THE APPLICATION OF WARM COMPACTION TO HIGH DENSITY POWDER METALLURGY PARTS

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ABSTRACT

The warm compaction process (ANCORDENSE®) has been shown to provide increased density in ferrous powder metallurgy parts. This improvement in density contributes significantly to mechanical properties and thus the overall performance of the part. The combination of increased density with high performance material selections, provides parts that can exceed the performance of forged or cast material counterparts while taking advantage of powder metallurgy's net shape forming capabilities.

Turbine hubs for automatic transmission torque converters have proven to be ideal candidates for the powder metallurgy (P/M) process. The complex shape of turbine hubs is costly to produce via conventional forging and machining operations. However, increases in engine size and torque requirements in several automotive designs have required that turbine hubs possess higher levels of mechanical properties. High density P/M manufacturing techniques, in combination with high performance ferrous materials produces components capable of replacing a forged and machined turbine hub.

This paper will review the conversion of a conventionally forged and machined turbine hub used in a high torque automatic transmission to a single pressed and single sintered P/M turbine hub. The material used for the P/M hub was an FD-0405. This diffusion alloyed material was evaluated in the laboratory and mechanical properties are reported at several density levels. Warm compaction processing achieved high overall sintered densities in the highly stressed internal spline region. Extensive mechanical and part specific testing was conducted to verify the suitability of the P/M part.

INTRODUCTION

The use of powder metallurgy (P/M) components has grown at an annual rate of approximately 7% since 1990. [1] During this period, the usage of P/M components in the North American automotive sector increased from 23 pounds per vehicle to in excess of 28 pounds per vehicle. [1] Recent reports suggest that the usage of P/M parts could reach 50 pounds per vehicle by the year 2000. [2] Additional opportunities for P/M can only be realized if the P/M process continues to utilize technological advances to produce higher performance components at lower cost. Traditional methods to increase density and improve the mechanical properties of P/M parts include double pressing/double sintering, copper infiltration, powder forging or high temperature sintering. However, the cost and limitations involved in these processes can prove to be a hindrance to rapid acceptance within the automotive sector.

The introduction of warm compaction technology enables P/M part fabricators to single press and single sinter multi-level complex P/M parts to densities in excess of 7.25 g/cm^3. [3] Warm compaction processing, although applicable to all ferrous material systems, produces the greatest benefits when coupled with high performance ferrous alloy compositions. Achieving densities in excess of 7.25 g/cm^3 using diffusion alloyed materials and molybdenum prealloyed steels results in mechanical properties that are comparable to steel forgings and ductile iron castings. [4] This paper will first review the requirements for production of turbine hubs via the P/M process. The mechanical property data for the warm compacted FD-0405 will then be presented followed by an evaluation of the performance of a warm compacted single press single sinter P/M component along with a comparison with the forged and machined steel turbine hub produced using AISI 1045 steel.

TURBINE HUB PRODUCTION REQUIREMENTS AND THE WARM COMPACTION PROCESS

Turbine hubs in automatic transmissions are torque carrying components that have both internal and external splines with a provision for riveting. Their function is to transmit torque from the riveted turbine assembly to the transmission input shaft. [5] Figure 1 shows the warm compacted version of the turbine hub following final machining. The obvious complexity of the part lends itself to the net shape capabilities of the P/M process.

Powder metallurgy first was used in the manufacture of turbine hubs in the early 1960's. The original P/M turbine hubs were compacted to a nominal 6.2 g/cm^3 density and subsequently copper infiltrated for higher strength As a result of this early pioneering effort, nearly all current automatic transmissions now utilize P/M turbine hubs. The most commonly specified material is an FC-0208, which is a premix of pure iron powder with a nominal 2 w/o (weight percent) copper, 0.8 w/o graphite plus lubricant. [6] These current turbine hubs are processed to a nominal sintered density of 6.8 to 7.0 g/cm^3 with sectional densities varying from 6.6 g/cm^3 to 7.1 g/cm^3.

