Effect of Conventional and Microwave Sintering on the Properties of Yttria Alumina Garnet–Dispersed Austenitic Stainless Steel

S.S. PANDA, V. SINGH, A. UPADHYAYA, and D. AGRAWAL

The current study examines the effect of heating mode, temperature, and varying yttria alumina garnet (YAG) addition (5 and 10 wt pct) on the densification and properties of austenitic (316L) stainless steel. The straight 316L stainless steel and 316L–YAG composites were heated in a radiatively heated (conventional) and 2.45 GHz microwave sintering furnace. The compacts were consolidated through solid state as well as supersolidus sintering at 1200 °C and 1400 °C, respectively. Both 316L and 316L–YAG compacts couple with microwaves and heat to the sintering temperature rapidly (~45 °C/min). The overall processing time was reduced by about 90 pct through microwave sintering. As compared to conventional sintering, compacts sintered in microwaves exhibit higher densification and finer microstructure but no corresponding improvement in mechanical properties and wear resistance. This has been correlated to elongated, irregular pore structure in microwave-sintered compacts.

I. INTRODUCTION

In recent years, powder metallurgical (P/M) stainless steel components are increasingly being used for automotive and structural applications. As compared to conventional casting techniques, P/M processing offers advantages such as lower processing temperature, near-net shaping, high final density, greater material use (>95 pct), and a more refined microstructure that provides superior material properties. Among various grades of P/M stainless steels used, austenitic grades are the most widely used, with type 316L accounting for more than one third of the total P/M stainless steel consumption. Typically, P/M stainless steels are consolidated through solid-state sintering, which is conducted at relatively lower temperatures. Consequently, the sintered compacts have residual porosity, which restricts their applications. Several researchers have examined the effect of sintering temperatures on the densification and mechanical properties of 316L austenitic stainless steel. However, nearly all of the earlier reported sintering investigations have been conducted at temperatures ranging from 1100 °C to 1350 °C, which corresponds to solid-state sintering. Dyke and Ambes have reported an increase in the ultimate tensile strength and elongation with an increase in sintering temperature. However, they observed the opposite trend in yield strength and hardness variation. At lower sintering temperatures, densification enhancement can be achieved by using sintering aids that can form liquid phase at those temperatures. Shaw and Combe reported that additives that stabilize α-phase increase densification rate during sintering of austenitic stainless steels.

Despite densification enhancement, additives result in poor mechanical properties as they tend to segregate at the intergranular regions and form brittle phases. To overcome this, supersolidus liquid-phase sintering is employed for consolidating single-phase prealloyed powders. In this process, compacts are heated in between the solidus and liquidus temperatures, causing formation of liquid phase preferentially at the grain boundaries. The presence of liquid phase generally enhances densification by increasing diffusion kinetics. This, in turn, leads to particle fragmentation and subsequent repacking, which results in densification due to capillary stress-induced particle rearrangement. As stainless steels powders are typically fabricated through atomization, they have prealloyed, single-phase structure, and therefore are amenable to supersolidus sintering.

The P/M processing allows the flexibility to tailor the microstructures, which has been used in fabricating high-strength, wear-resistant P/M stainless steels through particular dispersoid additions. The effect of alumina (Al₂O₃), yttria (Y₂O₃), and silicon carbide (SiC) particulate additions on the densification, mechanical, and tribological properties of solid-state-sintered 316L have been extensively investigated. Patankar and Tan have reported densification enhancement in 316L with SiC addition due to the chemical interactions between the stainless steel matrix and carbide to form a low melting eutectic (Fe-SiC). However, the brittleness of this phase resulted in deterioration in the mechanical properties. Elsewhere, Al₂O₃ addition has been shown to increase wear resistance, but it adversely affects densification and mechanical properties. In contrast, Y₂O₃ addition in an optimal amount has been shown to enhance densification of stainless steel compacts. This was attributed to the interaction of Cr₂O₃ with the Y₂O₃ dispersoids. Furthermore, it was observed that the porosity was more homogeneous for the Y₂O₃ containing composites than for the pure 316L under identical sintering conditions. For cost effectiveness, Jain et al. have proposed the use of mixed oxides of yttria and alumina as additives. Recently, they have reported that YAG addition does not degrade densification of stainless steel compacts in either solid state or supersolidus sintering conditions.

