MANUFACTURING 400 SERIES COMPONENTS USING EASY-MACHINABLE STAINLESS STEEL POWDERS

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ABSTRACT

Automotive exhaust flanges and HEGO bosses are common components manufactured by powder metallurgy (PM) using 400 series stainless steel powders. These components often require secondary machining in order to meet final dimensions or add features which couldn’t be achieved through PM compaction and sintering processes. The machining of PM stainless steel can be challenging due to the inherent microstructure of stainless steel and the resulting low particle hardness of matrix. Recently, Stainless Steel EZ™ powders have been introduced to improve productivity when machining operations are necessary. In this study, a component manufactured from 400 series PM was selected to evaluate against a Stainless Steel EZ™ version in a production environment to quantify machinability improvement. Since 400 series components are also typically welded into place, welding evaluation of the materials was also conducted.

INTRODUCTION

The highest volume application utilizing powder metallurgy (PM) stainless steels is the manufacture of components in automotive exhaust systems, specifically, flanges and HEGO (hot exhaust gas oxygen) sensors. The use of PM components in exhaust systems has grown due to stricter emission standards and increased operating temperatures in the exhaust systems. The PM process is advantageous for manufacture of flanges and HEGO bosses due to high material utilization, near net shape capability, dimensional precision, flatness, and gas sealing capability.
The primary function of the flange is the gas sealing capability which requires the flange to have a number of characteristics including sufficient mechanical strength at room and elevated temperature, oxidation resistance, thermal fatigue, corrosion resistance and weldability.\(^1\) To meet these demanding properties, 400 series powders are chosen as the preferred alloys for manufacture of the flanges. Besides performance, 400 series alloys are preferred because of their compatibility with the exhaust tubing, coefficient of thermal expansion, avoidance of corrosion due to galvanic coupling and weldability.\(^1\) Numerous studies have shown that 400 series PM flanges have the ability to meet the demanding application requirements.\(^1,4,5\) In a number of evaluations, the 400 series PM flanges outperformed their wrought counterparts.

The most popular alloy in the manufacture of flanges is 409L with modified versions 409LE and 409LNi also being used. These alloys contain a small amount of niobium which serves as a stabilizer against sensitization and allows for improved weldability.\(^6\) The alloys are sintered at high temperature in a 100% hydrogen atmosphere in order to meet the minimum density requirement of 7.20 g/cm\(^3\) and achieve low levels of interstitial elements. This sintering practice results in a material with rounder porosity and the necessary mechanical performance for the application. Studies have illustrated that components not meeting the minimum density requirement of 7.20 g/cm\(^3\) will not meet performance expectations in application testing.\(^4,5\)

The as-sintered parts often require machining in order to add features which cannot be imparted during compaction and also to correct any distortion in the part resulting from the high rate of shrinkage during sintering (~4% linear). The most common machining operations are the addition of grooves and threads. Past studies have shown manganese sulfide (MnS), a common additive in ferrous PM, to provide a significant improvement to the machinability of stainless steel PM parts.\(^8,9\) While the machinability can be improved by alloying or admixing in MnS, the corrosion resistance is significantly decreased.\(^10-12\) The admixing of additives can also interfere with the welding process which is why it’s not commonly used in 400 series applications where welding is required.\(^6\)

A family of machinable grades of stainless steel powders, called Stainless Steel EZ\(^{TM}\), was recently introduced to provide improved machinability performance while maintaining corrosion resistance.\(^13,14\) These alloys are produced using a proprietary production process to improve the machinability of the stainless steel powder. Designed specifically for stainless steel powders and their inherent microstructure, the process is a departure from the typical PM practice of admixing in machinability additives. These powders have been demonstrated to provide significant improvement in machinability for both 300 and 400 series alloys. No degradation of mechanical properties or corrosion resistance was observed when using these materials making these new powders a tool to improve the overall manufacturability of PM stainless steel parts.

The previous study on 400 series materials investigated two common alloys: 409L and 430L.\(^14\) These alloys, while both ferritic, have different applications. The 409L alloy is commonly used when welding is required for final assembly. A niobium addition is added to the material which serves to stabilize the alloy against sensitization.\(^6\) With a niobium content of 0.4 – 0.8 w/o this alloy system is commonly used as a flange material. While weldability is one important characteristic, the mechanical performance, especially at high temperature, is also of great importance.

