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Sintering Schedule for Near-Net Shapping of Mechanical Components Formed Through Warm Compaction Route

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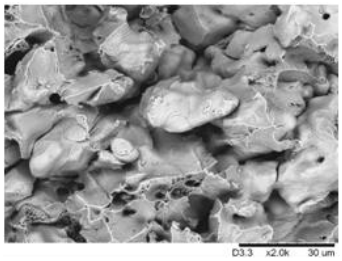
Graphical abstract



Abstract

This paper presents the characterization of solid state sintering schedule for the production of near-net shape mechanical components through warm compaction route. A lab-scale warm forming rig was designed and fabricated which enabled the generation of green compacts at elevated temperature. The feedstock from iron powder ASC 100.29 was prepared by mechanically mixing the powder with 0.4wt% zinc stearate for 30 minutes. The feedstock was formed at 180ºC to generate green compacts. The defect-free green compacts were subsequently sintered in an inert gas fired sintering furnace for different sintering schedules. The sintered products were characterized through mechanical testing and microstructure evaluation. The result revealed that the mechanical properties and microstructures of sintered products are affected by sintering parameters. Results shown that part sintered at 1000ºC, 10ºC/min heating rate for 60 minutes give the highest bending strength of 630 MPa and relative density of 0.869 g cm^{-3}. It also exhibited acceptable dimensional changes which is below 1%. It can observed by micrograph part at sintering temperature of 1000ºC, neck formation is also observed and more metal-metal bonding is visible. From this study, the suitable sintering parameters are identified for the production of near-net shape yet high quality mechanical component.

Keywords: Warm powder forming, sintering schedule, mechanical properties, microstructure

1.0 INTRODUCTION

The Powder Metallurgy (P/M) is a technology of producing mechanical components from powder by compaction and sintering. P/M provides cost effective yet improved quality products [1-4] and it is a green process [5]. In P/M, powder compaction is to transform powder to become solid components [6]. This process is dependent on the compaction pressure, temperature and friction [7], and it provides just sufficient strength for handling during further process [6]. In late 90's, warm compaction was introduced where it was conducted at a temperature range of 100ºC to 150ºC [6-8]. The compaction process also involves the particle rearrangement where large amount of friction exists, resulting from inter-particle and particle to die wall movement which leads to non-uniform density distribution thus promoting crack initiation [9-11].

The higher sintered density can be obtained by sintering at higher temperature for a longer time where grains grow in size and porosity reduced. The high sintering temperature promotes stronger metal-metal contacts, more pore rounding, and also accelerates the reduction of surface oxides and produces clean surfaces on the powder particles, which helps neck formation. Consequently, the effective load bearing surface area increases, thus improves the mechanical properties. However, high sintering temperature is expensive in industrial applications. Unacceptable distortion of the part geometry may be occurred by sintering it for a longer time at higher temperature [12, 18]. Shrinkage is also found to increase as increased in sintering time and temperature while shorter sintering time produces parts with non-uniform microstructure, which disables the part to meet the engineering specification in terms of strength [19, 20]. Therefore, the geometrical distortion and microstructural defects can be minimized by selecting the appropriate sintering time and temperature. Hence, this paper presents the outcome of the characterization of sintering schedules in obtaining optimize sintering parameter for achieving good mechanical and microstructural properties of sintered product.

2.0 EXPERIMENTAL WORKS

Iron powder ASC 100.29 having particle size range of 20-180 µm was used as main powder constituent. Zinc stearate ($C_{36}H_{70}O_4Zn$) was used as admixed lubricant due to its low melting temperature, i.e., 125°C, hence it can vaporize even to the very core of the part, through the part's pore structure, at the preheat zone [7,21]. Iron powder was mixed mechanically with 0.4 wt% zinc stearate in for 30 minutes for uniform distribution of zinc stearate [22]. Then, all the die assembly together with the powder mass was heated up to 180ºC. The compaction was conducted by applying simultaneous upward and downward constant load of 130 kN. Subsequently, the sintering process was conducted using custom made sintering furnace (HT3 - 1400 - SIC). The sintering was conducted at 850ºC to 1000ºC, while two heating rates of 5ºC/min and 10ºC/min and two holding times of 30 and 60 minutes were tested. The sintered samples were investigated for their densities, dimensional changes, bending strengths and microstructures.

