High Density Processing of Ancorloy MDC Materials

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ABSTRACT

Previous experimental work has shown that silicon containing steels exhibit high tensile properties and impact strength at relatively low densities ranging from 7.0 to 7.1 g/cm^3. Higher densities via AncorMax D™ processing has shown that sintered densities in excess of 7.3 g/cm^3 are possible at compaction pressures ranging from 550 to 760 MPa. (40 to 55 tsi) This paper will examine the metallurgical and mechanical enhancements achieved through the AncorMax D process and high temperature sintering of the Ancorloy™ MDC and Ancorloy™ MDCL materials at densities ranging from 7.0 to in excess of 7.3 g/cm^3.

INTRODUCTION

Several silicon-containing materials were introduced by Hoeganaes Corporation to compete with malleable and ductile cast irons. These materials are designated as Ancorloy MDA, MDB and MDC. [1,2] Previous experimental work on these materials has focused on compaction utilizing conventional lubricants and has shown to exhibit tensile strengths up to 1250 MPa (180,000 psi), tensile elongation greater than 3%, impact energies of 10 – 28 Joules (7 – 21 ft-lbf) and apparent hardness values up to 73 HRA. [2] As an alternative route to improve these materials by increasing their densities, this work will investigate the AncorMax D process, which provides a higher green density by reducing the amount of additives within the premix. The materials chosen for this study were Ancorloy MDC and Ancorloy MDCL.

BACKGROUND

The AncorMax D process enables the end user to achieve up to 98% pore-free densities. This premix technology features a proprietary lubricant/binder system. AncorMax D processed premixes require a high compaction pressure of 550 – 823 MPa (40 – 60 tons/in^2). Additionally, die temperatures must be maintained in the range 60 – 70 °C (140 – 150 °F) which is easily achieved with cartridge heaters incorporated within the die. Warm die compaction, coupled with advanced lubricant/binder systems have been shown to increase green densities without heating the powder [3].

EXPERIMENTAL PROCEDURE

Two press ready, binder treated materials, MDC and MDCL were tested in a production environment to evaluate their properties through a single press/single sinter process. MDCL is a leaner version of MDC,

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with a silicon content of 0.35 w/o instead of 0.70 w/o. A total lubricant content of 0.55 w/o was used for each premix. The material chemical analysis is presented in Table I.

The Ancorsteel 85HP is premixed with 4.0 w/o nickel, 0.60 w/o graphite and 0.70 w/o silicon. A 225 kg. (500 lb.) premix was made for each composition. The nickel used was INCO 123 and the graphite was Asbury 3203.

Table I. Base Chemistries for MDC and MDCL

ID	Fe w/o	Mo w/o	Ni w/o	Si w/o	Cr w/o	Mn w/o	Gr w/o
MDC	**Bal.**	**0.85**	**4.00**	**0.70**	**0.03**	**0.13**	**0.60**
MDCL	**Bal.**	**0.85**	**4.00**	**0.35**	**0.03**	**0.13**	**0.60**

TEST SPECIMEN

Transverse rupture (ASTM B-528), tensile (ASTM E-8), and impact (ASTM E-23) and fatigue tests were conducted on both premixes. The samples were compacted at pressures varying from 550 to 760 MPa, (40 to 55 tsi) using heated die systems at 63 °C (145 °F). Green density, sintered density, and transverse rupture strength was determined from the average of five compacted transverse rupture (TRS) specimens. Tensile strength, yield strength, and maximum elongation were obtained from the average of five dog-bone tensile samples. Impact energy was determined from the average of five un-notched Charpy Impact bars. Apparent hardness measurements were performed on the surface of the TRS bars using a Rockwell hardness tester. All measurements were conducted using the HRC scale for ease of comparison.

Tensile testing were performed on a 267,000 N (60,000 lb.) Tinius Olsen universal testing machine with a crosshead speed of 0.635 mm/min (0.025 in/min). Elongation values were determined by utilizing an extensometer with a range of 0 - 20%. The extensometer was attached to the samples up to failure. Transverse rupture strength and dimensional change from die size were measured according to MPIF Standard 41. Impact energies were determined according to ASTM E 23.