The 430L alloy, with higher chromium content, offers superior corrosion resistance to the low chromium 409L material. While the corrosion resistance is not comparable to the austenitic alloys, the higher chromium containing 430L is a popular choice when good corrosion is required. Due to the higher chromium content, this material is more difficult to machine compared to the lower chromium containing ferritic alloys.\(^6,14\)
The current study evaluates both 409L and 430L against their easy machinable counterparts. The mechanical properties and weldability of 409L were compared against 409L-EZ. Since the 430L material was found more difficult to machine, it was evaluated against 430L-EZ in a current production application which is heavily machined.

EXPERIMENTAL

Mechanical Property and Weldability Evaluation

Commercially available, water atomized SS-409L and SS-409L-EZ powders were used for the study. The chemical compositions of each material are shown in Table 1.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Cr</th>
<th>Nb</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>C</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>409L</td>
<td>11.6</td>
<td>0.44</td>
<td>0.11</td>
<td>0.74</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>Bal.</td>
</tr>
<tr>
<td>409L-EZ</td>
<td>11.9</td>
<td>0.41</td>
<td>0.10</td>
<td>0.91</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Both powders were annealed with a nominal particle size of minus 150 µm (-100 mesh). For each base powder, mixes were manufactured in the North American Höganäs Pilot Mixing Center with 1.0% by weight of Acrawax C added for lubricity. From each mix, a number of different specimens were compacted as part of the experimental program to evaluate mechanical properties and weldability. Since elevated temperature tensile testing was included in the study, Izod impact specimens were compacted to a green density of 6.5 g/cm³. Prototype flanges were manufactured by compacting the two mixes into 165 mm diameter by 11.5 mm thick (6.5 inch x 0.45 inch) discs to a green density of 6.5 g/cm³. The compaction of the discs was completed by Casting Services Inc. (Menominee, MI). The discs were utilized for weldability testing.

The specimens were delubricated prior to sintering. Sintering was conducted in a production high temperature pusher furnace. All specimens were sintered at 1316 °C (2400 °F) in 100% hydrogen atmosphere. The time at temperature was 45 minutes.

After sintering, the Izod bars were machined into standard round PM tensile test specimens (4.75 mm diameter x 25.5 mm, 0.187 inch diameter x 1.00 inch) in accordance with ASTM E8-13.15 Threaded grips were used to accommodate the fixturing available for the elevated temperature tensile testing. Tensile testing was conducted at three temperatures: room temperature, 650 °C (1200 °F) and 870 °C (1600 °F). All specimen machining and testing was conducted by Westmoreland Mechanical Testing & Research Inc. (Youngstown, PA).

For each prototype flange disc, a 50 mm (2 inch) diameter through hole was machined at the center to allow for assembly with wrought tubing. A 150 mm (6 inch) length of SS 439 exhaust tubing was used for the assembly. SS 439 is a weldable grade of stainless steel which has similar composition to SS 434L, except for a small addition of titanium to stabilize the alloy. In wrought stainless steel, titanium is a more common stabilizer compared to niobium which is commonly used for PM stainless steel alloys. The tubing was a standard exhaust grade having a 50 mm outer diameter and 1.5 mm wall thickness (2.0 inch O.D. and 0.060 inch wall thickness). Welding was conducted by Specialty Fabrication Inc. (Detroit, MI) which specializes in prototype exhaust assemblies for the automotive industry.

In each case, the tubing was inserted into the machined hole to the full thickness of the prototype disc and then fillet welded to the disc on one side. Metal inert gas (MIG) welding was employed using a Miller 250 MIG Welder. The welding parameters are shown in Table 2.
Table 2. Welding Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>-22.7 volt</td>
</tr>
<tr>
<td>Shielding gas</td>
<td>90% Helium, 7.5% argon, 2.5% carbon dioxide</td>
</tr>
<tr>
<td>Wire speed</td>
<td>5300 mm/min (211 inch/minute)</td>
</tr>
<tr>
<td>Welding Wire</td>
<td>ER 409</td>
</tr>
</tbody>
</table>

The welded assemblies were labeled according to the base material used. The 409L assemblies were labeled as “O” (original) and the 409L-EZ assemblies were labeled as “T” (test material). A visual examination of the weld bead was performed examining for gross defects. The assemblies were subsequently evaluated by X-Ray radiography to determine the presence of any weld defects (voids, undercuts, cracks, etc.). The radiography testing was carried out by XRI Testing Lab (Cleveland, OH). The assemblies were then tested for joint strength by Element (Wixom, MI). Using specially designed fixtures for prototype flange – tube weld assemblies, the flange body and the wrought stainless steel tubing are gripped in vertical alignment and then pulled in tension until failure. The break loads were recorded.

