Reduced sintering temperature creates new opportunities for PM Stainless Steel Exhaust components

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ABSTRACT

Currently PM exhaust flanges and HEGO bosses are manufactured from 409L or 434 L stainless steel powder by employing high temperature, hydrogen sintering. The high temperature sintering is necessary to achieve the large shrinkage needed to reach the specified sintered density set forth by OEM. Producers of exhaust components are today sintering between 1290 C to 1390 C to reach desired densities.

410LV is a newly developed low chromium ferritic stainless steel which exhibits greater sintering activity at lower temperatures compared to the standard 409L. By selecting this alloy it is feasible to achieve a sintered density of 6.9 g/cc under mesh-belt sintering conditions (below 1180 C). This permits a significant reduction in the manufacturing cost and allows possible production of exhaust components without investment in high temperature capability. 410LV sintered at reduced temperature may offer adequate mechanical strength, corrosion resistance, and weldability for the exhaust flange and HEGO boss applications. This paper treats the properties of low temperature sintered 410LV, and compares those with the properties of low and high temperature sintered 409L.

INTRODUCTION

Introduced in the early1990s, the PM stainless steel exhaust flanges and HEGO bosses have found wide acceptance in the North American automobile industry. These components compliment the wrought stainless steel exhaust tubing, and as such impart durability, long-term leak tightness, and serviceability to the entire exhaust sub-assembly. In comparison to wrought stainless steel, the PM option offers advantages in terms of cost, design flexibility, dimensional accuracy, and flatness [1].

Low chromium ferritic grades of stainless steel, namely 409L and 409LE (per MPIF Standard 35) are the most commonly used materials for the exhaust flange and HEGO boss applications. The production of the PM ferritic stainless steel exhaust components typically involves high temperature, hydrogen sintering, in order to meet a minimum sintered density of 7.20 g/cm^3 that is specified by most Tier 1's and OEMs. This relatively high density requirement is based on equivalent performance of the PM components to the wrought stainless steel components, in terms of corrosion/oxidation resistance and mechanical strength. Sintering in a nitrogen bearing atmosphere is strictly unacceptable because of the strong propensity of the low and medium chromium ferritic stainless steels to form martensite and nitrides by the absorption of nitrogen from the sintering atmosphere. High temperature sintering is usually carried out in ceramic lined pusher furnaces at temperatures ranging from 1288 ^{0}C to 1388 ^{0}C (2350 ^{0}F to 2530 ^{0}F). In comparison to the conventional metal mesh-belt sintering, this process has the disadvantages of high capital and operating costs. High temperature sintering is also associated with large amounts of shrinkage and distortion, which frequently necessitates sizing/coining. This also adds to the cost. More ever, as high temperature pusher-type sintering furnaces are not very common in the PM industry, this requirement limits the number of parts makers that are able to participate in this business.

A vanadium stabilized, low chromium ferritic stainless steel, namely 410LV, is found to offer enhanced sinterability over the traditional 409L. A markedly higher sintered density is achieved with 410LV in belt furnace sintering in comparison to 409L and 409LE. Although, the sintered density of the mesh belt furnace sintered 410LV is lower than 7.20 g/cm^3, the density and properties achieved may still be adequate for some exhaust flange and HEGO boss applications. This paper compares the properties of low temperature sintered 410LV with properties of similarly processed 409L.

MATERIALS

The chemical compositions of the 410LV and 409L alloy powders used in the study are listed in Table 1. Since the atomic weight of vanadium is much lower than that of columbium (51 vs 93), a proportionately smaller amount (by weight %) of vanadium is required for providing the same degree of protection from sensitization. The vanadium content of the 410LV powder used here was 0.24 weight %.

Alloy	Fe	Cr	Si	Mn	P	S	C	Nb	V	N	O
410LV	Bal	12.14	0.83	0.13	0.01	0.012	0.020	0.00	0.25	0.030	0.22
409L	Bal	11.34	0.87	0.10	0.01	0.007	0.020	0.49	0.00	0.030	0.20

Table 1: Chemical compositions of powders used

For each alloy, powders having two different in particle size distributions were used. One powder had a particle size distribution with 45% fines (< 44 microns), while the other had a particle size distribution with 50% fines. All four powders were nominally -100 mesh (<149 microns). All were produced by water atomization, followed by annealing, and were lubricated with 0.75% Acrawax. Table 2 lists the physical properties and compacting characteristics of the four lubricated powders.

