The effect of high temperature shot peening on the surface integrity of 2024-T351 aluminum alloy.

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ABSTRACT

Shot peening is considered to be an important surface modification procedure for structural materials to improve their fatigue properties. The surface properties can be further improved by changing the temperature of the surface during the process of peening. In this study, shot peening at room temperature and at high temperatures ranging from 100°C to 250°C was conducted using an Almen intensity of 0.12 mmA to study the influence of the process on the arc height, the surface roughness, and the work hardening of AA2024-T351 specimens. Arc height measurements, 2D roughness measurements, and Rockwell B hardness tests were performed on each shot peening condition. The results show that the high temperature shot peening process at 200°C had an effect on increasing the arc heights of specimens when compared to specimens peened at the other high temperatures, the surface roughness increased with the increase of the peening temperature, and the highest value of surface hardness was seen at a temperature of 250°C.

Keywords High temperature shot peening, Almen intensity, 2024-T351 aluminum alloy, Surface roughness, Surface hardness, Arc height.

Introduction

Shot peening (SP) is a surface treatment where a metallic surface is impacted with high velocity shot to introduce plastic deformation. The plastic deformation induces compressive residual stresses (CRS) and grain refinement that can delay crack initiation at the surface and crack propagation beneath the surface, and therefore increase the fatigue life of the component [1]. However, the induced CRS in shot peened specimens relax under cyclic loading [2], which reduces the effectiveness of the SP process at increasing fatigue life. When compared to SP at room temperature (RT), SP performed at higher temperatures leads to better fatigue strength for steels [3-6] , titanium and aluminum composites [7-8], as well as for magnesium alloys [9]. The fact that the CRS span over a larger depth, are more compressive and relax less than those induced by room temperature (RT) SP under cyclic loadings [3-6]–[6] could explain this increased performance. The publicly available literature related to the mechanical performance after high temperature surface treatments of aluminum alloys focusses on high temperature laser shock peening (HTLSP) [10] and high temperature deep rolling (HTDR) [11]. High temperature surface treatments such as HTLSP and HTDR increase the surface hardness of aluminum alloys by 17% to 73%, respectively. This surface hardening phenomenon is due the dynamic strain aging (DSA) that occurs during the high temperature deformation of aluminum alloy. The DSA combines both strain hardening effect through the surface plastic deformation and the precipitation hardening effect through the generation of nano-precipitates in the surface of treated materials. No study has been reported in the publicly available literature on the effect of high temperature shot peening HTSP on the surface integrity of aluminium alloys. In this research, we investigate the effects of the HTSP on AA2024-T351 specimens having dimensions of Almen strips. The AA2024-T351 aluminum alloy is widely used in the aerospace industry for manufacturing airplane components due to its high strength to weight ratio and excellent fatigue resistance [12]. The HTSP temperature investigated range lies between RT and 250°C. HTSP specimens are characterized in terms of arc height, surface roughness, and hardness. The relationships between the treated temperatures and the resulting arc height of the strips, the surface roughness and hardness were obtained.

Experimental methods

The material used for this study is AA2024-T351, supplied from 12.9 mm thick rolled plate. Its composition range is listed in Table 1. The T351 treatment for aluminum alloy indicates that it is solution heat treated followed by a stress relieving operation where it is stretched by 1-1.5% and then naturally aged for 96 hours [4]. AA2024-T351 specimens having dimensions of 76 mm × 19 mm × 2 mm were prepared from rolled plates and the as-rolled surface was mechanically polished to a mirror finish with a 0.05 µm colloidal silica solution prior to the shot peening process.