Rotating bending fatigue samples were pressed at 690 MPa (50 tsi) and machined from blanks that were sintered at 1176 - 1260 °C (2150 - 2300 °F) under an atmosphere of 90 v/o N_2 -10 v/o H_2. Testing was performed on six randomly selected Fatigue Dynamics RBF-200 machines' at a rotational speed of 8000 rpm. ASTM staircase method utilizes 30 samples and a run-out limit of 10^7 cycles. The staircase method of testing was regulated so that there were both failures and run-outs at a minimum of two stress levels. [4] The percentage of failures for each stress level was calculated and plotted on a log-normal graph. From these plots, the fatigue endurance limit (FEL) at 50% and 90% was determined by linear extrapolation. The 50% FEL represents the stress level where 50% of the specimens will break and 50% will run-out. The 90% FEL represents the stress level where 90% of the specimens will run-out and 10% will break. [The MDCL samples sintered at 1176 °C (2150 °F) were not completed at time of publication]

SINTERING

All test pieces were sintered under production conditions in an Abbott continuos belt high temperature furnace at the Hoeganaes R&D facility, Cinnaminson, NJ. The sintering cycles used for the test specimen are listed below. Three sintering temperatures and atmospheres were varied.

Sintering Temperature:	Various (from 1120 – 1260 °C / 2050 – 2300 °F)
Atmosphere:	Various (form 10 v/o H_2, 50 v/o H_2 to 100 v/o H_2)
Time in Hot Zone:	20 minutes
Tempering:	205 °C (400 °F) for 1 hour

RESULTS AND DISCUSSION

Compaction – Green and Sintered Density

In order to establish a frame of reference for the AncorMax D process, the mechanical properties were compared to the standard Ancorloy MDC and MDCL. With the AncorMax D process, higher green densities were achieved with the warm compaction over the conventional compaction process. Figure 1 compares green density of the AncorMax D processing along with conventionally pressed material. Green densities ranged from 7.18 – 7.38 g/cm^3 for the alloys examined. With the AncorMax D processing a difference of 0.11 g/cm^3 for the MDCL and 0.13 g/cm^3 for the MDC at 550 MPa. (40 tsi) was observed. With increasing compaction pressures the difference increased for both compositions up to 0.15 g/cm^3 at a pressure of 760 MPa (55 tsi) over the conventionally pressed materials. This indicates that the AncorMax D process is a more effective process for densification at higher compaction pressures. Figure 2 illustrates sintered density for both processes as a function of compaction pressure. Increases in sintered densities for MDC Max D were .10 - .12 g/cm^3 and for MDCL Max D were .08 - .13 g/cm^3.

