Sintering response of austenitic (316L) and ferritic (434L) stainless steel consolidated in conventional and microwave furnaces

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Abstract

This study compares the effect of heating mode on the densification, microstructure, strength and hardness of austenitic and ferritic stainless steel. The compacts were sintered in a radiatively heated (conventional) and a 2.45 GHz microwave furnace. Both 316L and 434L compacts couple with microwaves and heat up to the sintering temperature rapidly (~45 °C/min). The overall processing time was reduced by about 90% through microwave sintering. While the microwave sintered compacts exhibit a finer microstructure, there is no corresponding improvement in densification and mechanical properties. This has been correlated with elongated and irregular pore structure.

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1. Introduction

In recent years, there has been an increasing trend to use powder metallurgical (P/M) processed stainless steels for automotive and structural applications [1]. As compared to conventional casting techniques, P/M stainless route offers advantages such as a relatively lower processing temperature, near-net shaping, greater material utilization (>95%) and a more refined microstructure. Among various grades of P/M stainless steels, austenitic and ferritic grades are the most widely used [1]. Typically, P/M stainless steels are consolidated through solid-state sintering, which is conducted at relatively low temperatures. Consequently, the sintered compacts have residual porosity, which restricts their applications. In recent years, there has been a thrust towards consolidating compacts at higher sintering temperatures through supersolidus liquid phase sintering [2,3]. Supersolidus sintering involves heating between the solidus and liquidus temperatures to form the liquid phase. The presence of liquid phase generally enhances densification by increasing diffusion kinetics. Besides this, the capillary stress induced pore filling also contributes to densification. As stainless steels powders are typically fabricated through atomization, they have prealloyed, single phase structure, and therefore, are amenable to supersolidus sintering. However, one of the limitations of using higher sintering temperatures is microstructural coarsening. Typically, in conventional (electrically-heated) furnaces compacts get radiatively heated during sintering. Consequently, to prevent thermal gradient within the compact, a slower heating rate coupled with isothermal holding at intermittent temperatures is provided, which increases the process time, thereby, contributing to coarsening. To eliminate this problem, a faster heating rate during sintering is envisaged. However, fast heating rates in conventional furnaces result in a thermal gradient within the compacts and lead to compact distortion and inhomogeneous microstructure. One of the techniques to achieve relatively homogeneous as well as fast sintering in compacts...
is through microwave heating [4–6]. Microwaves directly interact with the particulates within the pressed compacts and thereby provide rapid volumetric heating [7]. This reduces processing times and results in energy saving. In addition, the uniform heating minimizes problems such as localized microstructural coarsening, thereby yielding better properties. Microwaves have been used to sinter ceramics, refractory materials and ferrites [8–11]. Recently, it was shown that metals too could couple with microwaves, provided the metals are in powder form rather than monolithic [12]. However, as compared to ceramics, microwave sintering of particulate metals and alloys has increased in popularity only recently [13–15]. Though there have been attempts to explain microwave heating of metal powders, there is still not a consensus on a comprehensive theory to explain the mechanism. Recently, it has been shown that steel powder compacts with Cu and Ni additives couple with microwaves and can be effectively sintered [16–19].

The present study investigates the microstructural, densification, and mechanical property response in straight 316L (austenitic) and 434L (ferritic) stainless steel consolidated using both microwave as well as conventional furnace sintering through the supersolidus sintering route.

2. Experimental procedure

The as-received gas-atomized 316L [Fe–16.5Cr–12.97Ni–2.48Mo–0.93Si–0.21Mn–0.025C–0.008S (in wt.%)] and 434L [Fe–17Cr–1Mn–0.22C–0.028–0.02P] stainless steel (Ametek Specialty Metal Products, USA) powders were uniaxially compacted at 600 MPa into green densities ranging between 80% and 82%. The sintering response on densification and microstructures were evaluated on cylindrical pellets (16 mm diameter and 6 mm average height). For measuring the tensile properties, flat tensile bars were pressed as per MPIF standard 10 [20]. 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 microwave furnace. The conventional sintering of green compacts were sintered using conventional and microwave furnaces. The conventional sintering of green compacts were sintered using conventional and microwave furnaces. The conventional sintering of green compacts were sintered using conventional and microwave furnaces. The conventional sintering of green compacts were sintered using conventional and microwave furnaces. The conventional sintering of green compacts were sintered using conventional and microwave furnaces.

3. Results and discussion

Fig. 1 compares the thermal profiles of the 316L and 434L compacts sintered in conventional and microwave furnaces. It is interesting to note that both 316L and 434L compacts couple with microwaves and get heated up rapidly. In the case of microwave heating, the temperature could only be measured from 700 °C onwards. However, it takes about 5.5 min to heat up 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 the isothermal holds at intermittent temperatures in a conventional furnace, there is about a 90% reduction in the process time for the sintering of stainless compacts in a microwave furnace. In the case of microwave sintering, a slight difference in the heating rates for the 316L and 434L compacts is observed, which is attributed to the dependence of microwave–metal coupling on the composition.

Table 1 compares the densification response of both the 316L and 434L stainless steels sintered in conventional and microwave furnaces. In the case of the 316L stainless steel compacts, densification during microwave sintering was lower than that achieved through conventional sintering. In contrast, the straight 434L compacts showed an almost comparable densification in both the sintering modes. This is also validated by comparing the densification parameters which follows a similar trend as the sintered density. It is interesting to note that irrespective of the heating mode, the ferritic stainless compacts undergo a higher densification as compared to their austenitic counterparts. This can be attributed to relatively higher diffusivity in the more open body-centred cubic structure of the 434L compacts.

