Production of High Density PM Automotive Components Utilizing Advanced Warm Die Compaction Technology

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Abstract

High density compaction techniques (warm die compaction) has broadened the potential application base for PM components. Because single press – single sinter (1P1S) compaction can now achieve densities in excess of 7.3 g/cm³; this cost effective part production approach is often the preferred methodology for new new high density automotive applications. A key initiative in achieving higher part densities is the advance in lubricants and premixing technology enabling reductions in the amount of lubricant required to as little as 0.25% by weight of the premix. Discussed in this paper is a new lube system that enables the use of lubricant levels as low as 0.25 w/o enabling higher green densities up to approximately 7.5 g/cm³. In addition to the high green densities, green strengths approaching 30 MPa are achieved; minimizing the potential for green cracking during compaction and subsequent green part handling. Although not applicable to all types of parts, this new powder premix has proven successful at Cloyes Gear in the production of automotive valve train components. Details of the development activity and resulting part production experiences will be discussed. A discussion of the benefits and limitations will be also be presented.

Introduction

Warm die compaction is an advanced PM compaction technology targeting higher densities for demanding applications eliminating the need for either copper infiltration or double pressing / double sintering (2P2S). Warm die compaction differs from warm compaction in that there is no need to preheat the powder prior to die filling. [1] Compaction die temperatures are typically 75 °C to 110 °C and heating of the powder is achieved via conductive heat transfer from the die during the compaction cycle. [2] As such, there are some part size limitations for warm die compaction with the size of parts having limitations of less than 1 kilogram with a maximum one dimension thickness less than 15 mm. Since the introduction of warm die compaction premixes in 2007, the annual growth of high density parts via this technology has grown at a rate faster than the growth rate of conventional PM. A key development for warm die compaction is the use of engineered lubricant systems which permits the reduction of lubricant levels. Most recently, AncorMax 225® was introduced with a total lubricant level of 0.25 w/o. Despite this low lubricant level, good powder flow with customary compaction and part ejection characteristics were maintained. [3]

The rationale for reduced lubricants can be best summarized by Whittaker: "the PM industry has a love-hate relationship with pressing lubricants. Lubricants are necessary for part ejection but have the disadvantage of decreasing the pore-free-density thus lowering the achievable compacted and sintered part density". [4] Figure 1 illustrates the benefit of reducing the lubricant from the traditional 0.75 w/o to 0.25 w/o: in this idealized data, the increase in pore free density is approximately 0.25 g/cm³. Along with lower lubes, higher densities can be achieved via exposing the powder mass to increased temperatures up to ~150 °C. Figure 2 presents the effects of raising the die temperature during compaction of an FLN2-4400 material which illustrates that increasing the compaction die temperature increases the part density via softening of the lube and a subsequent lowering of inter-particle and die wall friction. [5]

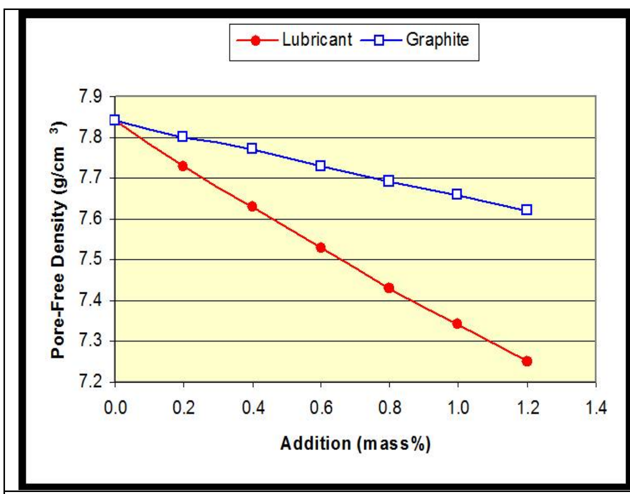

Figure 1: Influence of lubricant and graphite additions on pore-free density

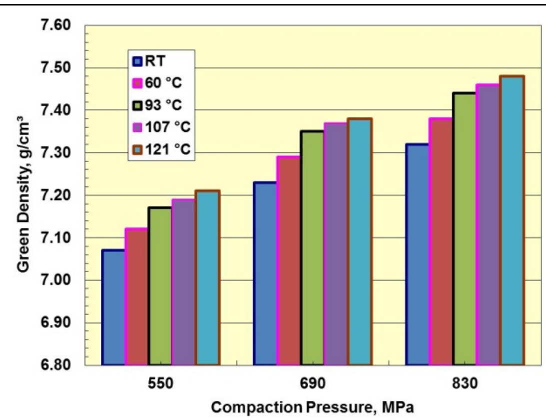

Figure 2: Effect if die temperature and compaction pressure on green density of an FLN2-4400