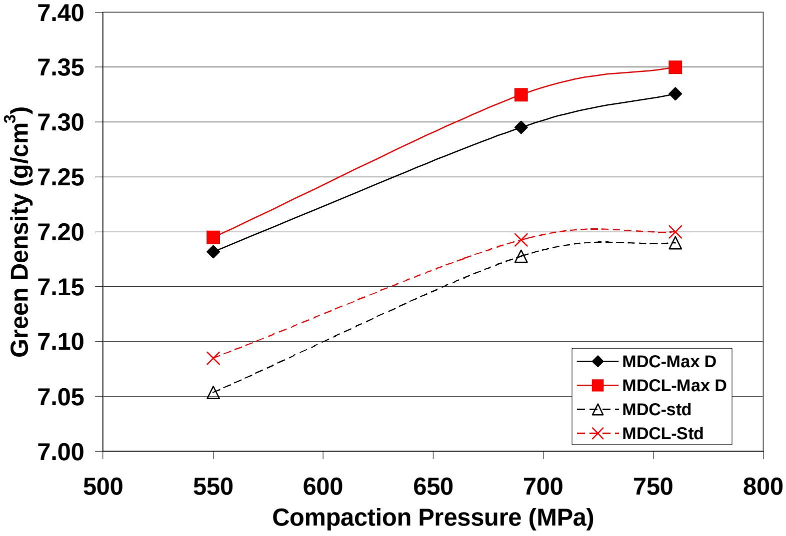

Figure 1: Effect of alloy and processing condition on green density

Dimensional Change

The dimensional change after tempering the samples can be found in Table II. As expected the dimensional change of the samples sintered at 1260 °C (2300 °F) varied from the samples sintered 1120 °C – 1176 °C (2050 °F – 2150 °F). The high temperature samples increased in density with a higher degree of shrinkage from die size. The samples sintered at the lower temperatures exhibited dimensional changes with less shrinkage resulting in the lower sintered densities. It is interesting to note that even with the higher densities, the AncorMax D samples exhibited lower dimensional change that were closer to die size. Therefore the potential distortion associated with high temperature sintering is less of a problem with these higher density alloys. Dimensional changes for the alloys are listed in Table III and Figure 3.

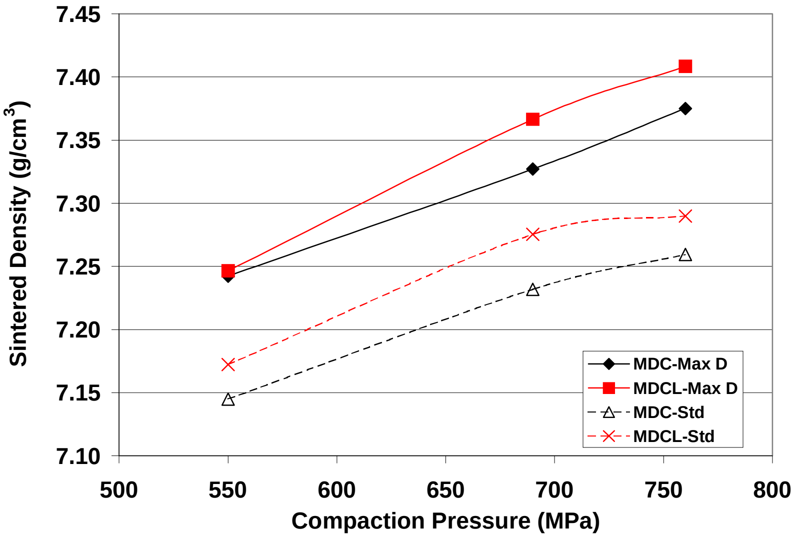

Figure 2: Effect of alloy and process condition on sintered density (sintered at 2300°F - atmosphere of 90 v/o N_2 – 10 v/o H_2).

Table II: Dimensional Change from Die Size Collected over a Range of Sintering Temperatures (atmosphere of 90 v/o N_2 – 10 v/o H_2), Tempered in Air at 205 °C (400 °F) for 1 hour

Material	Comp Pressure MPa / tsi	1120°C / 2050°F DC (%)	1176°C / 2150°F DC (%)	1260°C / 2300°F DC (%)	Total DC Range (%)
MDC-Max D	550 / 40	-0.14	-0.25	-0.33	-0.019
	690 / 50	0.02	-0.08	-0.15	-0.017
MDCL-Max D	550 / 40	-0.10	-0.22	-0.33	-0.023
	690 / 50	-0.03	-0.18	-0.27	-0.024

Table III: Dimensional Change Comparison (sintered at 1260 °C (2300 °F) - atmosphere of 90 v/o N_2 – 10 v/o H_2), Tempered in Air at 205 °C (400 °F) for 1 hour

Comp Pressure MPa / tsi	MDC-Max D	MDCL-Max D	MDC-Std	MDCL-Std
550 / 40	-0.33	-0.33	-0.47	-0.41
690 / 50	-0.15	-0.27	-0.31	-0.31
760 / 55	-0.11	-0.20	-0.29	-0.30