Powder type	Alloy	Fines content, %	A D, g/cm^3	Green density, g/cm^3	Green strength, MPa (PSI)	Hall flow rate, s/50 g
410LVR	410LV	45.0	2.94	6.59	13.6 (1972)	32
410LVF	410LV	49.9	2.92	6.57	12.8(1856)	34
409LR	409L	45.2	2.93	6.57	12.5(1813)	29
409LF	409L	50.0	2.91	6.55	11.9(1726)	32
Note: Green density and green strength testing was carried out at 620 MPa (45 TSI)						

Table 2: Compacting properties of powders used

PROCESSING

Since the primary goal of this study was to determine the performance of PM 410LV material produced under mesh-belt production conditions, all sintering in this study was carried out in a production scale, metal mesh-belt furnace at FJ Sintermetal (Denmark). Two compaction pressures were employed: 600 MPa and 700 MPa (43.5 and 50.8 TSI). In all cases, the sintering temperature was kept at 1160 ^{0}C (2120 ^{0}F) and the sintering time was kept at 45 minutes. Delubrication was carried out in the same furnace run as the sintering. The furnace atmosphere was 100% hydrogen.

Transverse Rupture Strength test (TRS) bars, 'dog bone' Tensile Test specimens, and Impact Energy Test specimens, conforming to MPIF Standard Test Methods, were used for various tests as appropriate. Round, disc shaped samples, measuring 70 mm in diameter x 12 mm in thickness (2.75 inch x 0.50 inch) were utilized for Salt Spray Corrosion testing, and for weldability testing. Holes measuring 45 mm in diameter (1.77 inch) were cut in the 70 mm diameter discs for weldability testing. Standard wrought 409L tubing was welded onto the cut discs, using MIG welding, for evaluation of weldability.

The powder and process combinations employed are shown in Table 3, along with the material designations that are referenced in all subsequent data tables.

RESULTS AND DISCUSSION

Sinterability

All sintering was carried out at 1160 ^{0}C (2120 ^{0}F) in a 100% hydrogen atmosphere for 45 minutes. Table 4 lists the sintered densities and interstitial contents of the sintered samples. Density measurements were made on cut pieces (25 mm x 25 mm x 12 mm;1.0 inch x 1.0 inch x 0.50 inch) taken from the 70 mm diameter x 12 mm thick discs, by Archimedes technique of water immersion.

Material designation	Powder type	Compaction pressure, Mpa	Sintered density, g/cm^3	Sintered density difference, g/cm^3	Nitrogen ppm	Oxygen, ppm	Carbon, %
VR6	410LVR	600 (43.5)	6.73	0.19	23	2635	0.014
CR6	409LR	600 (43.5)	6.54		122	2726	0.014
VR7	410LVR	700 (50.8)	6.79	0.10	46	2992	0.016
CR7	409LR	700 (50.8)	6.69		146	2852	0.022
VF6	410LVF	600 (43.5)	6.75	0.18	43	2640	0.010
CF6	409LF	600 (43.5)	6.57		147	2452	0.021
VF7	410LVF	700 (50.8)	6.90	0.14	37	2786	0.016
CF7	409LF	700 (50.8)	6.76		215	2814	0.020

Table 3: Sintered densities and interstitial contents

Within each type of powder, the 700 MPa (50.8 TSI) compacted discs typically exhibited 0.15 g/cm^3 higher density compared to the 600 MPa (43.5 TSI) compacted discs. The increase in fines content (by 5%) led to an average increase in sintered density by 0.06 g/cm^3. The vanadium stabilized alloy typically exhibited 0.15 g/cm^3 higher sintered density in comparison to the columbium stabilized alloy. The highest sintered density achieved in this study was 6.90g/cm^3, and this was achieved with the 50% fines containing 410LV powder compacted at 700 MPa (50.8 TSI).