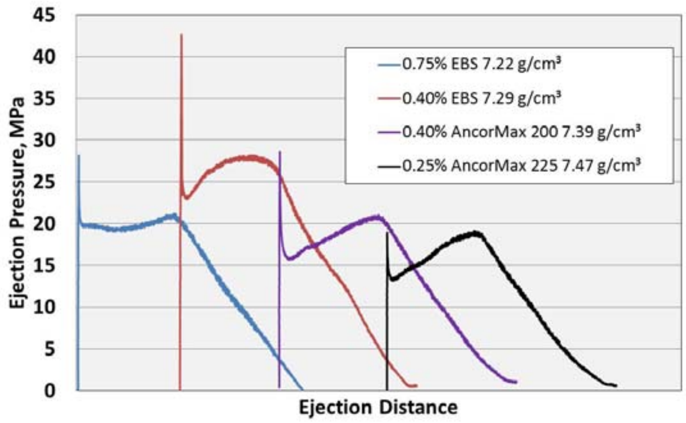

Figure 3 Strip and Slide Pressure of Various lubricants

Simply lowering the amount of conventional lubricants is not always straightforward because consideration for the resulting part ejection must be given. Advanced lubricant systems utilize the heating of the powder plus engineered lubricants to optimize compaction and ejection characteristics. Figure 3 shows the ejection characteristics of a series of lubricants utilizing a standard 14 mm diameter by 25 mm long solid slug as compacted. Through optimization of the lubricant and binder systems, these reduced lubricant levels achieve similar ejection characteristic to 0.75 w/o of the commonly used PM lubricants. Shown in Figure 3 are the ejection curves for a common PM lube and the recently introduced engineered lubricant systems, all ejection curves were generated at a compaction pressure of 830 MPa with a 25 mm long as compacted sample. Combining engineered lubes with elevated die temperature give both higher as compacted density in addition to achieving ejection characteristics equivalent to the much higher percentages of traditional lubricants. Secondary benefits of reducing the lubricant levels include reduced amounts of lubricant to remove prior to sintering; thus creating less carbon dioxide emissions and making this process more environmentally friendly. Also the reduced lube content could possibly reduce furnace maintenance resulting from the de-lubrication cycle.

Cloyes Gear of Subiaco, AK has utilized both warm compaction and warm die compaction to achieve higher part densities via 1P1S techniques since the early 1990's. [6] Continuously exploring opportunities to expand their application and technology base, Cloyes Gear evaluated and initiated production utilizing an AncorMax 225 premix for automotive valve train components. This paper describes the manufacturing details and subsequent key production results. Figure 4 presents photographs of the components chosen for this study. Both parts were previously manufactured via PM utilizing warm compaction method (heated powder and heated die). Key attributes essential with this new production technique were: the needs to achieve comparable density without significant increases in compaction pressures, maintaining good surface finish, good dimensional precision, robust manufacturing, and repeatability from set-up to set-up. Both parts are produced from an FLN2-4400 with 0.35% graphite and a total lube addition of 0.25 w/o. The balance of this paper will detail the initial powder testing and the production results achieved at Cloyes Gear.

4 a. Main running gear, weight ~450 grams | 4 b. Spro gear, weight ~1100 grams

Figure 4: Automotive valve train components evaluated by Cloyes Gear (material: pre-alloyed 0.85% molybdenum steel with 2% nickel, 0.35% graphite (FLN2-4400)

Experimental Procedure

Prior to the onset of production, laboratory work was performed to determine the powder characteristics, compressibility, and sintered mechanical properties of the AncorMax 225 prepared FLN2-4400 material. This ‘bonded’ premix was prepared with 0.25 w/o of the proprietary lubricant. Powder flow and apparent density was determined using MPIF standard test methods (03 & 04). [1] Compressibility was determined using standard green strength bars at compaction pressures of 550, 690, and 830 MPa (40, 50 and 60 tsi) with a die preheat temperature of 107 °C (225 °F). Laboratory sintering was done at 1120 °C (2050 °F) for ~20 minutes at temperature in a 90% nitrogen – 10% hydrogen atmosphere with conventional cooling. TRS and tensile properties were determined using MPIF test standard methods (#41 and #10).