Consumer demand for higher performance engines in the light truck and van market segments resulted in the development of new engines with higher torque for greater towing capabilities. One consequence of this higher engine output was that performance demands exceeded the torque carrying capability of conventionally pressed and sintered turbine hubs. To guarantee system reliability, the transmission designer was forced to switch from conventional P/M to alternative technologies to meet these new performance demands. Steel forging was one alternative processing method chosen. The complex shape of the turbine hubs processed by the forging and machining process proved to be a costly option. A high performance P/M process that would survive the higher torque output of the new engines and prove economical to manufacture was needed.

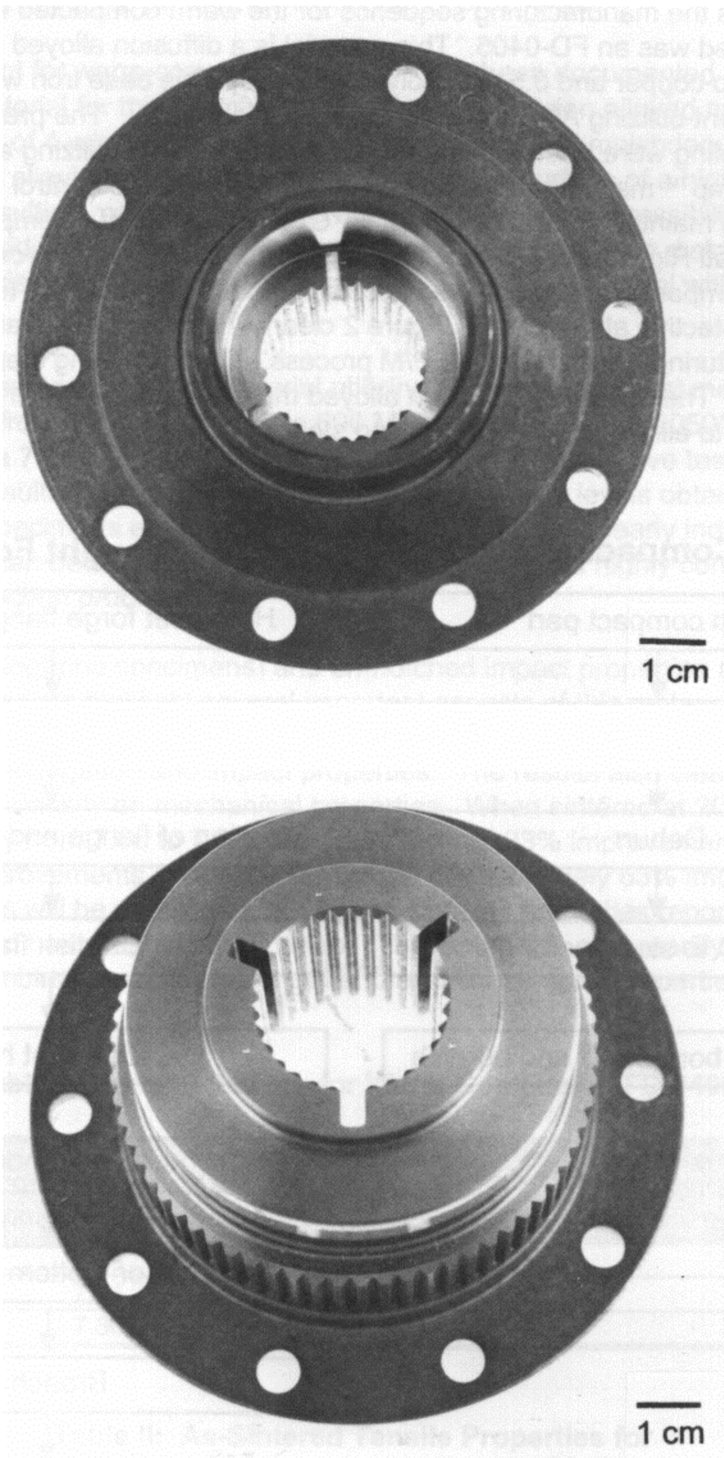

Figure 1: Photograph of the Warm Compacted Turbine Hub

Figure 2 shows schematically the sequence for manufacturing the wrought turbine hub. AISI 1045 bar stock is hot upset forged to form the flange and top cone. After forging, the blank undergoes eight distinct machining operations including turning and broaching of the outer (OD) and inner diameters (ID) and facing of the flange. The machining operations are followed by an induction hardening operation on the ID spline to provide strength and wear resistance.