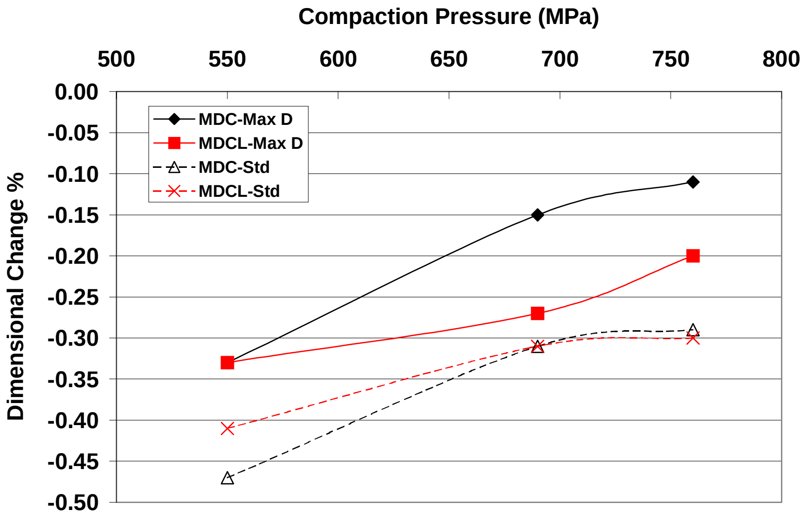

Figure 3: Effect of alloy and process condition on dimensional change (sintered at 1260 °C (2300 °F) - atmosphere of 90 v/o N_2 – 10 v/o H_2) tempered in air at 205 °C (400 °F) for 1 hour

Apparent Hardness / Impact Energy

The impact energies and apparent hardness values are listed in Tables IV and V. It is apparent that the higher sintering temperature resulted in the high impact properties. The MDCL-Max D material attained impact energies as high as 41 J (30 ft-lbf). A general trend line of impact energy and apparent hardness for common P/M grades is illustrated in Figure 4.[5] The impact energies of the samples sintered at 1176 °C (2150 °F) follow the same trend for the common P/M grades. The samples sintered at 1260 °C (2300 °F) demonstrated superior impact characteristics, which may open P/M up to more highly stressed, impact loaded applications.

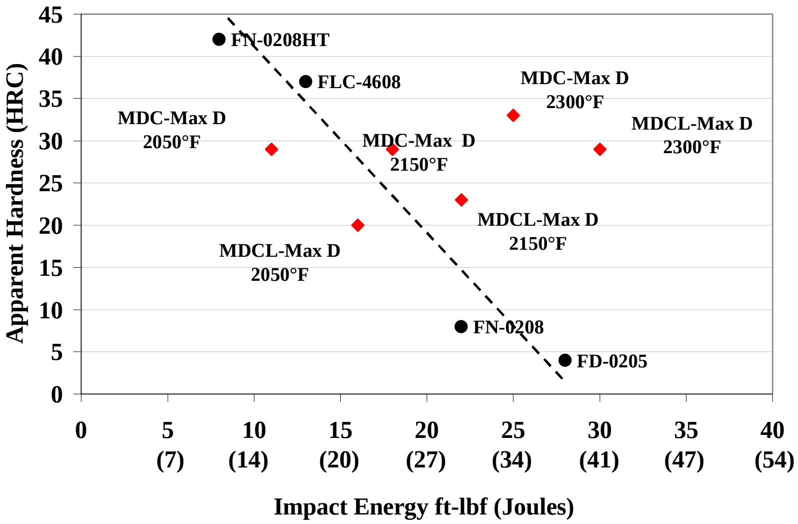

Figure 4: The relationship of impact energies and hardness for AncorMax D MDC and MDCL compared with common P/M grades (as listed in MPIF Standard 35)

Table IV: Apparent Hardness and Impact Energies for Samples Sintered at 1176 °C (2150 °F) in Different Sintering Atmospheres, Tempered in Air at 205 °C (400 °F) for 1 hour