AA2024-T531 specimens were peened for a single Almen intensity of 0.12 mmA with full coverage, at RT and at high temperatures ranging from 100 to 250 °C with an interval of 50°C. Fifteen tests (5 temperatures x 3 repetitions) in total were performed. The AA2024-T351 strips were fixed to a steel holder. A high temperature setup for performing HTSP tests was installed inside a conventional SP machine, which includes an induction coil and a pyrometer. The induction coil during HTSP tests heats the steel holder by induction, and the holder heats the sample by conduction. The pyrometer is used to record the surface temperature during the tests. The determination of the SP process conditions consisted in performing several tests based on a previous experience on the SP machine. Ceramic media Z425 (0.425 mm diameter), a stand-off distance of 152.4 mm, a peening angle of 90° between the nozzle and the specimen holder, an air pressure of 48 kPa, and a mass flow of 4.5 kg/min were applied to obtain an Almen intensity of 0.12 mmA. The specimens were heated simultaneously during the SP process and the temperature profiles were recorded using the pyrometer. Figure 1 shows a typical surface temperature profile for a target temperature of 200 °C. To obtain a stable temperature during the shot peening process, the induction heating was programmed at a temperature (induction temperature) of 10 °C lower than the target SP temperature to avoid the overheating of the steel holder. The HTSP process included 3 main steps, as shown in Figure 1. Step 1 is a simple heating phase where the induction is activated to heat the holder and specimen at the target peening temperature. Only air is blown on the surface without media. At the end of this step the nozzle moves above the specimen to activate the media. Step 2 is the HTSP process. In this step, the induction heating is always activated, and the media are impacted onto the surface of the specimen. At the end of this step, the nozzle is moved above the specimen for one second to deactivate the media, which explains the increase in the temperature at that stage. Step 3 is a cooling phase. The induction heating and the mass flow are deactivated. However, the air still blows to cool down the specimen.

Table 1: Chemical composition (wt%) of the 2024-T351 aluminum alloy [3].

Element		Cu	Mg	Mn	Fe	Si	Zn	Ti	Cr
% weight	Min	3.8	1.2	0.3	-	-	-	-	-
	Max	4.9	1.8	0.9	0.5	0.5	0.25	0.15	0.1