One of the limitations of using a higher sintering temperature and conventional heating mode is microstructural
coarsening. Typically, in a conventional (electrically heated) furnace, compact heating occurs mainly through radiation. Consequently, to prevent thermal gradient within the compact, a slower heating rate coupled with isothermal hold at intermittent temperatures is provided, which increases the process time. In recent years, materials are being increasingly heated using microwaves.\textsuperscript{21,22,23}\ Microwaves are the electromagnetic waves that have a frequency range around 0.3 to 300 GHz with corresponding wavelengths ranging from 1 m to 1 mm. In the microwave frequency range, the absorption properties of nonmetallic materials vary greatly and depend on the dielectric properties. Microwaves directly interact with the particulates within the pressed compacts and thereby provide rapid volumetric heating. This reduces processing time and results in energy saving. In addition, the uniform heating minimizes problems such as localized microstructural coarsening and results in improved properties.\textsuperscript{24} Until recently, most of the microwave sintering was restricted to ceramic materials and cemented carbides.\textsuperscript{25,26,27} Recently, it was shown that metals too could couple with microwaves provided they are in powder form.\textsuperscript{28} Subsequently, microwave sintering of steel powder compact was conducted.\textsuperscript{29,30,31} More recently, it has been shown that bronze and steel powder compacts too couple with microwaves and can be effectively sintered.\textsuperscript{32,33,34} Though there have been attempts to explain microwave heating of metal powders, there is not yet any consensus on a comprehensive theory to explain the mechanism.\textsuperscript{35}

The current study investigates the microstructural, densification, mechanical, and tribological property response in straight 316L and 316L-YAG composites consolidated using both microwave and conventional furnace sintering through solid-state and supersolidus sintering routes.

### II. EXPERIMENTAL PROCEDURE

The as-received gas-atomized 316L austenitic stainless steel (Ametek Specialty Metal Products, Eighty Four, PA) and YAG (Treibacher, Austria) powders had an average size of 60 and 1.5 μm, respectively. Tables I and II provide the nominal chemical composition and characteristics of the as-received powders. The two powders were mixed in the required proportions (5 and 10 wt pct of YAG) in a turbula mixer (T2C, Bachofen, Switzerland) for 20 minutes.

The mixed powders were uniaxially compacted at 600 MPa in a 50T hydraulic press (CTM-50, FIE, Ichalkaranji, India) with floating die. To minimize friction, the compaction was carried out using zinc stearate as a die wall lubricant. The stainless steel compacts (straight and YAG containing ones) were pressed in the form of cylindrical pellets with 16-mm diameter and about 6-mm height. As evident from Table III, YAG has very little adverse effect on the compressibility of the 316L powders. For measuring the tensile properties, flat tensile bars were pressed per MPF standard 10.\textsuperscript{36}

The green (as-pressed) compacts were sintered using conventional and microwave furnaces. The conventional sintering of green compacts was carried out in a MoSi2 heated horizontal tubular sintering furnace (OKAY 70T-7, Bysakh, Kolkata, India) at a constant heating rate of 5 °C/min. To ensure uniform temperature distribution during heating,

<table>
<thead>
<tr>
<th>Powder</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>S</th>
<th>P</th>
<th>Fe</th>
<th>Y</th>
<th>Al</th>
<th>Ti</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>316L</td>
<td>0.025</td>
<td>0.93</td>
<td>0.21</td>
<td>12.97</td>
<td>16.5</td>
<td>2.48</td>
<td>0.008</td>
<td>0.001</td>
<td>bal</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>YAG</td>
<td>0.08</td>
<td>0.014</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>0.014</td>
<td>45.05</td>
<td>22.5</td>
<td>&lt;0.01</td>
<td>bal</td>
</tr>
</tbody>
</table>

### Table II. Characteristics of the Powders Used in the Present Investigation

<table>
<thead>
<tr>
<th>Powder</th>
<th>Theoretical Density, g/cc</th>
<th>Apparent Density, g/cc</th>
<th>Flow Rate, ω/50 g</th>
<th>Cumulative Powder Size, μm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>316L</td>
<td>8.1</td>
<td>2.7</td>
<td>28</td>
<td>D₁₀ 10.3</td>
</tr>
<tr>
<td>YAG</td>
<td>4.5</td>
<td>0.7</td>
<td>98</td>
<td>D₅₀ 45.9</td>
</tr>
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<td></td>
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</tbody>
</table>