Density and apparent hardness were evaluated on all components in accordance with MPIF standard test methods. Interstitial elements were evaluated and metallographic analysis completed on the tested components. During the metallographic analysis of the prototype flange assemblies the integrity of the welded area was also examined for any abnormalities.

Production Machining Trials
The production component which was studied is currently manufactured from water atomized 430L powder. A sample mix of the current material and 430L-EZ were manufactured in the North American Höganäs Pilot Mixing Center. The chemical composition of the materials is listed in Table 3.

Table 3. Chemical Composition of Alloys for Production Machining Trials (w/o)

<table>
<thead>
<tr>
<th>Grade</th>
<th>Cr</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>C</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>430L</td>
<td>16.8</td>
<td>0.16</td>
<td>0.90</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
<td>Bal.</td>
</tr>
<tr>
<td>430L-EZ</td>
<td>16.6</td>
<td>0.14</td>
<td>0.91</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Components were compacted from both materials using the standard production practices of SMC Powder Metallurgy. Sintering was carried out by SMC Powder Metallurgy in a production high temperature pusher furnace. All specimens were high temperature sintered in 100% hydrogen atmosphere according to their current production practices.

Machinability testing was conducted at SMC Powder Metallurgy in their fully automated production machining line for this component. The component undergoes a rough ID turning operation, facing, final ID turning and grooving. All of the tooling used was coated carbide. The machining parameters used were developed using the standard 430L material. No changes to the parameters were made for the machining trials. Based on production history, tool adjustments are required over a run of parts manufactured from the 430L material. A tool change is typically required after 150 components are machined due to surface finish requirements of the component. From each material, therefore, 150 components were machined and thereafter the tooling analyzed for wear. Based on those results, another set of components manufactured from the 430L-EZ material was machined with a new set of tools to determine the potential improvement in tool life. The component prior to and after machining is depicted in Figure 1.
Density was evaluated on all components in accordance with MPIF standard test methods.\textsuperscript{16} Interstitial elements were evaluated and metallographic analysis completed on the machined components.\textsuperscript{17}

**RESULTS**

**Mechanical Properties**

The physical and chemical analysis of the tensile and prototype flanges is shown in Table 4.

Table 4. Physical and Chemical Analysis of Tensile and Prototype Flange Specimens

<table>
<thead>
<tr>
<th>Material</th>
<th>Specimen</th>
<th>Density (g/cm(^3))</th>
<th>Carbon (%)</th>
<th>Nitrogen (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>409L</td>
<td>Tensile</td>
<td>7.23</td>
<td>0.01</td>
<td>30</td>
</tr>
<tr>
<td>409L</td>
<td>Prototype Flange</td>
<td>7.26</td>
<td>0.01</td>
<td>88</td>
</tr>
<tr>
<td>409L-EZ</td>
<td>Tensile</td>
<td>7.26</td>
<td>0.01</td>
<td>40</td>
</tr>
<tr>
<td>409L-EZ</td>
<td>Prototype Flange</td>
<td>7.24</td>
<td>0.01</td>
<td>100</td>
</tr>
</tbody>
</table>

The density and interstitial levels observed in the tensile and flange specimen are typical of a high temperature sintering in an 100% hydrogen atmosphere. The mechanical properties of the 409L and 409L-EZ at the three test temperatures are shown in Table 5.

Table 5. Elevated Temperature Tensile Properties of 409L and 409L-EZ

<table>
<thead>
<tr>
<th>Grade</th>
<th>Test Temperature °C, (°F)</th>
<th>Ultimate Tensile MPa, (10(^3) psi)</th>
<th>Yield Strength MPa, (10(^3) psi)</th>
<th>Elongation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>409L</td>
<td>20, (72)</td>
<td>379 (55.1)</td>
<td>200 (29.0)</td>
<td>27</td>
</tr>
<tr>
<td>409L-EZ</td>
<td>20, (72)</td>
<td>387 (56.1)</td>
<td>205 (29.8)</td>
<td>27</td>
</tr>
<tr>
<td>409L</td>
<td>650 (1200)</td>
<td>200 (29.1)</td>
<td>98.6 (14.3)</td>
<td>15</td>
</tr>
<tr>
<td>409L-EZ</td>
<td>650 (1200)</td>
<td>201 (28.6)</td>
<td>97.2 (14.1)</td>
<td>18</td>
</tr>
<tr>
<td>409L</td>
<td>870 (1600)</td>
<td>28.6 (4.1)</td>
<td>16.5 (2.4)</td>
<td>80</td>
</tr>
<tr>
<td>409L-EZ</td>
<td>870 (1600)</td>
<td>26.2 (3.8)</td>
<td>16.5 (2.4)</td>
<td>90</td>
</tr>
</tbody>
</table>