Figure 2 also shows the manufacturing sequence for the warm compacted P/M component. The powder specified was an FD-0405. This material is a diffusion alloyed powder containing 4 w/o nickel, 1.5 w/o copper and 0.5 w/o molybdenum. [6] This base iron was mixed with graphite and lubricant utilizing ANCORDENSE premix technology. The press-ready powder and compaction tooling were heated to the required temperatures utilizing a Cincinnati Incorporated El-Temp™ material delivery system. [7] Temperature control of the die and heated powder was maintained within +/-5°F (+/- 2.5°C) of the set point. Compaction took place in an 825 ton Cincinnati Rigid Reflex press. The turbine hubs weighed approximately 1100 grams each. Following compaction, sintering was accomplished at conventional temperatures using an endothermic protective atmosphere. Figure 2 clearly indicates the advantages of the near-net shape manufacturing capability of the P/M process. The machining steps alone are reduced from eight to three. The use of the diffusion alloyed material and the warm compaction process provides the ability to eliminate the heat treating step.

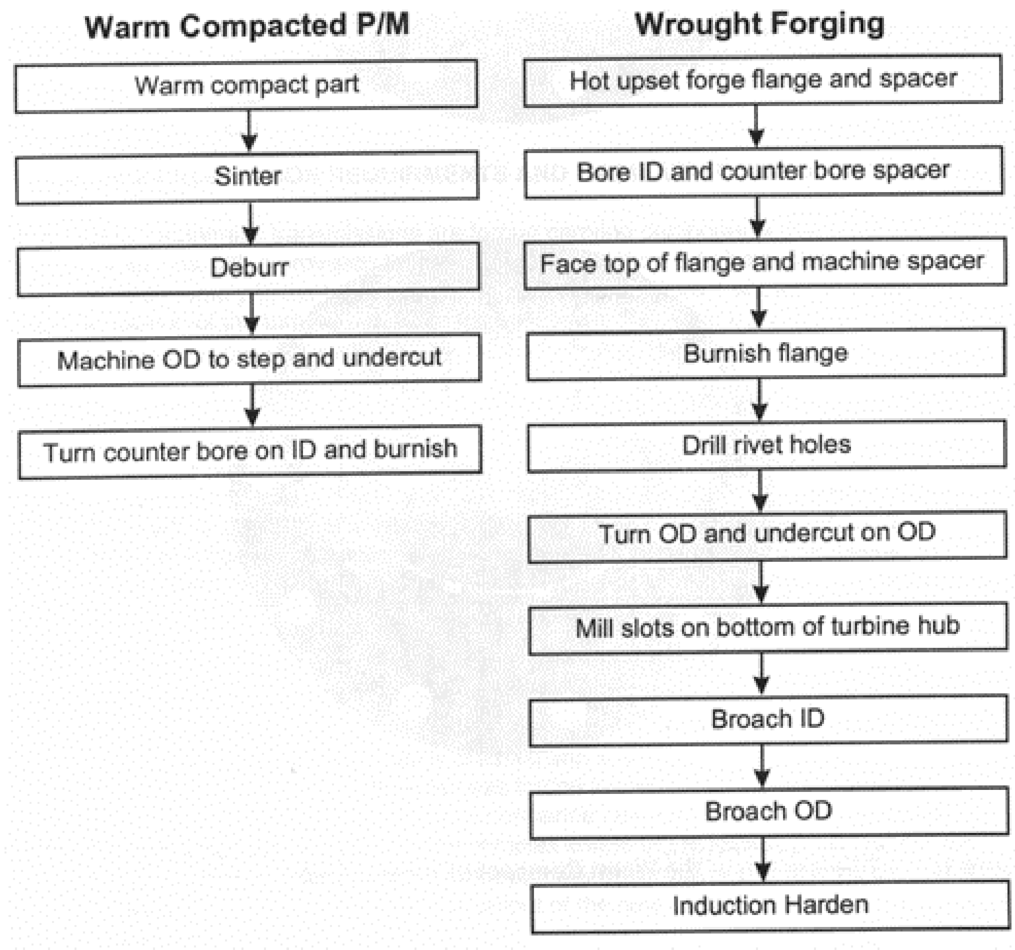

Figure 2: Manufacturing Steps for the Forged Steel Turbine Hub and the Warm Compacted Turbine Hub