### Table III. Effect of YAG Addition on the Density and Densification Parameter of Austenitic Stainless Steel Sintered in Conventional and Microwave Furnace at (a) 1200 °C and (b) 1400 °C

<table>
<thead>
<tr>
<th>Composition</th>
<th>Green Density, Pct</th>
<th>Sintering Temperature °C</th>
<th>Sintered Density, g/cm³</th>
<th>Densification Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>316L</td>
<td>82.0 ± 1.1</td>
<td>1200</td>
<td>6.5 ± 0.02</td>
<td>82.4 ± 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1400</td>
<td>6.8 ± 0.3</td>
<td>84.6 ± 3.7</td>
</tr>
<tr>
<td>316L-5YAG</td>
<td>81.2 ± 0.6</td>
<td>1200</td>
<td>6.4 ± 0.01</td>
<td>81.3 ± 0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1400</td>
<td>6.7 ± 0.3</td>
<td>86.2 ± 3.8</td>
</tr>
<tr>
<td>316L-10YAG</td>
<td>79.6 ± 0.8</td>
<td>1200</td>
<td>6.1 ± 0.02</td>
<td>79.3 ± 0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1400</td>
<td>6.3 ± 0.2</td>
<td>82.7 ± 2.6</td>
</tr>
</tbody>
</table>

C: Conventionally sintered; and M: microwave sintered.
intermittent isothermal hold for 15 to 30 minutes was provided at 500 °C, 750 °C, and 1000 °C. The compacts were sintered at 1200 °C and 1400 °C, which correspond to solid-state and supersolidus sintering temperatures, respectively. Sintering was carried out for 60 minutes in hydrogen atmosphere with dew point −35 °C. The latter sintering temperature was chosen based on a previous reported investigation on the same system by Tandon and Shankar et al. [19] Furthermore, the solids temperature of the 316L powder used in the current study was confirmed using differential scanning calorimetry (DSC) (STA409C, Netzsch, Selb, Germany). The powder was heated at a constant heating rate of 10 °C/min up to 1475 °C in argon. Figure 1 shows the DSC plot for the as-received 316L, which indicates onset of melt formation at about 1383 °C. Microwave sintering of the green compacts was carried out using a multimode cavity 2.45 GHz, 6 kW commercial microwave furnace (RC20SE, Amana RadaRange, Newton, IA). Unlike a conventional furnace, the temperature of the samples inside a microwave furnace cannot be monitored using a thermocouple. The presence of thermocouples can locally distort the electromagnetic field and can even lead to measurement errors.[38] The temperature of the sample was monitored using an infrared pyrometer (Raytek, Marathon Series, Santa Cruz, CA) with the circular crosswire focused on the sample cross section. The pyrometer is emissivity based; therefore, the temperature could not be measured below 700 °C.[39] Hence, the temperature measurements for all of the compacts were done by considering the emissivity of steel (0.35).[40] Typically, emissivity varies with temperature. However, because very little variation in the emissivity was reported in the temperature range used in the current study, the effect of variation in emissivity was ignored in the present investigation. Further details of the experimental setup of microwave sintering are described elsewhere.[31] For both microwave and conventional sintering, the samples were furnace cooled from the sintering temperatures (1200 °C and 1400 °C).

The sintered density was obtained by weight and dimensional measurements. For each sintered compact, the diameter and height were measured at five locations and the average value was taken to calculate the volume. The sintered density was expressed in grams per cubic centimeter and also normalized with respect to the theoretical density. Based on the weight fraction (w) of the respective component, the theoretical density, \( \rho_{th} \), of the powder mix was calculated using the inverse rule of mixtures and is expressed as:

\[
\frac{1}{\rho_{th}} = \frac{w_{YAG}}{\rho_{YAG}} + \frac{w_{316L}}{\rho_{316L}}
\]

where \( \rho_{YAG} \) and \( \rho_{316L} \) are the theoretical densities of YAG (4.97 g cm\(^{-3}\)) and 316L (8.06 g cm\(^{-3}\)), respectively. To verify the sintered density, the same was also evaluated using the Archimedes displacement method. For each condition, four samples were sintered and the average and the standard deviations were reported. The extent of densification during sintering was also determined by measuring the densification parameter, which is expressed as:

\[
\text{Densification parameter} = \frac{(\text{sintered density} - \text{green density})}{(\text{theoretical density} - \text{green density})}
\]

