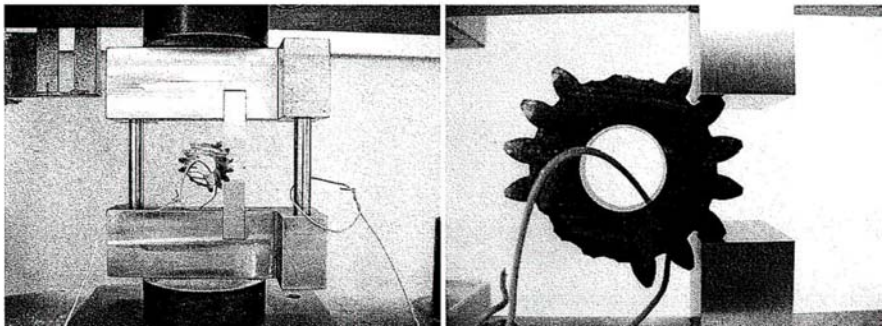


Figure5: Single Tooth Rupture Test Setup

The single tooth bending fatigue of the gears was also determined. Figure 6 shows the test set up and loading curve over four teeth used for the testing.

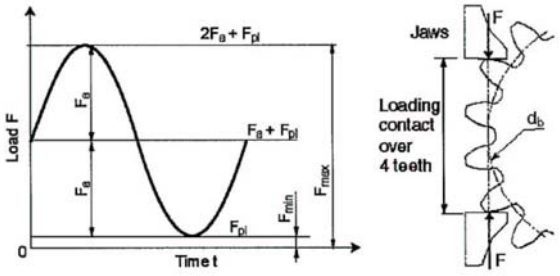


Figure 6: Loading Method for Single Tooth Bending Test

S-N curves were generated for each processing condition. The testing was begun at a level of approximately 25% of the static tooth rupture strength. Samples were processed to failure, in the limited endurance region, and then to run out. Figure 7 shows the single tooth bending fatigue achieved by the current process.

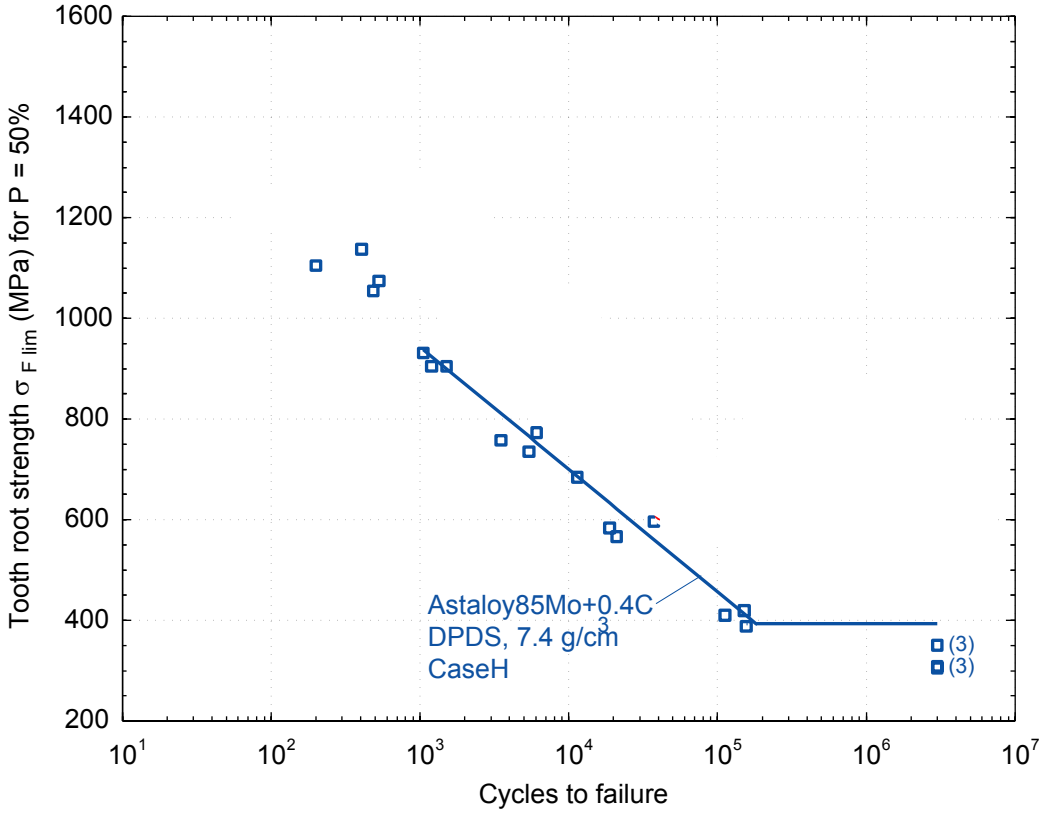


Figure 7: Single Tooth Bending Fatigue Strength

DISCUSSION

The green density levels attained by warm compaction are greater than or equal to the density levels achieved by double press/double sinter. The current process reaches green densities of 7.33 g/cm^3 after double press/double sinter. With warm compaction, WC Mix 1 and 3 reached 7.33 g/cm^3 and WC Mix 2 admixed copper and nickel reached 7.32 g/cm^3.