Figs. 2 and 3 compare the optical and SEM micrographs of conventional and microwave sintered straight 316L and 434L compacts. It is quite evident from Fig. 2 that for both stainless steels, microwave sintering restricts microstructural coarsening. For both the sintering conditions, grain coarsening occurred at 1400 °C. Furthermore, the optical and the SEM micrographs of the sintered compacts reveal distinct differences in the pore morphology of microwave compacts vis a vis their conventional counterparts. For both straight 316L and 434L compacts, pores have a relatively more rounded appearance in conventional sintering. In contrast, in microwave sintered compacts the pores appear distinctly elongated. Our results are at variance with those reported by Anklekar et al. [17,18] for copper-containing steel. Besides being a different system, the presence of copper results in the consolidation of steel through transient liquid phase sintering; hence, the pore shape is different. The distribution of pore area and shape factors of conventional and microwave sintered stainless steel compacts are shown in Figs. 4 and 5. Fig. 4 a and b compares the effect of the heating mode on the pore area distribution in 316L and 434L compacts, respectively. For both stainless steels, microwave sintering results in a smaller and narrower pore size distribution. This can be

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Austenitic stainless steel (316L)</th>
<th>Ferritic stainless steel (434L)</th>
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<tbody>
<tr>
<td></td>
<td>Conventional</td>
<td>Microwave</td>
</tr>
<tr>
<td>Sintered density, g/cm³ (% theoretical)</td>
<td>7.06 (87.5)</td>
<td>6.82 (84.6)</td>
</tr>
<tr>
<td>Densification parameter</td>
<td>0.31</td>
<td>0.14</td>
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<tr>
<td>Bulk hardness, HV₂</td>
<td>136</td>
<td>114</td>
</tr>
<tr>
<td>Strength, MPa</td>
<td>398</td>
<td>156</td>
</tr>
<tr>
<td>Elongation, %</td>
<td>63</td>
<td>3</td>
</tr>
</tbody>
</table>

Fig. 1. Effect of heating mode on the thermal profiles of 316L and 434L stainless steel compacts.

Fig. 2. Optical micrographs of (a) 316L and (b) 434L compacts sintered at 1400 °C for 1 h in conventional (left) and microwave (right) furnaces.

Fig. 3. Micrographs of conventional and microwave sintered straight 316L and 434L compacts.
attributed to the lower propensity for pore coarsening due to the lesser sintering time in the case of compacts consolidated in microwave furnace. However, the trend in the pore shape factor distribution exhibits a reverse trend. In both austenitic as well as ferritic stainless steels, the microwave sintered compacts exhibit a broader range of shape factors compared to their conventionally sintered counterparts and are skewed towards lower shape factor values, which is indicative of more irregular pores. The irregular porosity in microwave sintered austenitic stainless steel compacts is in contrast to the trend shown in iron–copper steels. Anklekar et al. [18] reported that Fe–2Cu–0.8C steels sintered in microwaves exhibit a more rounded pore morphology. This could be attributed to the faster processing cycle, which does not yield sufficient time for pore rounding.

Table 1 shows the effect of the heating mode on the bulk hardness, strength and ductility of sintered 316L and 434L stainless steels. It is evident that for both grades of stainless steel, microwave sintering invariably results in inferior mechanical properties. This trend is in contrast to recent observations by Anklekar et al. [17] on Fe–Cu–C steels, wherein microwave sintered compacts exhibited higher

Fig. 3. SEM micrographs of (a) 316L and (b) 434L compacts sintered at 1400 °C for 1 h in conventional (left) and microwave (right) furnaces.

Fig. 4. Comparison of pore area distribution of (a) 316L and (b) 434L stainless steel compacts sintered in conventional and microwave furnaces.

Fig. 5. Comparison of shape factor distribution of (a) 316L and (b) 434L stainless steel compacts sintered in conventional and microwave furnaces at 1400 °C.
strength as well as ductility. Fig. 6a and b show representative fractographs of conventional and microwave sintered austenitic and ferritic stainless steel, respectively. Conventionally sintered 316L and 434L show a distinct dimpled morphology which is characteristic of ductile failure. In contrast, the microwave sintered stainless steel compacts fail through intergranular decohesion. The inferior mechanical properties in the case of microwave sintered stainless steel can be attributed to the elongated pore morphology (Figs. 2 and 5), which act as stress-concentration sites and lead to premature, brittle failure at a relatively lower load. While our results are conclusive for stainless steels, the effects of microwave sintering on the mechanical properties of other metallic powder systems need to be carefully assessed. The present study therefore underscores the need for fine tuning the sintering time compression strategies through microwave heating in ways that do not result in the degradation of mechanical properties.

4. Conclusions

This study compares the effect of conventional and microwave heating on the densification, microstructural, and mechanical properties of 316L and 434L stainless steel sintered at 1400 °C. For the first time, it has been shown that both 316L as well 434L compacts can be consolidated using a multimode microwave furnace. As compared to conventional furnace heating, the sintering time in a microwave furnace was reduced by about 90%. While in 434L steels, the sintered density of microwave heated stainless steel was higher than those sintered conventionally, in 316L steels, microwave sintering resulted in lower density. The present study shows that despite restricted microstructural coarsening in both austenitic and ferritic stainless steel, microwave sintering results in lower hardness, strength and ductility. This has been correlated with the relatively irregular and elongated pore morphology in microwave sintered stainless steel compacts.

References