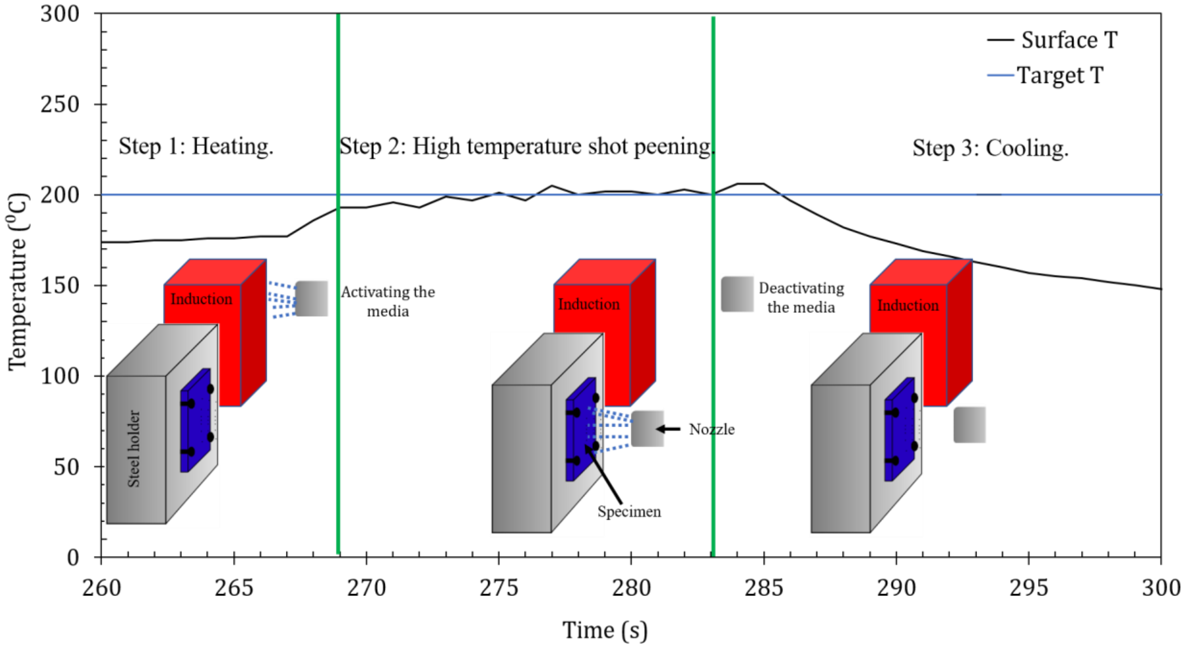

Figure 1: Typical temperature profile on the surface of the specimen while shot peening at 200°C. Step 1: the induction heating and the air pressure are activated to heat the sample at the desirable temperature. Step 2: start of the high temperature shot peening phase where the induction, the air pressure, and the media flow are activated. Step 3: an air-cooling phase where the induction and the media flow are deactivated, and the air flow is kept activated.

Three repetitions were made for each condition to evaluate the discrepancy by considering the initial deflection of the specimens. The deflections of the specimens were measured using an Almen gauge. A simple computation was made to obtain the arc height of the specimens by subtracting the initial measured arc height from its value after peening to consider the initial deflection of the specimens. A Mitutoyo profilometer was used to measure the surface roughness profiles along the longitudinal direction of the specimens. Rockwell B hardness tests using a 1/16 inch diameter ball indenter with a 100 kg load were carried out on the 15 AA2024-T531 peened specimens.

Results and discussion

Figure 2 (a) presents the resulting arc height values from shot peening of the AA2024-T351 specimens at different temperatures. The SP condition resulting in the highest arc height is at RT with an average arc height of 0.222 mm, followed by SP at 200°C with an average arc height of 0.195 mm. Whereas, SP at 100°C had the smallest average arc height of 0.105 mm, SP at 150°C and SP at 250°C, result in average arc heights of 0.113 mm and 0.120 mm, respectively. The resulting arc height is caused by the plastic deformation stored in surface layer of the specimen during SP [13]. It is thus not surprising to observe the maximum value at RT where the strain hardening is maximum. At higher temperature, the arc height decreases in most of the cases. This is due to strain softening mechanism that occurs at low temperature in aluminum alloys [14]. The outliers at 200°C, is due to the larger compressive residual stresses that have been produced at this peening temperature. This could be due to a change in the deformation mechanism operating in this temperature range. More investigation is required to understand the behavior of the alloy under HTSP conditions.

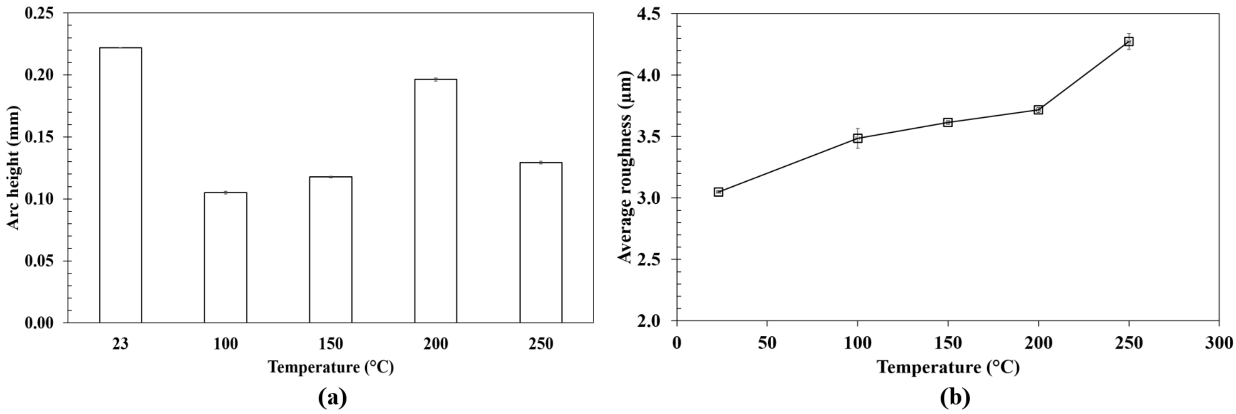

Figure 2: (a) Arc heights resulting from peening of AA2024-T351 strips at an Almen intensity of 0.12 mmA and at RT (23°C), 100, 150, 200, and 250°C. (b) The surface roughness profile under the same peening conditions.