MECHANICAL PROPERTIES OF WARM COMPACTED FD-0405

Property development for warm compacted FD-0405 has been documented in several places. [4,8,9] The base material for this premix composition is a diffusion alloyed material with a nominal composition of 4 w/o nickel, 1.5 w/o copper and 0.55 w/o molybdenum. In the diffusion alloying process, the alloying elements are diffused onto the surface of a highly compressible iron powder. The resulting material maintains a high degree of compressibility despite rather high levels of alloy additives. The process also provides a very uniform distribution of alloy throughout the material which provides more precise dimensional control within a lot and from lot to lot.

Property data was developed for this material utilizing MPIF standard test methods [8] for the material compacted from 30 to 50 tsi (415 to 690 MPa) and sintered at 2050°F (1120°C) and 2300°F (1260°C) in a 75 v/o H_2 - 25 v/o N_2 atmosphere. In all cases, five tests specimens were evaluated and the results averaged. Green and sintered density levels obtained from transverse rupture specimens are presented in Table I. This data clearly indicates the high level of density that can be achieved through the combination of a highly compressible powder and the warm compaction process.

As-sintered tensile (dogbone specimens) and un-notched impact properties are presented in Tables II and III. The data highlight several important aspects of this material system. In the as-sintered condition, high levels of strength are achieved. Additionally, the material shows high levels of tensile elongation and impact properties. The results also clearly point out the benefits of increased density on mechanical properties. When sintered at 2050°F (1120°C), increasing the density from 7.06 to 7.32 g/cm^3 resulted in a 23% improvement in ultimate tensile strength. Similar improvements in density resulted in approximately 63% improvement in impact properties. As will be detailed below, the as-sintered properties reported here exceed those for a forged and heat treated carbon steel. The material is also readily heat treated to achieve a unique combination of high strength and excellent impact properties. [8]

Table I: Density Results for Warm Compacted FD-0405

Compaction Pressure (tsi / Mpa)	Green Density (g/cm^3)	Sintered Density 2050°F (1120°C) (g/cm^3)	Sintered Density 2300°F (1260°C) (g/cm^3)
30 / 415	7.14	7.08	7.16
40 / 550	7.31	7.24	7.32
50 / 690	7.36	7.32	7.39

Table II: As-Sintered Tensile Properties for Warm Compacted FD-0405

2050°F (1120°C) Sinter				2300°F (1260°C) Sinter			
Sintered Density (g/cm^3)	0.2% Offset Yield Strength (10^3 psi/MPa)	Ultimate Tensile Strength (10^3 psi/MPa)	Elg. (%)	Sintered Density (g/cm^3)	0.2% Offset Yield Strength (10^3 psi/MPa)	Ultimate Tensile Strength (10^3 psi/MPa)	Elg. (%)
7.06	56/384	93/639	2.1	7.14	68/467	107/738	2.0
7.25	59/407	108/745	2.5	7.33	76/522	125/861	2.8
7.32	65/451	114/785	2.4	7.37	76/526	134/825	3.0

Table III: As-Sintered Un-notched Charpy Impact Properties for

Warm Compacted FD-0405

2050°F (1120°C) Sinter			1200°F (1260°C) Sinter		
Sintered Density (g/cm^3)	**Impact Energy (ft.lbf/J)**	**HRB**	**Sintered Density (g/cm^3)**	**Impact Energy (ft.lbf/J)**	**HRB**
7.13	19 / 26	88	7.15	17 / 23	91
7.23	25 / 34	90	7.31	28 / 38	94
7.3	31 / 42	94	7.35	31 / 42	95

Table IV summarizes the tensile properties, hardness values, and rotating bending fatigue characteristics of both the forged AISI 1045 and warm compacted FD-0405 materials (sintered at 2050°F /1120°C). Data for the forged AISI 1045 material is presented in the annealed and hardened condition (the ID is induction hardened). Property data for the FD-0405 is presented in the as-sintered condition at a density of 7.25 g/cm^3 (the overall density of the warm compacted and sintered turbine hub). Data for the P/M material is presented in the as-sintered condition only because it was determined that no surface hardening of the ID was necessary.