Figures 1 and 2 show the microstructures of Samples VF7 and CF7. Both materials exhibit a fully ferritic matrix. In each case some grain boundary precipitates are seen, which are considered to be the carbides and nitrides of the stabilizer used.

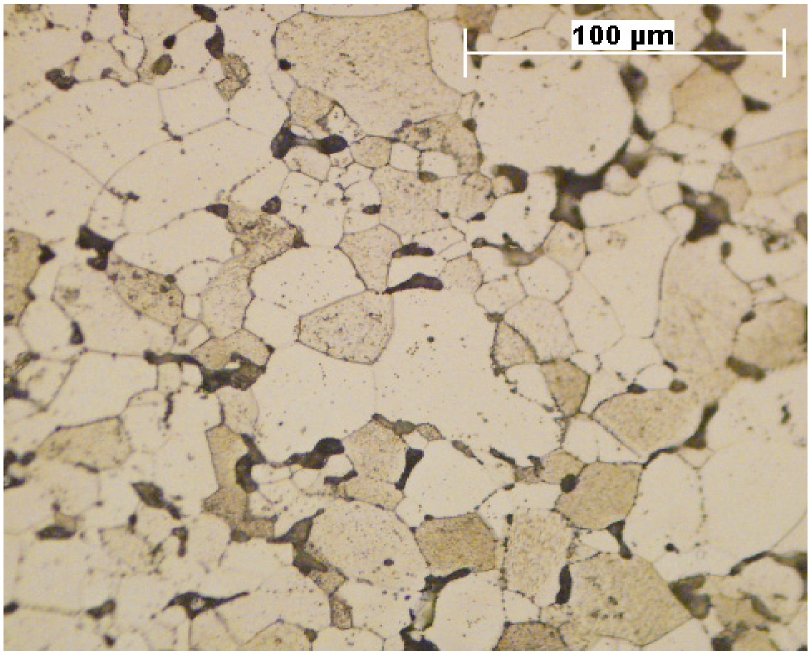

Figure 1: Photomicrograph of 410LV sample VF7 (Glyceregia etch)

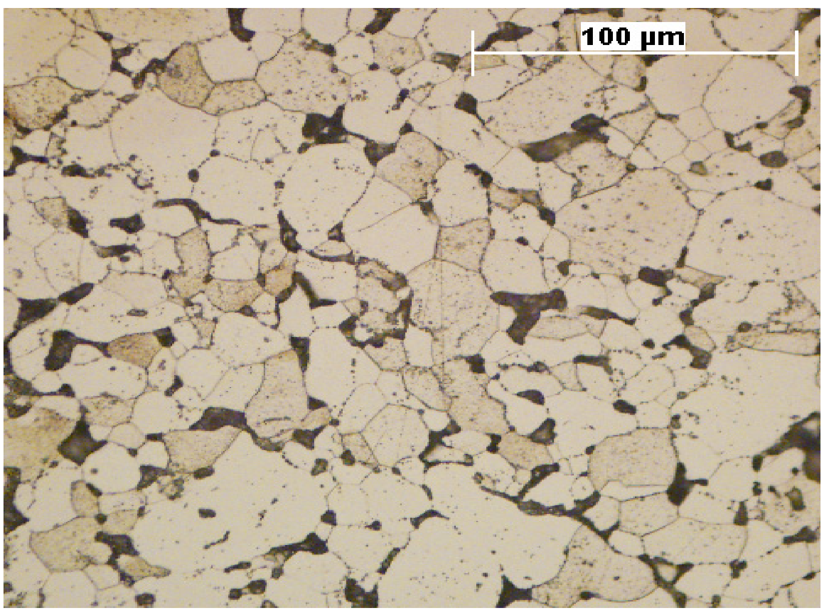

Figure 2: Photomicrograph of the 409L sample CF7 (Glyceregia etch)

Mechanical Properties
All tensile tests were carried out using the 'dog bone' tensile test specimens. Elevated temperature tensile tests were carried out in an atmosphere of argon. This was performed by Westmoreland Testing and Research Laboratories, Youngstown, Pa.