3.0 RESULTS AND DISCUSSIONS

Figures 1-2 depict the relative density variation of sintered product to the sintering temperature, holding time and heating rate. At 30 minutes holding time, increasing sintering temperature gives increased relative density. However, at 60 minutes holding time, the density is nearly the same for all the temperature. This shows that longer sintering time can improve the density of sintered product by improving the grain growth and the elimination of pores [17, 18]. It can be observed Figures 3A-3B where larger pores exist at 30 minutes sample, together with more interconnected pores. This implies that shorter sintering time limits the particle diffusion across the grain boundary and into the pore surface, which was not an optimum densification process.

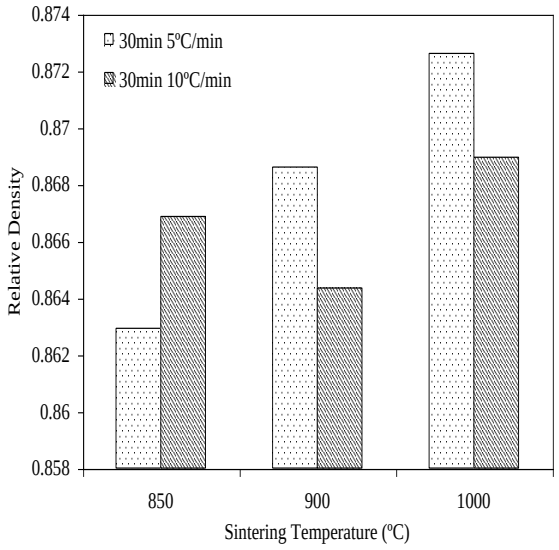


Figure 1 Relative density of sintered parts, 30 minutes holding time

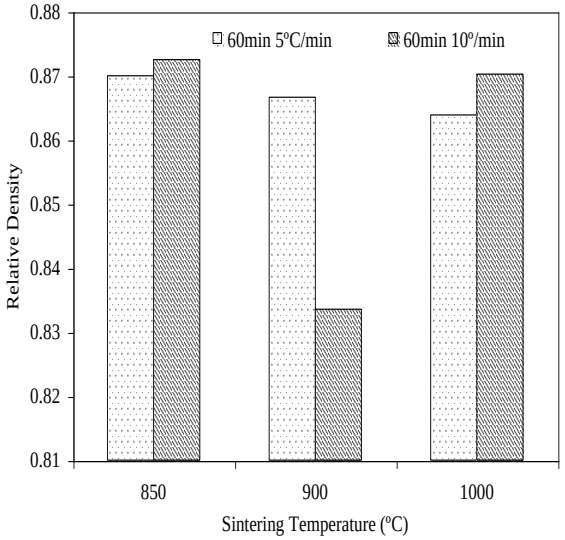
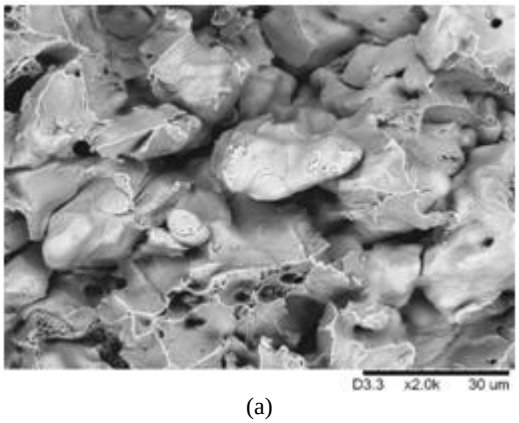


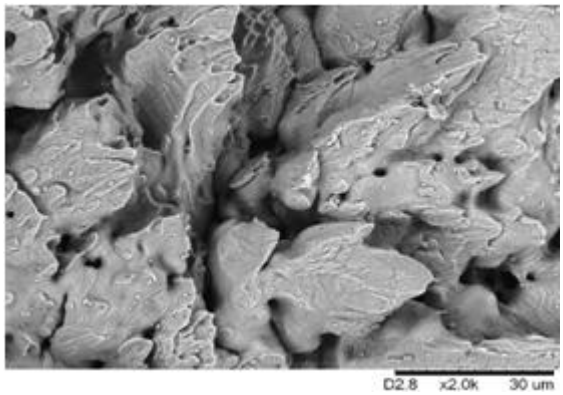
Figure 2 Relative density of sintered parts, 60 minutes holding time

The relative density also shows an increment when sintering temperature increases as in Figure 1. At higher temperature, diffusion increased at the grain boundary, lead to the grain growth while eliminating the pore, and thus increases the density. It can be compared with the microstructure in Figures 3C-3D where at 1000ºC, more round pores are observed while at 900ºC, there are more interconnected pores. Smaller grain size also observed in Figure 3C, which is a growth of nuclei of γ-iron [18] which shows that structure recrystallization process continues at this temperature.