The sintered compacts were polished to mirror finish and ultrasonically cleaned in acetone, followed by etching in Marvel's reagent (12 g CuSO₄ · 5H₂O-60 mL HCl-60 mL distilled water). The microstructural analyses of the samples were carried out through optical microscope (Q5001W, Leica Imaging System Ltd., Cambridge, United Kingdom). Both the pore size and shape factor distribution were determined from the optical micrographs of the unetched straight 316L compacts. The pore size was estimated by measuring the pore area, while the pore shape was characterized using a shape-form factor, \( F \), which is related to the pore surface area, \( A \), and its circumference in the plane of analysis, \( P \), as follows:

\[
F = \frac{4\pi A}{P^2}
\]

Both the pore area distribution and shape factor were directly measured using an image analyzer. A shape factor of 1 represents a circular pore in the plane of analysis, and as it is reduced, the pores tend to become more irregular.[42,43]

Vickers bulk hardness measurements were performed on the samples at 2-kg load. The observed hardness values are the averages of five readings taken at random spots throughout the sample. The tensile test was conducted only for supersolidus-sintered stainless steel compacts using a 10-kN capacity universal testing machine at a constant cross-head speed of 0.5 mm/min. From the tensile curves, the ultimate tensile strength and ductility were determined. To correlate the tensile properties with the microstructure, fractography analyses of the samples were carried out using scanning electron microscopy (SEM).
electron microscope (SEM) imaging (ISM-840A, Japan Electron Optics Ltd., Tokyo) with an energy dispersive x-ray analysis (EDAX) attachment.

The tribological response of the supersolidus-sintered 316L stainless steel and 316L-YAG composites were measured using a pin-on-disc wear tester (TR20, Ducom, Bangalore, India) at a load of 50 N and sliding velocity of 2 m/s.

III. RESULTS AND DISCUSSION

A. Heating Profiles

Figure 2 compares the thermal profiles of the compacts—for both solid-state and supersolidus sintering—heated in conventional and microwave furnaces. It is interesting to note that both straight and YAG-added 316L compacts couple with microwaves and get heated rapidly. In the case of microwave heating, temperature could only be measured from 700 °C onward. However, it takes about 5.5 minutes to heat the compacts from room temperature to 700 °C. The overall heating rate in the microwave furnace was around 45 °C/min. Taking into consideration the slow heating rate (5 °C/min) and isothermal holds at intermittent temperatures in the conventional furnace, there is about a 50% reduction in the process time during sintering of stainless compacts in the microwave furnace.

Microwave heating in a metallic material, such as stainless steel, is different than that observed in dielectric materials (mostly ceramics). Because they are good conductors, no internal electrical field is induced in metals. The induced electrical charge remains at the surface of the sample; hence, microwave heating is restricted only to the metal surface. This depth of penetration of microwaves in metals, also known as skin depth, typically varies between 0.1 and 10 μm and is inversely related to the electrical conductivity. For metallic systems, as the resistivity increases with the increase in temperature, the skin depth too increases. In particulate metals, the surface area and thereby the “effective skin” (portion of metal powder that couples with microwaves) is high enough to contribute to its heating.

B. Densification Response

Table III shows the effect of YAG addition and heating mode on the densification response in 316L compacts consolidated through solid-state and supersolidus liquid-phase sintering. The densification response was quantified through sintered density and densification parameter measurements. It is evident that as compared to 1200 °C, both the straight 316L and 316L-YAG containing compacts exhibit higher density, at 1400 °C. This is also validated by comparing the densification parameters of the compacts that exhibit a similar trend. The densification parameter

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Fig. 2—Comparison of conventional and microwave sintering cycles for compacts heated to 1200 °C and 1400 °C.

Fig. 3—SEM micrograph and composition line profile of 316L austenitic stainless steel sintered at 1400 °C using EDAX analysis.
Conventional

Microwave

(a)

(b)

Fig. 4—Optical micrographs of (a) 316L and (b) 316L-YAG compacts sintered at 1200 °C for 1 h in conventional (left) and microwave (right) furnaces.