The as-sintered yield and tensile strengths of the FD-0405 material were equivalent to the forged AISI 1045 steel. Ductility of the steel forging was higher than the warm compacted P/M part. The fatigue properties developed by rotating bending fatigue testing demonstrated that the steel forging in the as forged condition had a higher fatigue endurance limit relative to the as-sintered warm compacted P/M part. Specific part testing was necessary to determine if the difference in rotating bending fatigue performance was detrimental to actual component performance.

Table IV: Summary of Standard Mechanical Property Testing for Forged and P/M Hubs

Property	Forged AISI 1045	Heat Treated AISI 1045	Asn Sintered FD-0405 @7.25 g/cm^3
Yield Strength (psi / Mpa)	62,000 / 427	96,000 / 662	59,000 / 407
Tensile Strength (psi / Mpa)	90,000 / 621	130,000 / 896	108,000 / 745
Elongation, %	25	16	2.5
Hardness	97 HRB	43 HRC	17 HRC
Fatigue Limit (psi / Mpa)	45,000 / 310	100,000 / 690	35,000 / 241

PART PERFORMANCE

As part of new production approval process, the warm compacted turbine hubs were subjected to extensive performance evaluation. The warm compacted hubs were compared for internal spline durability and internal spline wear relative to both conventionally compacted P/M hubs and forged hubs. This evaluation was performed with an MTS test cell designed specifically for torque testing. The test procedure consisted of fixturing the OD and applying the design torque to the ID spline. For internal spline durability, the torque was dynamically applied, in one direction, from 0 to 890 foot pounds then back to 0 with a 75% spline engagement. The part test was deemed a failure if the specified torque was not achieved or if the angular rotation of the ID shaft exceeded a specified amount. Internal spline wear testing was performed in the same test cell with test conditions of a constant torque of 150 foot pounds with 90% spline engagement and 0.157 inches (4 mm) of sliding travel per cycle. The hub was removed at specified intervals up to 350,000 cycles for measurement of the spline wear.

Table V presents the internal spline durability test results of conventionally compacted turbine hubs, forged turbine hubs, and the warm compacted FD-0405 hubs. Part validation required that 12 hubs be tested to I million cycles with no failures, with one additional hub tested to 2 million cycles with no failure. This high torque regime of 0-890-0 foot pounds exceeded the strength capability of the standard FC-0208 material. Failures were observed below the specified minimum value. The forged turbine hub met the test requirements with no evidence of failures. At an overall sintered density of 7.25 g/cm^3, the warm compacted parts produced torque test results that exceeded the minimum specification requirements. To evaluate the durability of the high performance P/M hub, one was cycled to failure. Structural failure of the hub occurred at approximately 9 million cycles, significantly in excess of the specified minimum. Spline durability testing demonstrated that the high performance P/M turbine hub is capable of replacing a steel forging in this critical high torque application.

Table V: ID Spline Durability Test Results

	1 Million Cycles at 890 ft.lbf.	2 Million Cycles at 890 ft.lbf.	Cycles to Failure at 890 ft.lbf.
Standard P/M hub	Failures Observed	Failures Observed	
AISI 1045 hub	12 parts, no failures	1 part, no failure	
Warm Compacted	12 parts,	1 part,	~9,000,000

FD-0405	no failures	no failure	
Specification	12 parts, no failures	1 part, no failure	

Another performance criterion for the turbine hub was internal spline wear. As described earlier, the analysis of the spline wear was performed in the same test cell as the spline durability evaluation. Table VI summarizes the wear test results presented as relative measurements where the maximum wear allowed by the specification is equated to 1. Any wear number less than 1 implies the wear was less than the specified maximum, thus meeting the specification. Any number greater than 1 implies the wear exceeded the specification, thus not meeting the specification.