Table 4 lists the mechanical properties of all eight sets of materials, both for room temperature and for 659 ^{0}C (1200 ^{0}F) testing. For the same fines content and compaction pressure, the 410LV samples exhibited higher room temperature U. T. S. and yield strength. This is attributable to the higher sintered densities achieved with the 410LV powder. Samples VF6 and CF7 do permit a comparison of the mechanical strengths of the two alloys for very similar sintered densities. This comparison does show that the room temperature U. T. S. and yield strength of the two alloys are identical when the sintered density is the same.

Alloy 410LV exhibits significantly higher ductility over that of 409L for all process combinations. This is also an indication of the superior sinterability of 410LV. The elevated temperature U. T. S. and yield strengths of 410LV samples are somewhat lower than those of 409L.

		Room Temperature Tensile Testing						649 ^{0}C (1200 ^{0}F) Tensile Testing		
Matl. design -nation	Sintered density, g/cm^3	U. T. S, MPa (KSI)	Y S, MPa (KSI)	El., %	Impact Energy, J	Hardness HRB		U T S, MPa (KSI)	Y S., MPa (KSI)	El., %
VR6	6.73	262 (38.0)	185 (26.8)	7.4	28.5	26		102 (14.8)	68 (9.9)	9.5
CR6	6.54	217 (31.5)	172 (24.9)	3.4	9.0	23		130 (18.9)	83 (12.0)	5.5
VR7	6.79	295 (42.5)	204 (29.6)	9.4	36.1	35		100 (14.5)	66 (9.6)	10.0
CR7	6.69	234 (33.9)	185 (26.8)	3.4	10.9	32		132 (19.1)	91 (13.2)	4.5
VF6	6.75	281 (40.8)	193 (28.0)	10.3	20.2	29		100 (14.5)	63 (9.1)	11.0
CF6	6.57	269 (39.0)	185 (26.8)	6.8	20.2	29		143 (20.7)	90 (13.2)	5.0
VF7	6.90	303 (44.0)	205 (29.7)	10.6	25.1	37		105 (15.2)	63 (9.1)	12.8
CF7	6.76	280 (40.6)	192 (27.8)	6.7	25.0	35		149 (21.6)	94 (13.6)	4.5

Table 4: Room and elevated temperature mechanical properties

Accelerated Corrosion Test (GM 9540P)

The GM 9540P test is an oxidation/corrosion test, and it involves both salt solution exposure/spray, and a periodic 482 ^{0}C (900 ^{0}F) oven soak. The Accelerated Corrosion Test Package (GM9540P) is subdivided into 11 versions, with each one designed for a specific groups of automotive components. The version listed as “Option IX”, and designated for “Exhaust Manifolds and Flex Couplings” (Appendix A4.9), was employed here.

Each test cycle is 24 hours long and it comprises the following four steps:

1. Ambient soak (8 hours): 8 salt sprays starting at
   the end of 1st hour of the ambient soak period spaced 1 hour apart
2. Wet soak at 49 ^{0}C (120 ^{0}F) /100% RH (8 hours)
3. Dry soak 60 ^{0}C (140 ^{0}F) / < 30% RH (8 hours)
4. Oven soak at 482 ^{0}C (900 ^{0}F) for 4 hours, once every 4 days
   (- reduce ambient soak to 4 hours on those days)

One phase of testing equals 8 cycles. The recommended test duration is 10 phases (80 days). The test requires that standard reference coupons (wrought steel sheet) be placed in the test chamber along with the test specimens, and the mass losses of the test coupons are determined at the end of the test cycle in order to prove the validity of the test.

Normally, the evaluation criterion in this test is based on mass loss. Since the porosity present in the PM samples invariably leads to an increase in mass, this method of evaluation could not be applied here. Instead, sample evaluation was based on the ultimate tensile strength of the samples after completion of the test. Two dog bone specimens were used for each material. In addition, one pair of high temperature sintered (1316 ^{0}C, 2400 ^{0}F) 409L 'dog bone' specimens (7.20 g/cm^3 density) was included in the test to serve as a reference. Table 7 lists the breaking strengths of each pair of samples, and compares against the as-sintered U. T. S. values of the same material. As may be seen here, the oxidation/corrosion tested samples retained 70 to 80% of their original tensile strength. The percentage of strength retained in the case of the high temperature sintered 409L was similar to those of the low temperature sintered materials. This indicates that the deterioration of mechanical strength in this test was no greater than what is experienced with the currently used flange material, when viewed as a percentage of original strength.