(DP) is a better indicator of the sinterability, as it takes into account the variation in the compact green density as well. From Table III, it is evident that 316L compacts—both with and without YAG addition—do not exhibit significant densification (DP < 0.05) when sintered in a conventional furnace at 1200 °C. The densification enhancement at a higher sintering temperature (1400 °C) is attributed to increased diffusivity. Unlike conventional liquid-phase sintering, wherein a lower melting constituent is required, the prealloyed powders themselves undergo partial melting during supersolidus sintering.\(^\text{13,14}\) Furthermore, during supersolidus sintering of stainless steel, melt forms preferentially at grain boundaries. The melt formation at the intergranular region during supersolidus sintering was confirmed by doing elemental analysis on 316L sintered conventionally at 1400 °C. Figure 3 shows the SEM micrographs and the corresponding line analysis. It is evident that the composition varies at the intergranular region, which is indicative of melt formation. Tandon and German\(^\text{13}\) have shown that this melt formation enhances densification through capillary induced pore filling and grain rearrangement.

It is interesting to note that both straight 316L and 316L-YAG composites, sintered in microwaves, exhibit much better density. This further confirms that both straight 316L and 316L-YAG composites effectively couple with microwaves. The microwave-sintered straight 316L compacts show only a marginal improvement at 1200 °C (Table III) over their conventionally sintered counterparts, whereas at 1400 °C, they exhibit much higher sintered density. In the case of 316L-YAG compacts, their coupling with microwaves is expected to be more effective because the YAG particles provide an effective pathway for microwave absorption. This makes the stainless steel-YAG composites more amenable to microwave sintering. The enhanced densification in microwave-sintered compacts can be attributed to the fast heating rate, which restricts grain coarsening.\(^\text{45}\) Consequently, grain boundary diffusion is expected to be more pronounced in microwave sintering. Elsewhere, Sahay and Krishnan\(^\text{46,47}\) have shown a log-linear relationship between the heating rate and the activation energy for crystallization for glass (Se\(_7\)Te\(_{29}\)Sb\(_9\) and Ge\(_{20}\)Te\(_{80}\)) and linear aromatic polyester systems. This relationship has been attributed to the apparent decreases in the activation.
Fig. 5—Optical micrographs of (a) 316L and (b) 316L-YAG compacts sintered at 1400 °C for 1 h in conventional (left) and microwave (right) furnaces.

Fig. 6—SEM micrographs of (a) 316L and (b) 316L-YAG compacts sintered at 1400 °C for 1 h.

energy at higher heating rates. It is envisaged that activation energy during microwave sintering too follows a similar trend, thereby leading to enhanced densification. Recently, Porada and Park[90] have shown diffusional enhancement during microwave heating. To corroborate this in P/M stainless steel, future work should aim at comparing the densification response of ferritic stainless steel compacts under microwave and controlled fast-heating furnaces at equivalent
heating rates. Recently, Saitou\textsuperscript{[35]} compared the sintering response of microwave (80 K/min) and electric (10 K/min) furnace heated 316L stainless compact. He reported that the value of activation energy was not significantly different between the two. Therefore, it was concluded that microwave heating does not change the sintering mechanism. In view of this observation, it can be hypothesized that the densification enhancement during microwave sintering is primarily due to restricted microstructural coarsening.

From Table III, it is evident that in compacts sintered conventionally at 1200 °C, YAG addition reduces densification. This is in conformity with previous reports.\textsuperscript{[59]} The ceramic additive prevents the 316L particle-particle contacts, which restricts diffusion and thereby inhibits densification. In contrast to conventional heating, an optimal YAG addition results in densification enhancement during microwave sintering. For both solid-state and supersolidus conditions, 316L-5YAG composites exhibit highest densification during microwave sintering. This can be attributed to the interaction of the microwaves with the YAG particles. It is hypothesized that the YAG particles get heated differentially and more effectively than the stainless steel powders, which may further contribute to densification enhancement by providing localized hot spots. Elsewhere, Peelamedu et al.\textsuperscript{[60]} also observed differential microwave heating effects in multicomponent systems and termed such phenomenon “anisothermal sintering.” They showed that anisothermal heating results in densification enhancement during sintering. In the case of 316L-YAG composites, however, an optimal addition (5 wt pct) of YAG contributes most to compact densification. In the case of higher YAG content (10 wt pct), because of the fine particle size of YAG, there is a likelihood of YAG-YAG interaction and agglomeration, which causes a decrease in sintered density. However, a more detailed investigation is required to further optimize the YAG content.

![Diagram](image_url)

**Fig. 7**—Comparison of (a) pore area distribution and (b) shape factor distribution of the austenitic stainless steel compacts sintered in conventional and microwave furnaces.