The sintered density for the double press/double sinter premix was 7.31 g/cm^3. WC Mix 1 and 3 reached sintered densities of 7.33 g/cm^3. WC Mix 2, with admixed copper and nickel, reached a sintered density of 7.26 g/cm^3. This lower density is reflected in the larger dimensional change for this material, likely due to the addition of copper.

The hardness levels achieved by the secondary heat treatment were approached but not achieved during the sinterhardening test. The pre-mix using the double press/double sinter – heat treat process yields an apparent hardness of 563 HV10 (53 HRC). The highest apparent hardness achieved with the proposed materials was 332 HV10 (34 HRC) WC Mix 2, which has admixed copper and nickel. The WC Mix 3 composition reached an apparent hardness of 344 HV10 (35 HRC). The response to sinterhardening for

WC Mix 2 and 3 could also be improved by increasing the graphite level. WC Mix 1, based on the existing composition, only reached a hardness of 175 HV10 (85 HRB). The low hardness level was in part due to the low level of admixed graphite (0.4%) and the lack of additional alloying elements such as copper.

The available production sinterhardening furnace is not able to reach a sufficient cooling rate to achieve the amount of martensite transformation required. The cooling rate was estimated metallographically to be approximately 1.5 ^{o}C/s (2.7^{o}F/s). In order to achieve high levels of martensite with WC Mix 3, a minimum cooling rate of 4 ^{o}C/s (10^{o}F/s) would be required. WC Mix 1 would require a rate of approximately 50+ ^{o}C/s (90^{o}F/s). With WC Mix 2 there is a greater level of martensite transformation (approximately 55%), which can be attributed to increased graphite and the addition of elemental copper and nickel. The required cooling rates are not currently possible on the existing production equipment.

The sinterhardening process also approached but did not achieve the current levels of physical properties. Although the impact energy and elongation exceeded the current process, the ultimate tensile strength and yield strength were lower compared to the current process (see Table VII).

When warm compaction was combined with secondary heat treatment, hardness levels comparable to the existing process were achieved. Hardness levels on the Astaloy 85 Mo without copper and D.DC-1 Densmixes^{TM} reached hardness levels of 559 HV10 (53 HRC) and 522 HV10 (51 HRC), respectively. These numbers compare to the 563 HV10 (53 HRC) achieved by the current process. The Astaloy 85Mo WC Mix with copper reached a hardness of 492 HV10 (49 HRC).

The physical properties of the warm compacted – secondary heat treated materials also matched the current double press/double sinter process (see Table VII). The yield strength for all the materials, except for the Astaloy 85Mo with copper, was greater than 1000MPa (145,000psi). All other physical properties were comparable, including elongation and impact energy. Based on these results, bending fatigue testing was conducted on samples, with equivalent properties achieved (see Table VII). The testing was done at 10^6 cycles, with R = -1.

The pore structure on WC Mix 1 and 3 (Figures 2 and 4) consists of smaller, more evenly distributed pores than the double press/double sinter material (Figure 1). This improved pore structure would suggest that the dynamic properties of the warm compacted material would exceed the properties of the double press/double sinter material. Fatigue strength has been shown to increase when warm compaction is used. The increase in fatigue strength would not apply to WC Mix 2, due to the large pores remaining from the prior copper locations.

Actual warm compaction trials demonstrate that gears can be produced which match the density levels of the current process. The produced samples will allow actual application testing to be performed at the end user. This evaluation will determine if the lab testing results are reflected in the actual application.

CONCLUSIONS

The testing has shown that warm compaction with an Astaloy 85Mo based (matching current material) or a D.DC-1 (with 0.6%C) based Densmix^{TM} allows density levels to be achieved which meet or exceed the levels achieved by the existing double press/double sinter process. By reaching these density levels, the physical properties, including hardness, can match the current process and eliminate the pre-press and pre-sinter operations, offering a significant cost savings.

Based on the testing, it has been determined that the Astaloy 85Mo based processing using secondary heat treatment offers the best replacement for the existing process due to lower cost that the diffusion bonded alternative.

REFERENCES

[1] Höganäs Handbook for Sintered Components, 1998, Vol.6

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