Material designation	Sintered density, g/cm^3	Original U T S, MPa (KSI)	Breaking strength, MPa (KSI)	% Strength remaining
VR6	6.73	262 (38.0)	189 (27.4)	72.1
CR6	6.54	217 (31.5)	166 (24.1)	76.5
VR7	6.79	295 (42.5)	214 (31.0)	72.5
CR7	6.69	234 (33.9)	190 (27.5)	81.2
VF6	6.75	281 (40.8)	204 (29.6)	72.6
CF6	6.57	269 (39.0)	207 (30.0)	76.9
VF7	6.90	303 (44.0)	221 (32.1)	72.9
CF7	6.76	280 (40.6)	204 (29.6)	72.8
409L High Temp Sintered (Reference)	7.20	358 (51.9)	252 (36.5)	70.4

Table 5: Results of the Accelerated Corrosion Test (GM 1540 P)

Weldability testing

The purpose of this part of the study was to determine if the test materials can be welded satisfactorily to wrought 409L tubing using a commercially practiced welding method, namely MIG welding. In addition to observing the response of the PM material to the welding process, the breaking strengths of the weldments were determined.

Weld assemblies were constructed by welding two discs of the same material designation to a 20 cm long (44 mm O.D. x 1 mm wall) 409L tubing on its ends. Each end of the tubing was slid half way into the thickness of the cut disc, and a butt weld was made within the I D. of the disc. For each weld, the disc was first tack welded to the tubing at four spots, and then the work was rotated at a pre-set speed of 25 sec per rotation, while MIG welding was performed. Standard 409 metal core wire having a diameter of 0.90 mm (0.035 inch) was used, and the shielding gas was 90% helium, 7.5% argon and 2.5% CO_2. Welding was carried out at Specialty Fabrication Inc., Detroit, a prototype exhaust system manufacturer. Welded assemblies were examined and pull tested by Stork Climax research Services, Wixom, Michigan.

Table 5 summarizes the results of the weldability testing. The observations made by the welder, who routinely welds wrought 400 series exhaust components, are listed here. As expected, density played a strong role on the ease of welding, as well as on the soundness of the weld. The samples with sintered densities higher than 6.75 g/cm^3 were found to produce sound welds. With most of these samples the pull test failure occurred in the tubing and not in the weld. Sample VF7 (sintered density 6.90 g/cm^3) had the best result. In this case failure occurred midway along the length of the tubing (Figure 3). Figure 4 shows a typical failure of the tubing adjacent to the weld, which indicates that the weld joint was stronger than the tubing, and the tubing had suffered some deterioration of its mechanical strength in the heat affected zone. The breaking strengths of the three sample exhibiting this type of failure are close to that of Sample VF7. Hence, all four materials are considered to have sufficient weldability. This indicates that a minimum sintered density of 6.75 g/cm^3 is essential for both 409L and 410LV materials in order to be weldable by MIG.

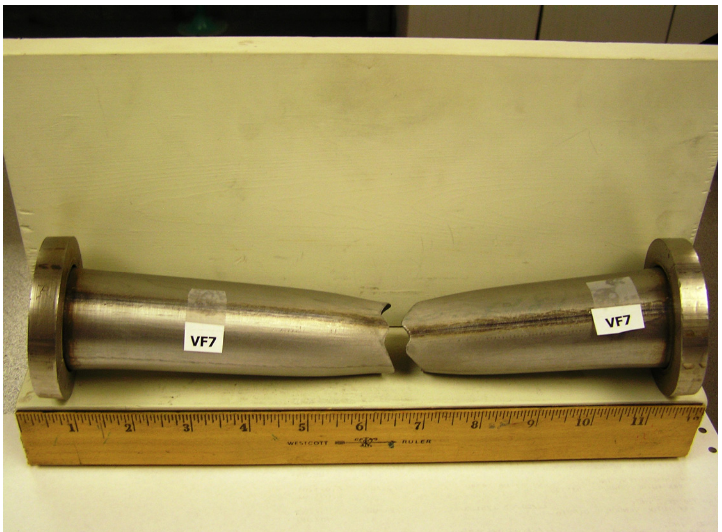

Figure 3: Welded and pull tested pieces of Sample VF7. Failure occurred in the wrought 409L tubing, and not in the weld or the PM disc.