During production at Cloyes, the gears shown in Figure 4 were evaluated for the following key characteristics:

- weight variability
- press tonnage

Both parts were compacted on standard mechanical PM compaction equipment. The tools were modified to incorporate cartridge heating elements into the stress ring of the die. No powder heating was done prior to introducing the powder into the die cavity. To measure the repeatability of the ‘bonded’ premix multiple set-ups and production runs were completed to insure product and press performance consistency.

Results

a.) Laboratory Evaluation at Hoeganaes

To date, more than 100,000 kilograms (220,000 pounds) of the ‘bonded’FLN2-4400 premix have been produced; this represents about 6 truckloads of powder. A summary of the flow and apparent density

(AD) of the material produced to date is given in Table 1. The AD of this material produced to date averaged 3.35 g/cm³ with a powder flow of <26 seconds per 50 grams through a Hall flow cup. The first production lot was sampled and evaluated for the standard MPIF testing for compressibility, green strength, as-sintered TRS, and heat treated TRS. For the heat treated properties, the samples were first austenitized at 870 °C for one hour at temperature followed by oil quenching into heated oil (70 °C) and then tempering at 200 °C for one hour. Results from this laboratory testing are shown in Table 2 and Table 3.

Table 1
Powder Properties of the FLN2-4400 Premix Prepared via AncorMax 225 Processing

Characteristic	Average	Range
AD, g/cm³	3.36	3.33 – 3.39
Flow, hall cup seconds per 50 gms	25	25-26
Compressibility, g/cm³ at 755 MPa and die temp. of 107 °C	7.40	7.37 – 7.44
Green strength, MPa (psi) After compaction at 755 MPa	32 (4575)	28 – 33 (4125 – 4825)
As sintered Density, g/cm³ After compaction at 755 MPa	7.44	7.43 – 7.45
As sintered TRS, MPa (psi) After compaction at 755 MPa	1415 (205400)	1325 – 1450 (192000 – 210300)
DC, % from die size After compaction at 755 MPa	0.08	0.06 -0.1
Sintered Carbon, %	0.24	0.23 - 0.25

Table 2
Laboratory Compressibility, Green Strength, As-Sintered and Heat Treated TRS values

Compaction Pressure (MPa)	Green density, g/cm³	Green Strength, MPa	As sintered				Heat Treated			
			Density, g/cm³	TRS, MPa	DC, %	HRA	Density, g/cm³	TRS, MPa	DC, %	HRA
550	7.20	29	7.20	1175	0	45	7.21	1535	-0.08	57
690	7.37	34	7.37	1325	+0.01	48	7.38	1875	-0.09	57
830	7.49	35	7.47	1455	+0.05	49	7.48	2105	-0.02	59

Table 3
Laboratory Sintered Tensile Data

Compaction Pressure	As sintered					Heat Treated			
	YS, MPa	TS, MPa	El, %	HRA		YS, MPa	TS, MPa	El, %	HRA
550	390	545	2.1	49		850	920	1.0	61
690	410	600	2.8	51		905	1025	1.1	64
830	415	605	3.0	52		955	1050	1.1	64

b.) Production Experience at Cloyes

Shown in Figure 4a is the main gear; this part is compacted to a nominal density of ~7.2 g/cm³ and was previously produced from an ANCORDENSE 450® premix that utilized both heated powder (135 °C, 275 °F) and heated dies (150 °C, 300 °F). From previous production experience, the nominal pressing force when running the main gears utilizing the warm compaction premix was 318 US Tons (2830 kilo-Newton). Switching to the AncorMax 225 material resulted in an increase in total compaction pressure of ~8 to 14 total tons (2.5% to 4.4%). This increase in total compaction force was expected because of the reduced powder temperature of the AncorMax 225 relative to the ANCORDENSE 450 process. The consistency of the pressing tonnage part to part (Figure 5) showed a maximum deviation of less than 1% over the two distinct production trials. Further improvements in part-to-part weight consistency are anticipated with additional operational experience and minor modifications to the filling cycle.

Shown in Figures 5 and Figure 6 are graphs representing the total compaction tonnage applied and the part-to-part weight variability. In each plot two evaluations are presented. These evaluations represent two distinct production sequences run approximately 4 weeks apart using two distinct lots of premixed powder.