Table VI: Summary of ID Spline Wear Tests

Process	Wear After 350,000 cycles
Standard P/M Hub	1.4
Forged and hardened AISI 1045 hub	0
Warm Compacted FD-0405	0
Specification	1

Conventionally compacted and sintered FC-0208 turbine hubs exhibited excessive wear in this high torque application with a relative wear value of 1.4. Wear measurements of the forged hub showed no wear at the specified number of cycles. However, it should be noted that the ID spline of the AISI 1045 hub was induction hardened to a hardness value 40 HRC. Without this hardening operation, the forged steel turbine hubs would not meet the specified minimum wear performance. Wear testing of the warm compacted FD-0405 showed no measurable wear during the test. The absence of wear in the warm compacted turbine hubs is significant because these components were evaluated in the as-sintered condition. The apparent hardness of the P/M components was approximately 15 HRC. The high density parts produced via the warm compaction P/M process coupled with the FD-0405 high performance material system eliminated the need for heat treating of the internal spline thus significantly reducing manufacturing cost and simplifying the manufacturing flow.

Figure 3 is a photomicrograph of the as-sintered microstructure of the warm compacted turbine hub. As a result of the diffusion alloyed base material, a unique microstructure of lamellar pearlite, bainite. nickel rich martensite areas, and ferrite. This microstructure was responsible for the excellent wear performance demonstrated in the as-sintered condition.

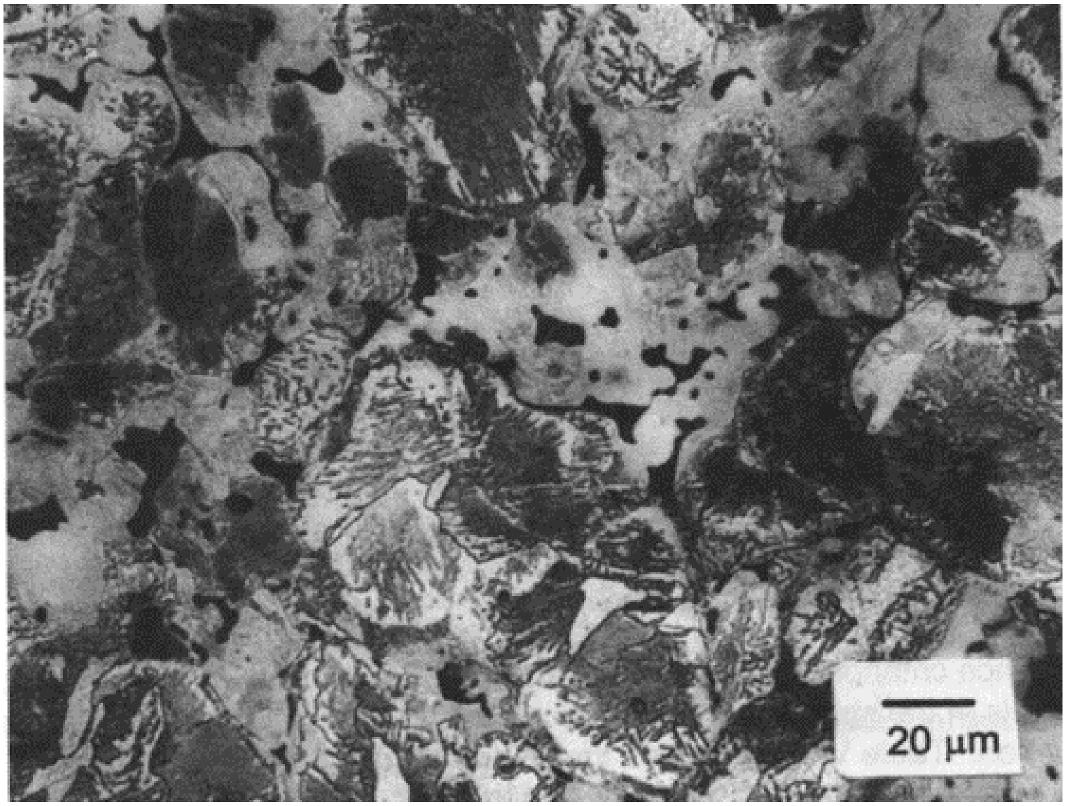

Figure 3: Microstructure of the As-Sintered Turbine Hub Original Magnification - 500X, 2% nital I 4% picral etch