![Diagram](image_url)

**Fig. 8**—Effect of YAG addition on the bulk hardness of austenitic stainless steel sintered in conventional and microwave furnaces at (a) 1200 °C and (b) 1400 °C.
C. Microstructure and Pore Evolution

Figures 4 and 5 compare the optical micrographs of conventional and microwave-sintered compacts of straight 316L and 316L-YAG composites. It is quite evident from both figures that compacts sintered at higher temperature exhibit microstructural coarsening, which is more pronounced in conventionally sintered compacts. During supersolidus sintering, the melt formation promotes coarsening. Figure 6 compares the SEM micrographs of straight 316L and 316L-YAG compacts sintered at 1400 °C. For both microwave and conventional sintering, YAG addition restricts microstructural coarsening. The initial interparticle contact is the "particle boundary" between the constituent powders. Subsequently, during sintering, chemical bonding occurs at the interparticle contacts, resulting in grain boundary formation\(^{105}\). The presence of YAG at the interparticle interface restricts the contact between the 316L grains. One of the mechanisms of grain growth is also through coalescence\(^{105}\). A reduction in 316L interparticle contact will entail less coalescence. Besides, YAG also inhibits the 316L grain boundary migration. As evidenced from Figures 5 and 6, YAG dispersoids remain preferentially segregated at the 316L interparticle interfaces, thereby restricting grain growth.

The optical micrographs of compacts (Figures 4 and 5) reveal distinct differences in the pore morphology of microwave compacts \textit{vis a vis} their conventional counterparts. For both straight stainless steel and stainless steel-YAG composites, the pores have rounded appearance in conventional sintering. In contrast, in microwave-sintered compacts, the elongated pores are discerned. This was verified by quantifying and comparing the distribution of pore sizes (measured as area) and shape factors of conventional and microwave-sintered compacts. Because subsequent mechanical properties of only the supersolidus-sintered compacts were compared, the pore measurement was done only for 1400 °C sintered compacts. Furthermore, this exercise was limited to straight 316L compacts only, as in case of YAG containing composites; it was difficult to distinguish between YAG and porosity in the optical micrographs. Figures 7(a) and (b) compare the pore area and shape factor distribution of conventionally and microwave-sintered 316L compacts. From Figure 7(a), it is obvious that, compared to conventional sintering, the pores in the microwave-sintered 316L are not only smaller but also have a narrower distribution. However, the microwave-sintered compacts exhibit a broader range of shape factors and, compared to their conventionally sintered counterparts, are skewed toward lower shape factor values, which is indicative of more irregular pores. While the pore area variation is narrower in microwave-sintered compact—with most pores having below 50 μm\(^2\) area—the shape factor shows steep variation with most clustering between 0.4 and 0.7. The conventionally sintered 316L compacts exhibit more regular pore morphology despite a wider variation in the pore area. The irregular porosity in microwave-sintered austenitic stainless steel compacts is in contrast to a trend shown in iron-copper steels. Anklekar \textit{et al.}\(^{50}\) have reported that Fe-2Cu-0.8C steels sintered in microwaves exhibit more rounded pore morphology. This could be attributed to the faster processing cycle, which does not yield sufficient time for pore rounding.

D. Mechanical Properties

Figures 8(a) and (b) show the effect of YAG addition on the hardness of austenitic stainless steels sintered in conventional and microwave furnaces. For straight 316L compacts sintered at 1200 °C, the bulk hardnesses are higher than those reported by Iglesias \textit{et al.}\(^{51}\) which were compacted at much higher pressure (700 MPa) and sintered at 1250 °C. The bulk hardnesses of 316L samples from the current study are even higher than those reported by Youssef \textit{et al.}\(^{52}\) on the same grade and sintered at 1200 °C and 1350 °C. For both convention and microwave
Fig. 10—SEM fractographs of (a) 316L, (b) 316L + 5YAG, and (c) 316L + 10YAG compacts sintered at 1400 °C in conventional (left) and microwave (right) furnaces and subjected to tensile test.

Sintering in both solid state and supersolidus conditions, the hardness of the compact increases with YAG addition. In the case of compacts consolidated at 1200 °C, the hardness of the microwave-sintered compact is higher. This is due to a higher densification of microwave-sintered 316L and 316-YAG compacts (Table III). Despite an increase in the sintered density at higher temperatures, it is interesting to note that the hardness of the microwave-sintered compacts is lower than their conventional counterparts at 1400 °C.