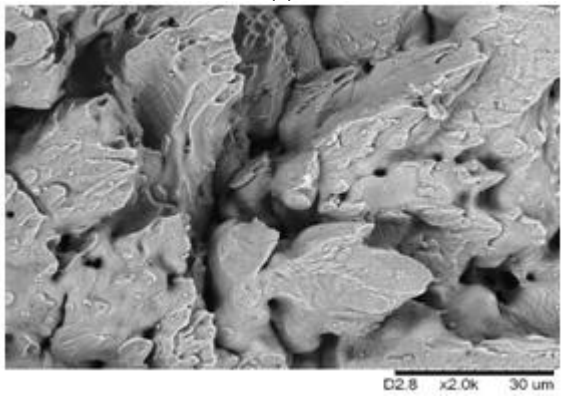
Figures 1-2 further show that slower heating rate is suitable in obtaining the higher density as it gives optimum diffusion rate at grain boundary. However, at longer sintering time, both sintering rate have less influence in densification as longer sintering time produces much surface diffusion of iron particles, i.e., less pore elimination.



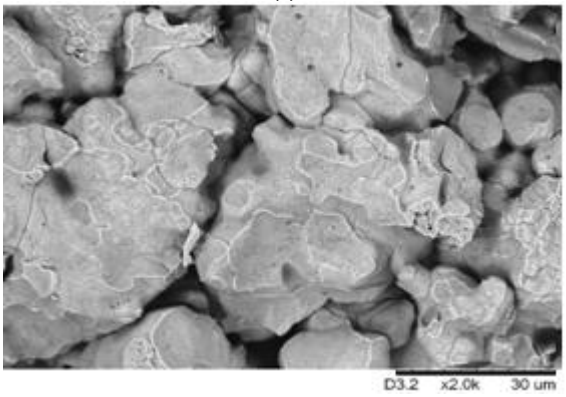
(a)



(b)



(c)



(d)

Figure 3 Microstructures (2000 mags) of final parts sintered at different schedules; (A) 1000ºC, 10ºC/min, 60 min, (B) 1000ºC, 10ºC/min, 30 min, (C) 1000ºC, 5ºC/min, 60 min, (D) 900ºC, 5ºC/min, 60 min

Figures 4-5 show the bending strengths of sintered products. It shows that at 10ºC/min, sintering temperature increment increased the bending strength. However, at slower heating rate, i.e., 5ºC/min, inconsistent trend is observed for 1000ºC and 60 minutes holding time. It may be due to the combination of slow heating rate, longer sintering time and highest sintering temperature which lead to formation of larger grains, hence the bending strength is decreased. Faster heating rate, i.e., 10ºC/min is found to improve the strength of sintered products at each holding time. It can be said that, this is an optimum sintering schedules to avoid the entrapment of gas inside the pores that caused by lubricant vaporization. As can be seen in Figure 3, more round pores are observed at higher sintering temperature and heating rate. At a sintering temperature of 1000ºC, neck formation is also observed and more metal-metal bonding is visible. Consequently, the effective load bearing surface area increased, thus improved the strength [16] of the sintered products.

Figures 6-7 depicted the dimensional changes of sintered components at different sintering schedules. It can be said that, the expansion occurs at very acceptable value which is not more than 1.3%. Generally, the expansion is due to the lubricant entrapment inside the pores [14] which reduced the grain boundary diffusion.