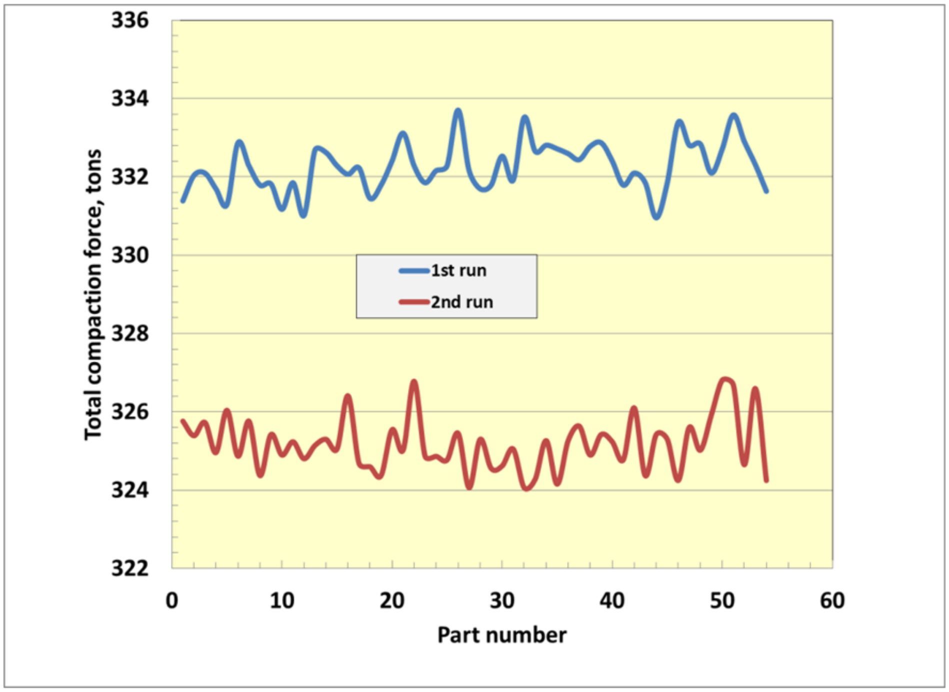

Figure 5: Main running gear total compaction tonnage for two distinct set up, approximately 1 month apart**.**

Complementing the pressing force, the weight consistency from the two production runs are shown as Figure 6. The total weight variation of both production runs was less than 2 grams or approximately 0.5% total weight variation of the part. This translates to a maximum Cpk of ~1.9. Some improvement from the first run to the second run was observed. This can be attributed to the learning curve during production of both the raw material and part production perspective. Another key aspect of using warm die compaction was the ability to stop the compacting press during the production run without the need to re-establish steady state conditions. This characteristic promotes operational efficiency at the part production level.