As mentioned earlier, the overall sintered density of the turbine hub was 7.25 g/cm^3. To achieve this high sintered density, the green compact was pressed to over 97% of the pore free density of the premix. One benefit of compaction to this high green density is the greater uniformity of density throughout the finished part. To document this, production processed hubs were sectioned and examined for porosity distribution along the length of the ID spline using quantitative image analysis. Figure 4 is a plot showing this density profile for a warm compacted production part. The drop off in density in the small neutral zone is approximately 0.15 g/cm^3 compared with the average sectional density in the spine area of about 7.3 g/cm^3. The results for a conventionally compacted turbine hub, of a different design, made from an FC-0208 material are shown in Figure 5. The density variation of the conventionally processed part (0.4 g/cm^3 total) is significantly higher than was noted in the warm compacted part. In addition, the increase in density with the warm compaction part is readily apparent.

In addition to the mechanical property testing, extensive dimensional and weight capability studies have been performed on the warm compaction process. The results indicate that the variations measured were consistent with those obtained in conventional P/M processing.

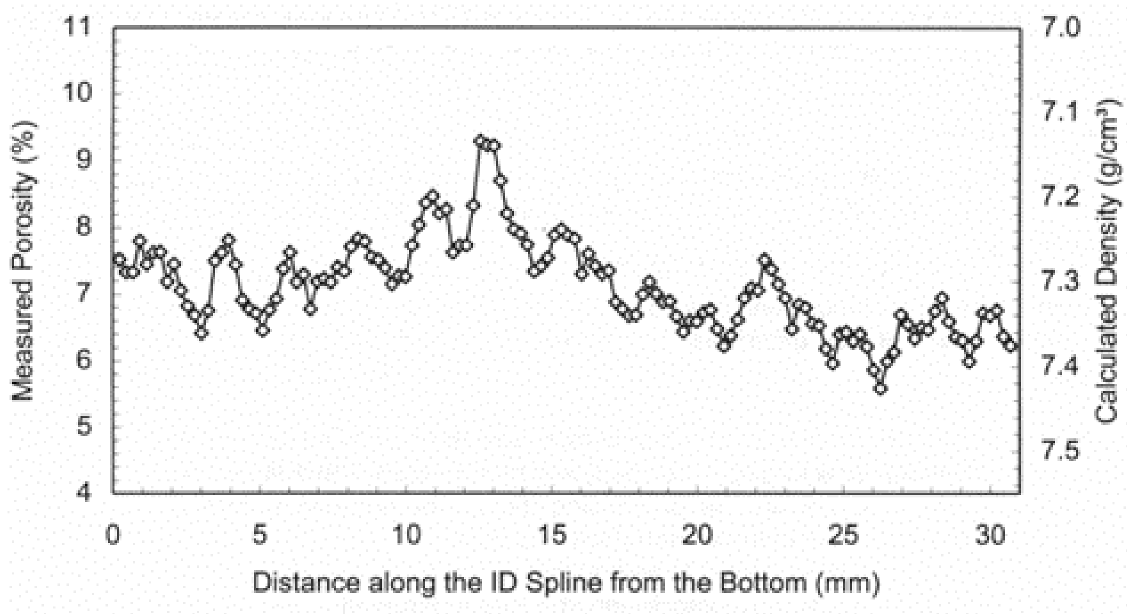

Figure 4: Porosity Distribution Along the ID Spline for a Warm Compacted Part

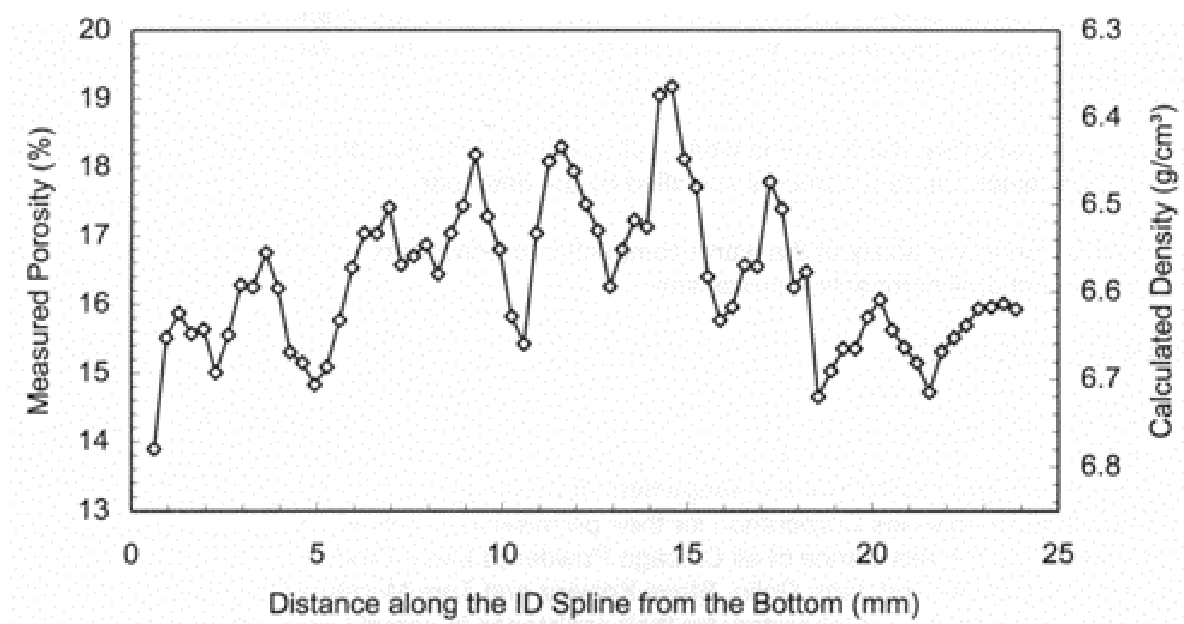

Figure 5: Porosity Distribution Along the ID Spline for a Conventionally Compacted Part

CONCLUSIONS

The production of a warm compacted, 1100 gram multi-level P/M turbine hub has produced a component with an overall as-sintered density of approximately 7.25 g/cm^3 utilizing conventional sintering temperature. Higher density levels were achieved in the critically stressed ID regions of the part. In combining the benefits of warm compaction technology with a high performance material system, the need for induction hardening of the ID spline was eliminated. These advantages allowed a simplified manufacturing process and an overall part cost reduction.