Material	Atmosphere v/o	Comp Pressure MPa/tsi	Hardness C / A	Impact Joules / (ft*lbf)
MDC-Max D	90 N_2 / 10 H_2	550 / 40	29 / 65	19 / 14
		690 / 50	31 / 66	16 / 12
	50 N_2 / 50 H_2	550 / 40	29 / 65	16 / 12
		690 / 50	31 / 66	19 / 14
	100 H_2	550 / 40	29 / 65	18 / 13
		690 / 50	29 / 65	20 / 15
MDCL-Max D	90 N_2 / 10 H_2	550 / 40	25 / 63	19 / 14
		690 / 50	25 / 63	26 / 19
	50 N_2 / 50 H_2	550 / 40	25 / 63	22 / 16
		690 / 50	27 / 64	25 / 19
	100 H_2	550 / 40	20 / 60	20 / 15
		690 / 50	25 / 63	27 / 20

Tensile Properties

The combination of strength and ductility for these materials was of primary interest. Reviewing the tensile properties at 1120 °C (2050 °F), 1176 °C (2150 °F) and 1260 °C (2300 °F), sintering atmosphere was found to have little effect on the increasing the density even at the higher sintering temperature. An atmosphere of 100% H_2 provided the best mechanical properties of the three gas mixtures. Figures 5 and 6 illustrate the advantages of the AncorMax D process for the two similar grades in terms of tensile strength, yield and elongation. In all categories both AncorMax D materials surpasses that of the conventionally processed material.

Table V: Apparent Hardness and Impact Energies for Samples Sintered at 1260 °C (2300 °F) in Different Sintering Atmospheres, Tempered in Air at 205 °C (400 °F) for 1 hour

Material	Atmosphere v/o	Comp Pressure MPa/tsi	Hardness C / A	Impact Joules / (ft*lbf)
MDC-Max D	90 N_2 / 10 H_2	550 / 40	31 / 66	25 / 19
		690 / 50	31 / 66	27 / 20
		760 / 55	31 / 66	34 / 25
	50 N_2 / 50 H_2	550 / 40	31 / 66	26 / 19
		690 / 50	31 / 66	29 / 21
	100 H_2	550 / 40	33 / 67	24 / 18
		690 / 50	37 / 69	27 / 20
MDCL-Max D	90 N_2 / 10 H_2	550 / 40	23 / 62	28 / 21
		690 / 50	29 / 65	40 / 29
		760 / 55	25 / 63	41 / 30
	50 N_2 / 50 H_2	550 / 40	27 / 64	28 / 21
		690 / 50	25 / 63	30 / 22
	100 H_2	550 / 40	23 / 62	26 / 19
		690 / 50	31 / 66	32 / 24

Table VI: Tensile Properties and Sintered Densities at 1176 °C (2150 °F) in Different Sintering Atmospheres, Tempered in Air at 205 °C (400 °F) for 1 hour

Material	Atmosphere v/o	Comp Pressure MPa/tsi	Sintered Density (g/cc)	UTS MPa / 10^3 psi	0.20% Offset MPa / 10^3 psi	El %
MDC-Max D	90 N_2 / 10 H_2	550 / 40	7.22	977 / 140	638 / 91	1.9
		690 / 50	7.31	1124 / 161	687 / 98	2.2
	50 N_2 / 50 H_2	550 / 40	7.23	998 / 143	674 / 97	1.6
		690 / 50	7.30	1180 / 169	743 / 106	2.5
	100 H_2	550 / 40	7.24	1117 / 160	798 / 114	1.9
		690 / 50	7.32	1228 / 176	787 / 113	2.1
MDCL-Max D	90 N_2 / 10 H_2	550 / 40	7.24	1012 / 145	682 / 98	2.1
		690 / 50	7.36	1131 / 162	722 / 103	2.6
	50 N_2 / 50 H_2	550 / 40	7.22	1012 / 145	634 / 91	2.1
		690 / 50	7.34	1159 / 166	702 / 101	2.6
	100 H_2	550 / 40	7.24	1117 / 160	751 / 108	2.1
		690 / 50	7.36	1215 / 174	781 / 112	2.5

Table VII: Tensile Properties and Sintered Densities at 1260 °C (2300 °F) in Different Sintering Atmospheres, Tempered in Air at 205 °C (400 °F) for 1 hour