The tensile testing indicated there was no difference in strength or elongation between the materials. The elevated temperature testing results were in line with previous studies.\textsuperscript{18}

**Weldability Testing Results**

The welded prototype assemblies were first examined visually for welding defects. No evidence of blow holes or gas evolution was observed. The remaining oxide layer on the weld was easily removed by wire brushing. The cleaned weld beads did not show evidence of undercuts, distortion, pits, or other discontinuities. Examples of the welded assemblies are shown in Figure 2.
Radiographic testing was conducted on the three test assemblies from each material. No discontinuities or internal voids were found in any of the samples. The weld strength was subsequently tested on the welded assemblies. The break loads recorded on the assemblies are shown in Figure 3.

In all cases, the weld remained intact and the failure occurred in the tubing. For sample 409L-EZ-T-3, the tubing necked considerably about 50 mm (2 inches) above the weld before failing. As expected, the failure occurred in the tubing as this area would be softened to a small extent from its heavy cold work state. Examples of a typical failure and the failure of sample T-3 is shown in Figure 4.
Measurement of the wall thickness of the failed tubing showed a reduction of cross-sectional area at the fracture of approximately 5% for all of the samples. This value is typical for a heavily cold worked ferritic wrought stainless steel. The break loads sustained translate into a tensile strength of 200 – 250 MPa (29,000 – 36,000 psi) for the tubing in this non-standard tension test. There was no deformation of the weld bead which indicates it was strong enough to carry the applied load.

**Production Machinability Trial Results**

The physical properties of the production flange are shown in Table 6.

<table>
<thead>
<tr>
<th>Material</th>
<th>Specimen</th>
<th>Density (g/cm³)</th>
<th>Carbon (%)</th>
<th>Nitrogen (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>430L</td>
<td>Production Flange</td>
<td>7.25</td>
<td>0.01</td>
<td>25</td>
</tr>
<tr>
<td>430L-EZ</td>
<td>Production Flange</td>
<td>7.26</td>
<td>0.01</td>
<td>40</td>
</tr>
</tbody>
</table>

The density and interstitial levels are typical of SMC production on this component. The critical feature of the machining operation is the surface roughness requirement of 0.8 Rₐ (µm) maximum. Therefore, surface roughness was measured during the machining trial using a diamond stylus profilometer. The measurements are summarized in Figure 5.

**Figure 5.** Surface roughness measurements on production machined components

Typical production machining of this component averages 150 components before a tooling change is required. The 430L components were approaching the maximum specification for surface roughness when the initial test was stopped at 150 components. When the 430L-EZ was stopped at 150 components for a direct comparison, the surface roughness was measured to be considerably less than the current 430L material. Another set of 430L-EZ components was machined to determine the maximum amount which could be machined without tool change and still meet the specification for surface roughness. After 260 pieces, the testing was stopped due to lack of parts. At this point, the surface roughness measured 0.16 Rₐ which is well below the specification.
DISCUSSION

With the growth of PM stainless steel components into automotive exhaust systems, elevated temperature mechanical properties grew in importance because of the elevated service atmosphere in which the applications function. Maintaining structural integrity at elevated temperatures is critical in order to achieve the required gas sealing capability. In this study, the 409L-EZ material had similar mechanical performance compared to the 409L material. At elevated temperatures, no difference was observed between the materials. No differences were expected since the 409L-EZ has the same chemistry as the 409L alloy.

Past studies have shown the machinability of 400 series alloys can be improved using MnS. However, MnS can degrade the performance of welding. So while machining performance showed improvement, it is also important to evaluate the weldability of the Stainless Steel EZ™ materials. Inspection of the welding conducted on the 409L-EZ prototype flanges found no defects or abnormalities in the weld. Metallographic evaluation of the welded area confirmed the radiographic testing. Photomicrographs of the as polished samples are shown in Figure 6 of the welded assemblies.

The weld zones were found to be free of pores, cracks and large inclusions. A few small slag inclusions were found in each sample. The inclusions measured less than 20 µm in size and had no effect on the strength or integrity of the weld. The metallographic samples were subsequently etched with Glyceregia etchant and examined. The photomicrographs of the weld assemblies in the etched condition are shown in Figure 7.
The coarse grain structure of the weld bead (remelted material) transitioned to the fine grained PM base material structure in a smooth and consistent manner for both materials. No boundary or discontinuity was observed at the interface. The etched microstructure showed a very good bond between the weld bead and the PM base material for both materials. Away from the weld bead, a uniform grain structure was observed for both materials. Both materials exhibited well rounded porosity and precipitate free grain boundaries typical of high temperature 100% hydrogen sintered ferritic stainless steel (Figure 8).