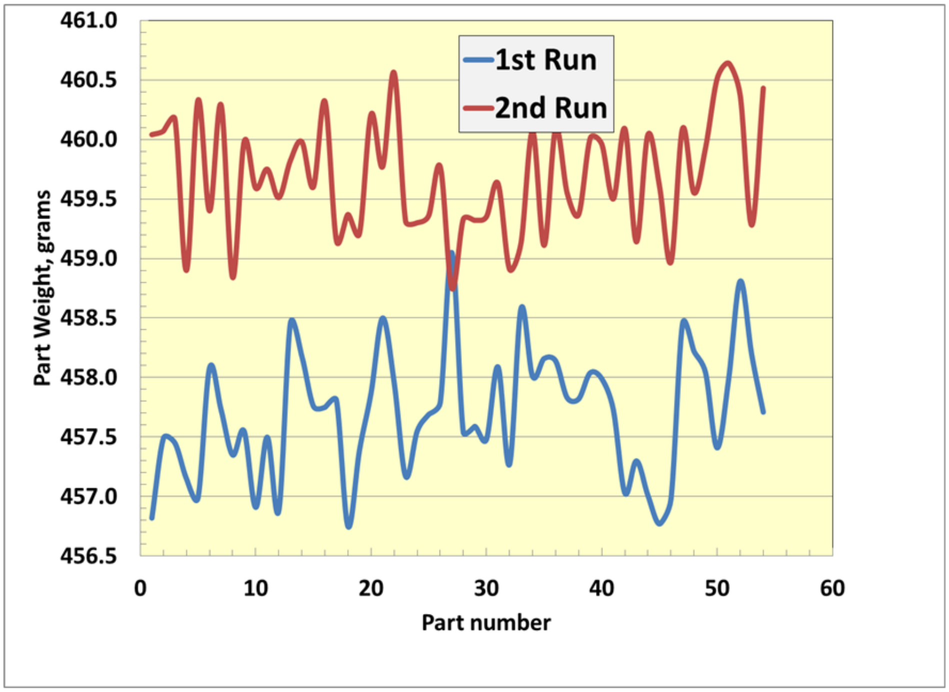

Figure 6: Part to part weight variance of the main gear as shown in Figure 4a.

Shown in Figure 7 is the relationship between total compaction force and weight of the part for the main gear. As noted, this part is approximately 7.2 g/cm³ density and the relationship between pressing tonnage and weight of the part is nearly linear. This near linear relationship is a direct result of the reduced lubricant in the part thus giving higher pore free density. For example, if the material contained 0.75 w/o standard compaction lubricant the 7.2 g/cm³ green density would represent about 97.5% of the pore free density. Thus any increases in the weight of the part would result in an exponential rise in total compaction force. However, utilizing the AncorMax 225, the 7.2 g/cm³ density represents only 94% of the pore free density. Consequently, minor variations in fill will not result in exponential increases in compaction loads and will reduce the potential for die damage and micro-laminations within the part from over compaction.

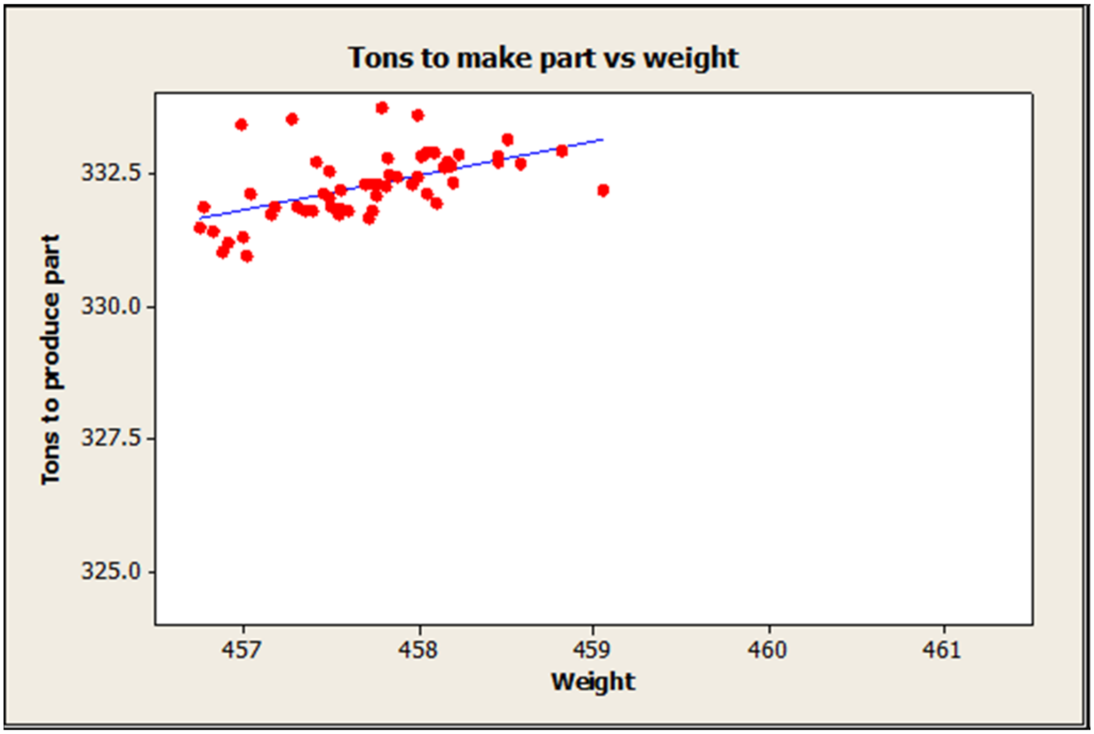

Figure 7: Weight of part vs. pressing tonnage

Figure 8 shows the pressing tonnage variation of the large ‘spro’ gear as shown in Figure 4b; previously it was also produced via the warm compaction technique. This particular component weighs approximately 1100 grams. This rather large part was successfully manufactured utilizing warm die techniques, achieving an overall density of >7.2 g/cm³. Figure 9 shows the part-to-part weight variation achieved with this part. There is a higher part to part weight variation with this component; however, it is believed that these variations can be minimized to the same level as the main gear with modifications to the pressing and filling cycle.