Material	Atmosphere v/o	Comp Pressure MPa/tsi	Sintered Density (g/cc)	UTS MPa / 10^3 psi	0.20% Offset MPa / 10^3 psi	El %
MDC-Max D	90 N$_2$ / 10 H$_2$	550 / 40	7.24	1215 / 174	773 / 111	2.3
		690 / 50	7.33	1368 / 196	871 / 125	2.8
		760 / 55	7.38	1361 / 195	838 / 120	2.9
	50 N$_2$ / 50 H$_2$	550 / 40	7.24	1221 / 175	796 / 114	2.4
		690 / 50	7.33	1396 / 200	906 / 130	2.7
	100 H$_2$	550 / 40	7.26	1305 / 187	880 / 126	2.3
		690 / 50	7.34	1473 / 211	999 / 143	2.6
MDCL-Max D	90 N$_2$ / 10 H$_2$	550 / 40	7.25	1117 / 160	723 / 104	2.3
		690 / 50	7.37	1312 / 188	781 / 114	3.0
		760 / 55	7.41	1326 / 190	824 / 118	3.1
	50 N$_2$ / 50 H$_2$	550 / 40	7.26	1215 / 174	781 / 112	2.4
		690 / 50	7.37	1320 / 189	838 / 120	2.8
	100 H$_2$	550 / 40	7.26	1277 / 183	873 / 125	2.2
		690 / 50	7.38	1402 / 201	933 / 134	2.7

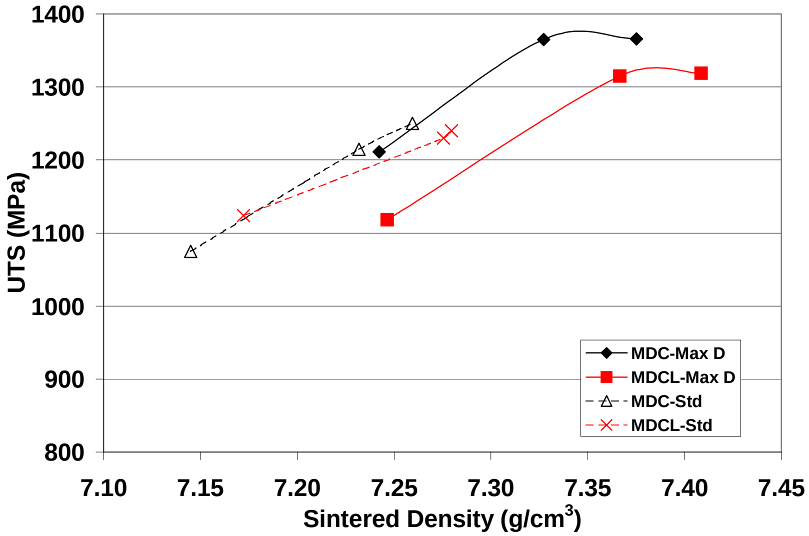

Figure 5. Effect of alloy and process condition on tensile strength as a function of sintered density (sintered at 1260 °C (2300 °F) - atmosphere of 90 v/o N$_2$ – 10 v/o H$_2$) tempered in air at 205 °C (400 °F) for 1 hour

Rotating Bending Fatigue Properties

Rotating bending fatigue data was collected on samples compacted at 690 MPa (50 tsi). The median fatigue endurance limits determined for both materials along with sintered densities are shown in Table VIII. As expected with the silicon containing materials, increasing the sintering temperature to 1260 °C (2300 °F) increased fatigue endurance limits 27% over the MDC-Max D. When sintered at 1260 °C (2300 °F), both material composition have similar fatigue endurance limits with each other.