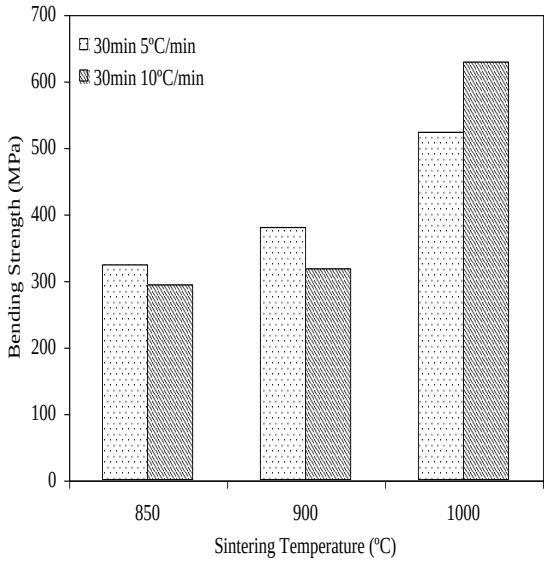


Figure 4 Bending strength of final sintered part at 30 minutes holding time

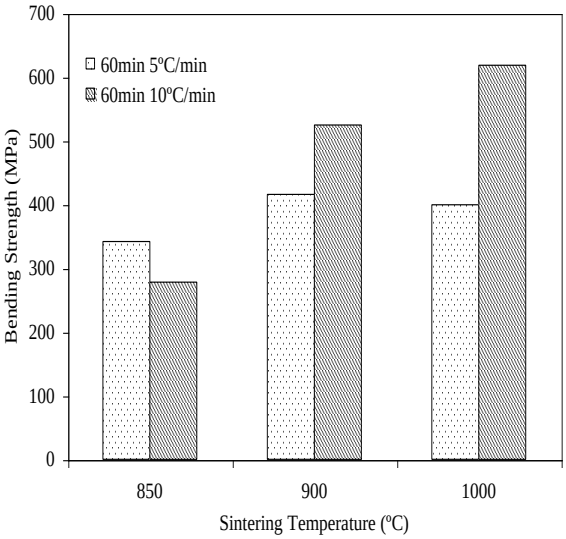


Figure 5 Bending strength of final sintered part at 60 minutes holding time

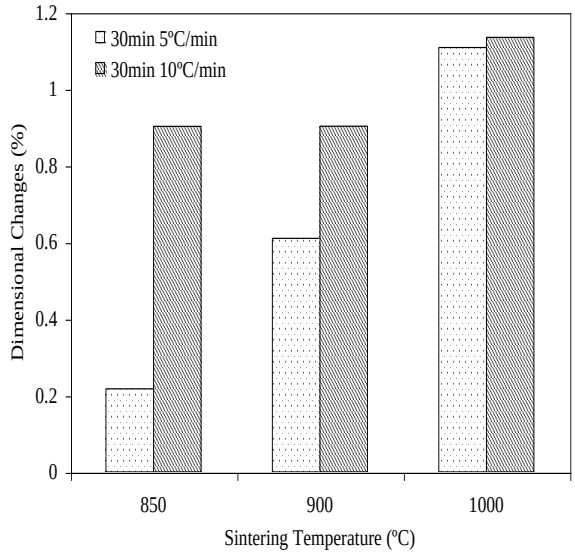


Figure 6 Dimensional changes of final sintered part at 30 minutes holding time

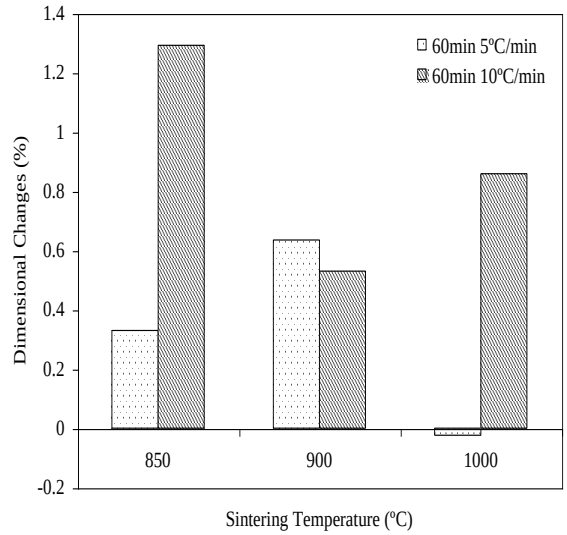


Figure 7 Dimensional changes of final sintered part at 30 minutes holding time

4.0 CONCLUSION

The sintering temperature and holding time influenced largely the densification process and strength, while the heating rate did not show significant effect to the densification and strength at longer sintering time. The products expanded at minimum value at every sintering schedule, thus implying a good porosity to densification relationship albeit of using the admixed lubrication method. It can be concluded that a near net shape product using admixed lubrication can be obtained by sintering at 1000ºC, 10ºC/min heating rate and sintering for 60 minutes.

Acknowledgement

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