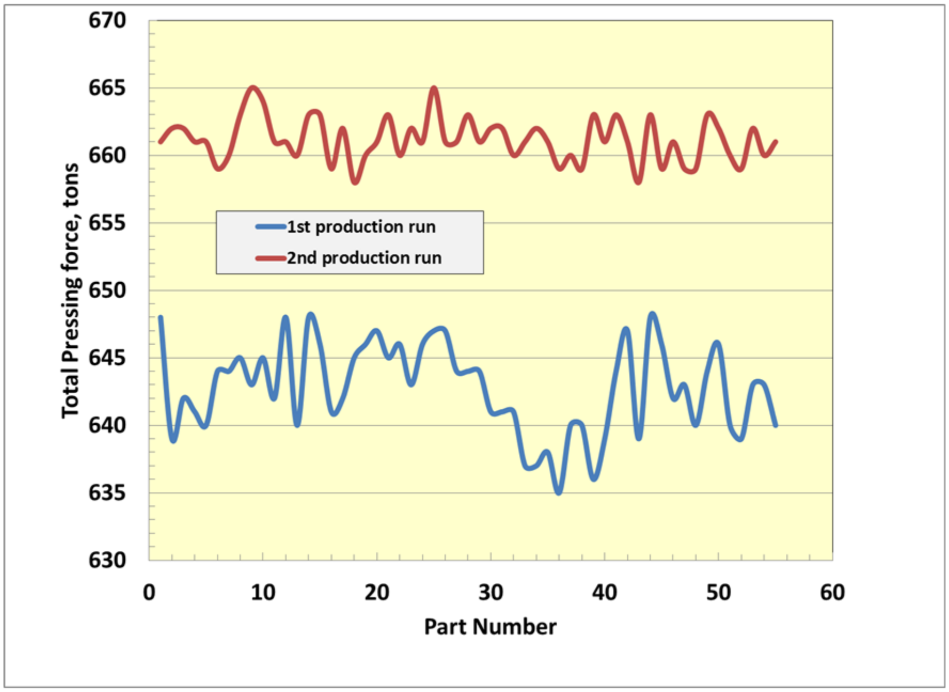

Figure 8: Total compaction force for spro gear in tons

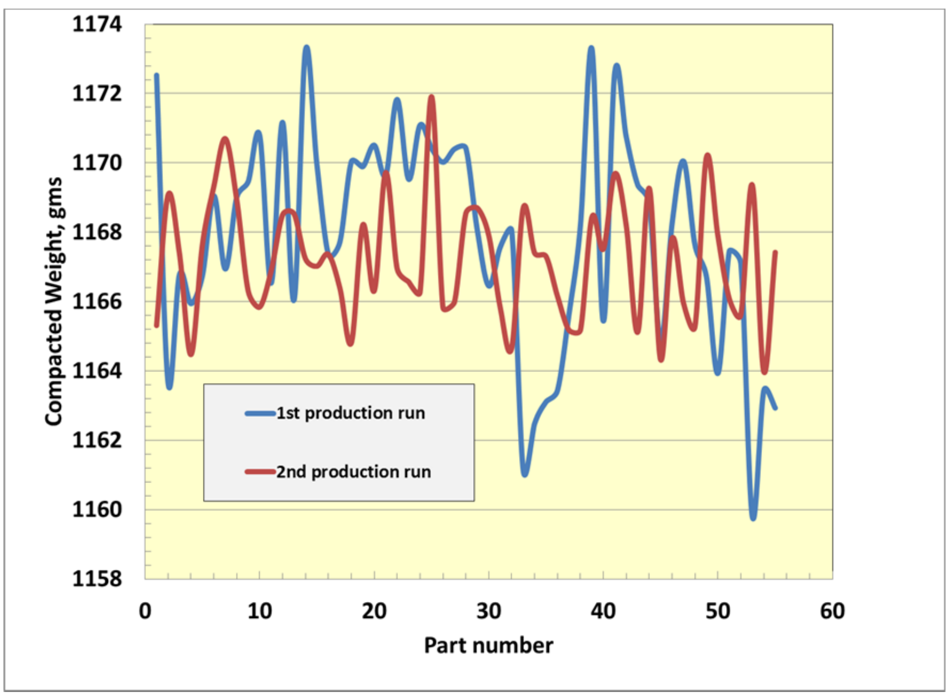

Figure 9: Weight Variation of 'spro' gear, in grams

Another key characteristic necessary for the conversion from warm compaction to warm die compaction was the need to maintain good surface finish. In the trials at Hoeganaes, the ejection characteristics of the