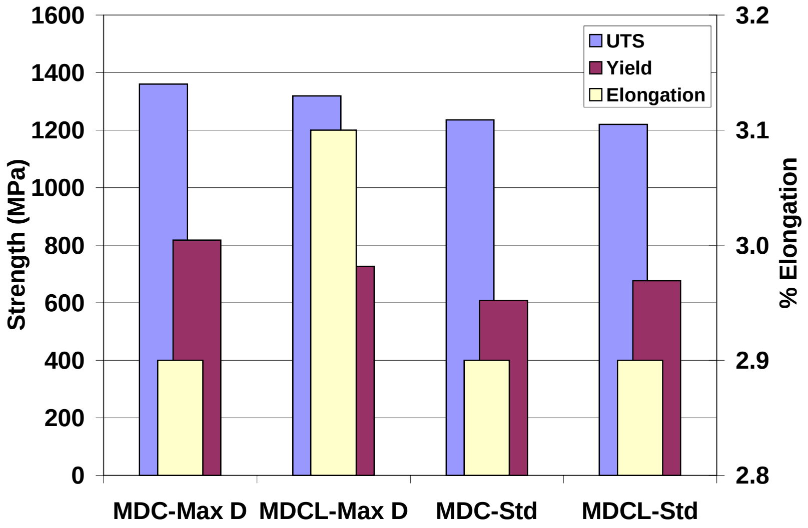

Figure 6: A comparison of tensile properties for the AncorMax D and conventional materials (samples compacted at 760 MPa (55 tsi) sintered at 1260 °C (2300 °F) - atmosphere of 90 v/o N_2 – 10 v/o H_2) tempered in air at 205 °C (400 °F) for 1 hour

Table VIII. Rotating Bending Fatigue Results – Pressed at 690 MPa (50 tsi) sintered at 1176 - 1260 °C (2150 - 2300 °F) - atmosphere of 90 v/o N_2 – 10 v/o H_2 and tempered at 205 °C (400 °F)).

Material ID	Sintering Temp °C / (°F)	Comp Pressure MPa / tsi	Density (g/cm3)	Survival Limit (MPa / 10^3 psi) 90%	50%
MDC-Max D	1176 / (2150)	690 / 50	7.25	258 / 37	265 / 38
MDC-Max D	1260 / (2300)	690 / 50	7.25	328 / 47	342 / 49
MDCL-Max D	1260 / (2300)	690 / 50	7.34	321 / 46	328 / 47

Metallography

Metallographic evaluation was performed on sections prepared from the dog bone tensile bars. Photomicrographs showing typical microstructures were taken following a 2% nital / 4% picral etch at an original magnification of 200X. Micrographs of the AncorMax D MDC, and MDCL are shown in Figures 7 and 8. MDC and MDCL have similar structures. Both samples consist mostly of tempered martensite with small regions of bainite, divorced pearlite, and unresolved pearlite. At the higher sintering temperature the nickel distribution and overall microstructure is more homogenous. This high temperature distribution coupled with high sintered densities resulted in the increase of the overall mechanical properties.