Extensive preproduction trials demonstrated that the warm compaction process is a viable manufacturing process for automatic transmission turbine hubs for high torque engines. The following can be concluded from the above investigation:

1. The FD-0405 material in combination with the warm compaction process was shown to produce high density levels in laboratory tests. The tests also indicated that the material and process were able to produce high as-sintered strength levels while maintaining good ductility and impact resistance.

2. Warm compaction processing of a complex multi-level turbine hub produced an overall sintered density of 7.25 g/cm^3 with high sintered densities achieved in the critical ID spline region.

3. Warm compaction processing of a high torque automatic transmission turbine hub successfully replaced a forged, machined, and heat treated AISI 1045 steel part. The P/M process significantly reduced the processing steps. The reduced number of processing steps resulted in an overall lower manufacturing cost.

4. Utilizing an FD-0405 material composition, the P/M turbine hub was used in the as-sintered condition eliminating the requirement for induction hardening of the ID spline as required in the forged component it replaced.

5. Standard tensile and fatigue testing of the P/M material demonstrated that the P/M component was equivalent in yield and tensile properties to the wrought steel. The P/M material had a lower rotating bending fatigue strength.

6. ID spline durability and ID spline wear testing of the warm compacted P/M component met and surpassed the requirements specified by the end user.

7. Manufacturing variability of the warm compaction process was equivalent to the variability of the conventional compaction processes.

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