Figure 4: An example of a weld pull test failure showing fracture of the wrought 409L tubing adjacent to the weld. The weld and the PM disc survived the test.

Material designation	Sintered density, g/cm^3	Breaking load, Kgf (lbf)	Break location	Welder's comments during welding
VR6	6.73	6,312 (13,915)	Weld	Not very good, some blow holes
CR6	6.54	6,414 (14,141)	Weld	Bad - weld metal migrating into pores
VR7	6.79	6,676 (14,718)	Tubing adjacent to weld	Good response, similar to wrought
CR7	6.69	6,150 (13,559)	Weld	Fair - some wetting problems
VF6	6.75	7,375 (16,258)	Tubing adjacent to weld	Good response, similar to wrought
CF6	6.57	4,660 (10,258)	Weld	Bad - weld metal migrating into pores
VF7	6.90	8, 624 (19,014)	Midway in tube	Best response, similar to wrought
CF7	6.76	8,257 (18,206)	Tubing adjacent to weld	Good response, similar to wrought

Table 8: Weldability test results

The mesh belt sintered 410LV with a density of 6.90 g/cm^3 shows a some what lower room temperature mechanical strength than that of the high temperature sintered 409L having a sintered density of 7.20 g/cm^3.

The strength requirements of the HEGO boss application is some what less critical than that of the exhaust flange application, especially with respect to the elevated temperature mechanical strength. Hence, it is likely that a 6.90 g/cm^3 dense 410LV may be considered satisfactory for this application.

CONCLUSIONS

1. Use of 410LV powder leads to achievement of a sintered density of 6.90 g/cm^3 when a compaction pressure of 700 MPa (50.8 TSI) and a sintering temperature of 1160 ^{0}C (2120 ^{0}F) are employed.

2. At a sintered density of 6.90 g/cm^3, the performance of the material with respect to corrosion/oxidation resistance and weldability are entirely satisfactory. Acceptable weldability performance is achieved with both 409L and 410LV materials when the sintered density is 6.75 g/cm^3 or greater.

3. The ductility of 410LV is higher than that of the 409L for similar processing and sintered density. For similar sintered density, the room temperature U. T. S. and yield strength of the two alloys, 409L and 410LV, are similar.

4. Overall, 410LV alloy does offer a promising option for manufacture of exhaust flanges and HEGO bosses via the mesh belt furnace sintering, as long as the engineering properties are taken into consideration in the part design.

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REFERENCES

1. P. K. Samal, J. B. Terrell, S. O. Shah, and M. T. Scott, Material and Design Optimization for Improved Performance of PM Stainless Steel Exhaust Flanges, *Proceedings of Euro PM 2000 Conference* (Munich, Germany, EPMA, Shrewsbury, UK.

2. T. R. Albee, P. dePoutiloff, G. L. Ramsey, and G. E. Regan, "Enhanced Powder Metal Materials for Exhaust Systems Applications", Paper 970281, presented at *SAE International Congress and Exposition,* Feb 1997, Detroit, MI.

3. T. Hubbard, K. Couchman, and C. Lall, "Performance of Stainless Steel PM Materials in Elevated Temperature Applications", Paper 980326, presented at *SAE International Congress and Exposition*, Feb 1998, Detroit, MI.

4. S. O. Shah, J. R. McMillen, P. K. Samal, S. A. Nasser, and E. Klar, "On the Real Life Performance of Sintered Stainless Steel ABS Sensor Rings", Paper 970423, presented at *SAE International Congress and Exposition*, Feb 1997, Detroit, MI.