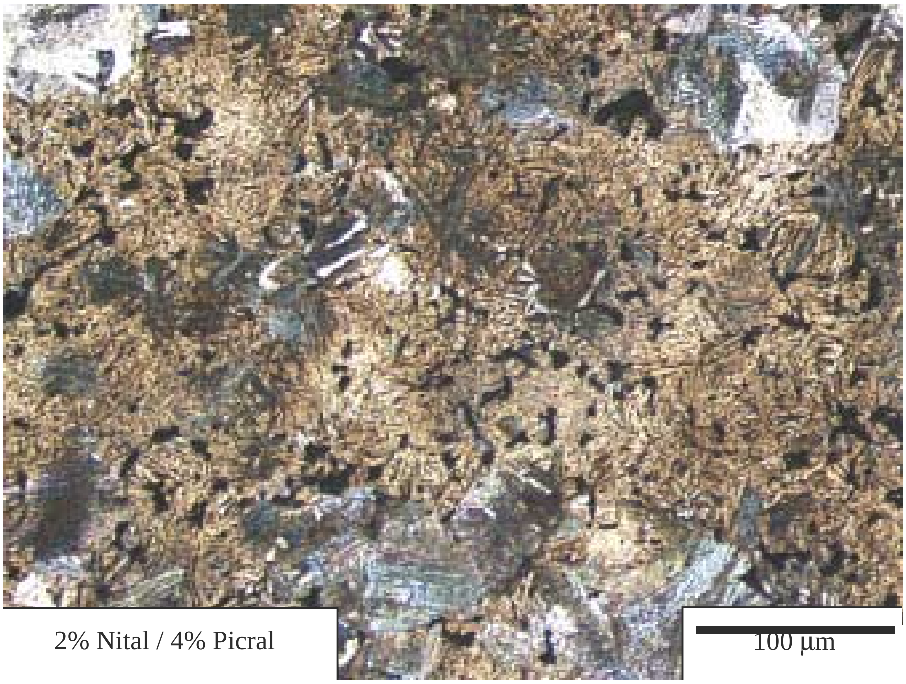

Figure 7. Microstructure of MDC-Max D compacted at 690 MPa (50 tsi), sintered at 1260 °C (2300 °F) - atmosphere of 90 v/o N_2 – 10 v/o H_2

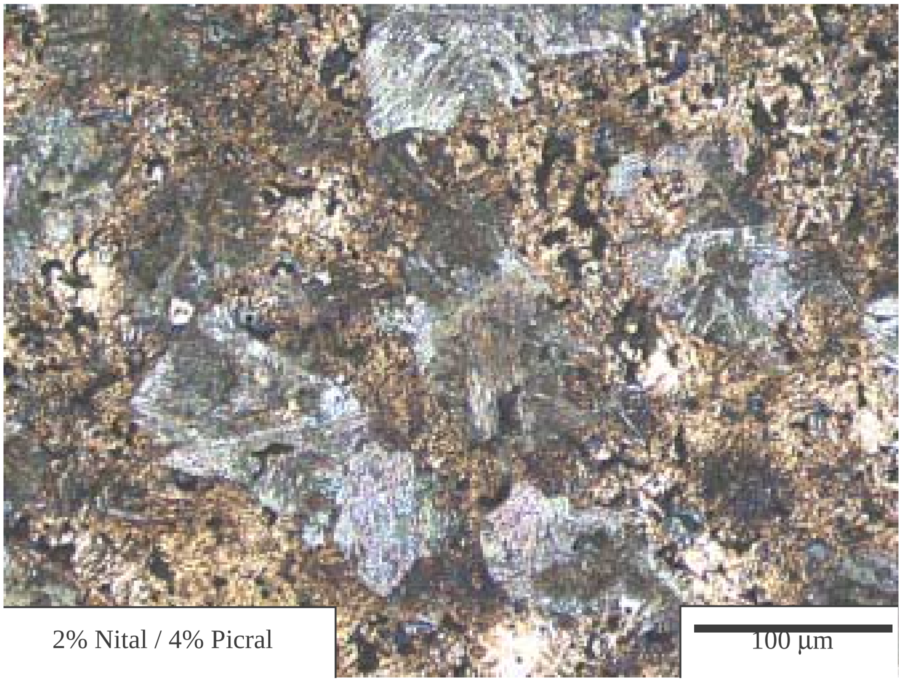

Figure 8. Microstructure of MDCL Max D compacted at 690 MPa (50 tsi), sintered at 1260 °C (2300 °F) - atmosphere of 90 v/o N_2 – 10 v/o H_2)

CONCLUSIONS

The AncorMax D process via warm die techniques illustrated its ability to improve mechanical properties when compared to conventional pressed MDC and MDCL materials. For both premixes, the compressibility of the AncorMax D process is considerably higher over the range of compaction pressures in comparison to the standard premixes. Increases in green densities ranged from 0.13 – 0.15 (g/cm^3), and 0.13 (g/cm^3) for the sintered densities were observed. Sintering at 1176 °C (2150 °F) resulted in good mechanical properties, raising the temperature to 1260 °C (2300 °F) resulted in exceptional combination of strength, ductility, and impact energies. Samples sintered at 1260 °C (2300 °F) resulted in yield strengths in excess of 900 MPa (130 ksi), UTS > 1400 MPa (200 ksi), elongations > 3%, and impact energies > 40 J (29 ft-lbf) were observed. The new high density process helps achieve dimensional stability that is closer to die size.

ACKNOWLEGEMENTS

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