AncorMax 225 were equivalent or superior to the ANCORDENSE 450. This laboratory experience was replicated in the production trials at Cloyes.

Discussion

Lowering the organic lubricant content of a PM premix increases the pore-free –density with corresponding benefits of increased green density, reduced carbon emissions during sintering, and the potential for higher green strength. The recently developed AncorMax 225 utilizes a 0.25 w/o total lubricant addition in combination with warm die compaction (die temperature of ~107 °C) to achieve high green density with acceptable compaction press performance. Additional benefits of this premix alternative are reduced green expansion after compaction and higher green strength approaching 35 MPa. The high green strength is advantageous because it lessens the potential for green part damage and could be less prone to ejections cracking resulting from minor weight deviations in the part inherent with the PM process.

The AncorMax 225 is a ‘bonded’ premix that started as a laboratory and pilot scale product and was then successfully scaled into production. Cloyes Gear evaluated this product on two difficult valve train components previously produced via warm compaction methods. Initial sampling was successful and full scale production was implemented. Production results showed good weight control and minimal press tonnage variation. These improvements can be correlated to the consistent powder properties of AD and flow. Sequential production runs verified the robustness of the process. Added benefits of this material system compared with the conventional warm die compaction is the capability to interrupt the production run without the need to re-establish steady state conditions.

Surface finish of the finished part was acceptable. Again it must be stressed that the new premix contained only 0.25 w/o total lubricant. Previous evaluations of the ejection characteristics (utilizing a standard test geometry) showed the AncorMax 225 premix option at a green density of >7.45 g/cm³ exhibited ejection characteristics equivalent to a standard premix containing 0.75 w/o standard lubricant with a green density of approximately 7.25 g/cm³. This equivalency in ejection characteristics result from the engineered lubricant and binder system in combination with warm die compaction techniques.

Laboratory evaluations of the production premix showed consistency of the key powder characteristics of apparent density and flow. Premix compressibility and the resulting green strengths of the production material were in-line with previous laboratory generated data. The as-sintered and heat-treated TRS and tensile properties meet the production part requirements. Comparisons with the standard MPIF Std. 35 data are not possible because MPIF does not list material properties for an FLN2-4400 material. The high density of the actual production component enables the attainment of a suitable carburized case because the high density minimizes the amount of interconnected porosity. [7]

One final note, a modification to the premix composition was necessary to utilize the existing dies (the modifications still met the MPIF standard for FLN2-4400). The AncorMax 225 material exhibited higher growth than the replaced ANCORDENS 450 premix. Exact reasons for this difference were not determined and are under investigation. It is noteworthy that existing tooling can be used but understanding the differences in sintered dimensional change must be considered.

Conclusions

From this study the following conclusions can be drawn:

1. Reduced powder lubricants contents are possible providing increases in green and sintered density with higher green strength
2. The new engineered lubricant system showed excellent ejection characteristics in a laboratory test set-up. These laboratory measurements of the ejection characteristics of this new premix material were verified in actual production experience.
3. Warm die compaction techniques offer robust manufacturing capability with minimal scrap resulting from compaction cycle interruptions.
4. Acceptable part-to-part weight control was experienced with the production material.
5. Good correlation between the laboratory generated compressibility and actual production experience was found.
6. The increase in total press tonnage when converting from warm compaction to warm die compaction technique was at most 4% higher for the warm die compaction.
7. The reduced lubricants offer the potential for less CO emissions during sintering and potentially reduced furnace maintenance resulting from the lube burn out.
8. The DC upon sintering for the new AncorMax 225 showed more growth than the standard ANCORDENSE 450 material that it replaced. This difference was eliminated thru a slight premix formulation alteration.
9. Production experience with the premix showed minimal variation in powder apparent density and powder flow characteristics.

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