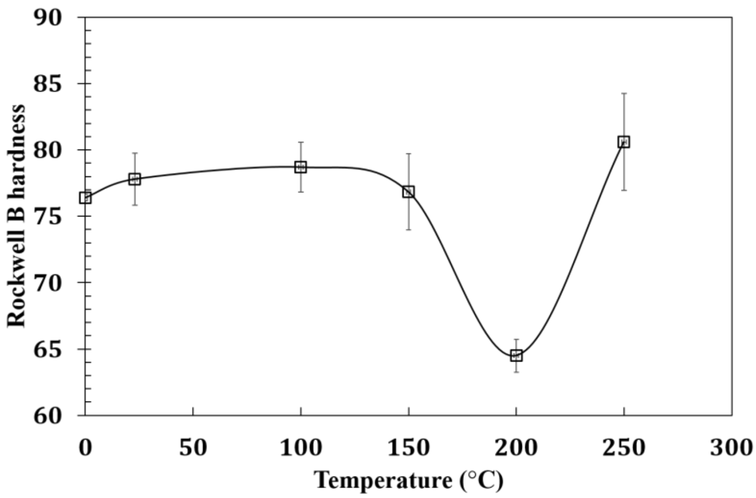

Figure 3: The Rockwell B hardness of the AA2024-T531 specimens treated using an Almen intensity of 0.12 mmA and at temperatures of 23, 100, 150, 200, and 250°C.

The change of surface roughness after shot peening is critical for the fatigue properties. Arithmetic average (Ra) was extracted from the roughness profiles to characterize the mean depth of the peening indentations. Figure 2 (b) shows the Ra of the AA2024-T351 specimens peened at different temperatures. The average surface roughness increases with the increase of temperature. When the temperature increases, the yield point and the hardening mechanisms of the material decrease. Therefore, the media indentation increases, which relates to larger surface roughness.

Figure 3 shows the relationship between the surface hardness and the SP temperature. The as-received specimens' hardness is shown by 0 °C in the temperature axis. From RT to 100°C, no significant change in hardness is observed. After 100°C a decrease in the surface hardness is shown. The hardness has a minimum value at 200°C and a maximum value at 250°C. We assume that the hardness evolution in the case of HTSP of AA2024-T351 comes from the two competing mechanisms: hardening and softening as shown in the case of HTLSP of AA6160 [10], HTLSP of AA7075 [15], and HTDR of AA6110 [11]. The decrease in the surface hardness is due to the softening mechanism activated in the temperature range of 100 to 200°C. We also assume that the increase in hardness at 250°C is maybe due to the hardening mechanism activated at this temperature as seen in the case of AA7075 after HTLSP at 250°C [15].

Conclusion

SP and HTSP treatments on AA2024-T351 specimens were carried out to reveal the effects of temperatures ranging from RT to 250°C on the resulting arc height of the specimen arc height, surface roughness, and the hardness of the aluminum alloy. At RT and at 200°C, the AA2024-T351 specimens showed high deflections, which indicate the large CRS. The average surface roughness increased with the increase of the peening temperature that can be related to the large surface plastic deformation induced during the HTSP process, which led to larger dents. When compared to the as-received specimen and the SP at RT, HTSP at 250°C led to highest material hardness. CRS measurements and microstructural observations will be conducted on the AA2024-251 specimens peened at RT and high temperatures to understand the material behavior after SP at different temperatures.

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