The reason for this behavior is not clear. In the case of conventional sintering, YAG addition increases bulk hardness, despite an overall decrease in the compact sinterability. From the microstructural observations, it is evident that YAG remains segregated at the grain boundaries (Figure 6(b)). This restricts microstructural coarsening, thereby resulting in a hardness increase. Furthermore, the high inherent hardness of the YAG particulate negates the effect of poor densification in lowering the bulk hardness. Just as
Figures 9(a) and (b) compare the strength and ductility of 316L and 316L-YAG compacts sintered at 1400 °C using both conventional and microwave furnaces. The strength of the microwave-sintered compacts is similar to that of hardness (Figure 8(b)) and correlates well with the densification. Interestingly, the ductility of the microwave-sintered compact increases with increasing YAG content, whereas it progressively decreases in the case of conventionally sintered compacts. However, as compared to microwave sintering, both the strength and the ductility of conventionally sintered straight 316L and 316L-YAG composites is higher. Elsewhere, Bose et al.\textsuperscript{[31]} have made similar observations in powder injection molded 17 to 4 PH stainless steel parts and reported that microwave sintering does not improve the mechanical properties as compared to conventional sintering. This trend is in contrast to recent observations by Ankalekar et al.\textsuperscript{[30]} on Fe-Cu-C steels wherein microwave-sintered compacts exhibited higher strength and ductility. While this is the first study wherein stainless steel has been consolidated by microwave sintering, conventionally sintered P/M stainless steels have been extensively evaluated for their mechanical properties.\textsuperscript{[9,24,53]} The strength and ductility of conventionally sintered stainless steel in the current study are much higher than those reported elsewhere.\textsuperscript{[9,24,53]} This underscores the importance of processing stainless steels in the supersolidus region.

Figure 10 shows representative fractographs of conventionally sintered and microwave-sintered austenitic stainless steel both with and without YAG addition. Conventionally sintered 316L shows a distinct dimpled morphology, which is characteristic of ductile failure (Figure 10a). In contrast, the microwave-sintered compacts fail through intergranular decohesion for both straight 316L stainless steel and 316L-YAG composites. This is attributed to the elongated pore morphology (Figures 4 through 7), which acts as a stress-concentration site and leads to premature, brittle failure at relatively lower load. In the case of conventionally sintered compacts, an increase in YAG content changes the fracture mode from dimpled to intergranular mode, thereby resulting in a lowering of ductility. This is attributed to a lowering of sinterability with the YAG addition and the presence of a brittle additive phase at the 316L interparticle interface.

E. Sliding Wear Response

Figures 11(a) through (c) compare the sliding wear behavior of 316L, 316L-5YAG, and 316L-10YAG compacts, respectively, sintered at 1400 °C in conventional and microwave furnace. From the graphs, it is evident that microwave sintering degrades the wear resistance for austenitic stainless steel compacts. The increase in the wear rate of microwave-sintered compacts despite their higher density is attributed to poor interfacial bonding between 316L and 316L-YAG particles due to the presence of elongated, sharp-edged porosity. Due to this, YAG addition further degrades the wear resistance of microwave-sintered 316L compacts. In the case of conventional sintering, the 316L-5YAG alloys have the least wear rate, which follows the densification trend. Recently, Jayant et al.\textsuperscript{[13]} using electron probe microanalysis, showed that YAG particles that are segregated at the 316L interparticle interfaces
chemically interact with the stainless steel. Thus, in addition to higher densification and rounded pore morphology, a good bonding at the 316L-YAG interface enhances the wear resistance of conventionally sintered compacts.

IV. CONCLUSIONS

The investigation into microwave sintering of 316L and 316L-YAG composites has shown that these systems can be consolidated by microwaves. Both straight 316L and 316L-YAG composites can be processed through solid state and supersolidus sintering using a multimode microwave furnace. As compared to conventional furnace heating, the sintering time in a microwave furnace was reduced by as much as 90 pct. Despite the reduced processing time, the microwave-sintered compacts in general exhibit higher sintered density and bulk hardness compared to their conventionally sintered counterparts. However, the microwave-sintered compacts have relatively elongated and sharp-edged porosity. This results in reduction in the tensile strength and ductility and lowers the wear resistance. For conventional sintering, YAG addition reduces the sinterability of 316L compacts and thereby degrades their ductility. In contrast, the 316L-YAG composite exhibits the highest densification during microwave sintering, which, in turn, results in higher hardness, ductility, and strength.

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