The production machining trial found the 430L-EZ material to outperform the current 430L for surface roughness. When a second trial was conducted to determine the maximum amount of components which could be machined and still meet the surface roughness specification, 110 extra pieces were machined before the testing was stopped due to lack of components. This represents at least a 75% increase in productivity as more pieces would have been able to be machined based on the surface roughness measurements. To understand the reason for the improvement in surface roughness, the tooling and microstructure were examined further.
The status of tool wear for the ID turning operation is shown in Figure 9.

**Figure 9.** Inset analysis of ID turning operation (Top: Rough cutting, Bottom: Finish cutting)

Significant material buildup was observed on the rough cutting insert used to machine the 430L material after 150 pieces. Only a small amount of material buildup was found on the insert used to rough turn the 430L-EZ components. When the amount of pieces was increased for the 430L-EZ to 260, the tool wear and material buildup was similar to the insert after machining 150 pieces. A similar trend was observed for the finishing insert. The insert used to machine the 430L components had elevated material buildup and increased tool wear compared to the insert used to machine the 430L-EZ even after 260 components were machined.

The facing insert analysis is shown in Figure 10.

**Figure 10.** Facing insert analysis

Similar trends to the turning operations were observed for the facing operation. The insert used to machine the 430L showed more wear and build up compared to the inserts used to cut the 430L-EZ components.
The analysis of the grooving inserts is shown in Figure 11.

Figure 11. Grooving insert analysis

Material buildup was observed on the grooving insert used to cut the 430L parts. The insert used to machine the 430L-EZ material did not show significant buildup after 150 pieces. After 260 pieces, only a small amount of material was built up on the insert. To further quantify the differences in machining performance, metallographic analysis was conducted on the machined groove (Figure 12).

Figure 12. Overview of machined groove with the circle indicating the evaluation area

The radius on the ID and OD groove on the final machined component for each material was metallographic examined. The photomicrographs of the OD radius at a higher magnification are shown in Figure 13.
A significant difference in the radius of the cut groove was observed between the materials. Measurements were made from the intersection of the bottom and side of the groove to the groove radius. The measurement values are shown in Table 7.

### Table 7. Measurement of Radii

<table>
<thead>
<tr>
<th>ID</th>
<th>Distance (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>430L Part 1</td>
<td>84.8</td>
</tr>
<tr>
<td>430L Part 150</td>
<td>98.1</td>
</tr>
<tr>
<td>430L-EZ Part 150</td>
<td>87.9</td>
</tr>
<tr>
<td>430L Part 260</td>
<td>88.2</td>
</tr>
</tbody>
</table>

The radius is greater for the 430L material at 150 pieces compared to the 430L-EZ material at the same amount of components machined. Even after machining 260 components, the 430L-EZ had less radius compared to the 430L at 150 pieces. This difference in radius between the 430L and 430L-EZ components indicates a worn tool with decreased cutting ability and confirms the SEM analysis of the insert. A similar phenomenon was observed for the ID radius as well.

The surface finish measurements correlate with the observation of adhesive material buildup and tool wear on the inserts. The insert used to machine the 430L components had a large amount of material buildup which explains the poor finish of the machined parts since the excess material on the tool would hinder the ability to cut. For the 430L-EZ material, almost no material was found to have adhered to the tooling which led to a good machined surface.
CONCLUSIONS

From this study, the following conclusions can be drawn:

- Tensile strengths were determined at room and elevated temperature. No difference between the 409L and 409L-EZ was found. The strength values measured were in line with past studies.

- The welding performance of the 409L-EZ material was similar to that of the 409L. No defects were found in the welded area and in all cases the strength of the weld was satisfactory. All of the pull tests on the prototype assemblies failed in the exhaust tubing which is the desired failure mode. Metallographic analysis of the weld joint found good adhesion between the welding material and the PM matrix.

- A 75% improvement in machining productivity was observed for the 430L-EZ material. The surface roughness measurements, lack of wear and material build up on the inserts used to machine the 430L-EZ components indicate the improvement could be greater.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the production personnel at SMC Powder Metallurgy for their assistance in the production of the components and the machining trials conducted. Their planning and execution of the experimental steps were valuable in achieving meaningful data from the production machining trials.

REFERENCES