High strain rate behaviour at high temperature of AlSi12 parts produced by selective laser melting

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Abstract. High strain rate dynamic behaviour of metals is normally studied at room temperature using a split Hopkinson pressure bar (SHPB) equipment. This paper presents an investigation on a high strain behaviour at a high temperature for AlSi12 aluminium alloy parts produced by selective laser melting (SLM) additive manufacturing technology. Dynamic tests of parts were carried out at room temperature as well as at 200 °C using the split Hopkinson pressure bar to understand the dynamic behaviour of AlSi12 and the results were compared with quasi-static compression tests carried out at the same temperatures. The effect of flow stress due to an increase in temperature was analysed. Further observations through microstructure were also conducted. Negative strain rate effect was observed at room temperature, while positive strain rate effect was observed at high temperature.

1. Introduction

Selective laser melting (SLM) has become a widely used additive manufacturing (AM) process for 3D printing of metal parts in a range of materials including steels, titanium and aluminium alloys. In the SLM process, parts are produced directly from CAD file data using laser melting and rapid cooling of metal powder spread on a platform in a layer-by-layer fashion. One of the advantages of SLM includes geometric freedom and realisation of intricate parts, normally not possible by conventional manufacturing processes. SLM involves rapid cooling of the melt pool, resulting in a very fine microstructure and with enhanced mechanical properties [1]. The SLM is one of the few AM processes, which has been successful in processing certain aluminium alloys. However, processing of aluminium alloys by AM offers several challenges due to its poor powder flowability, high thermal conductivity and atmospheric oxidation [2]. Louvis et al. [3] have reported the difficulties in processing of aluminium alloy by high power SLM and considered the changes that can be made to the SLM process so as to reduce the laser power required and increase the laser scanning rates, while still producing components with a high relative density. They reported that combination of laser power and scan speed causes the balling effect in the aluminium parts, and oxidation was the other major problem, which must be eliminated for parts with 100% density. More in-depth understanding of the mechanical behaviour of aluminium parts made by SLM is essential for its potential application under various loading conditions in several industry sectors such as aerospace and automotive.

Several investigators have attempted to characterise the mechanical behaviour of aluminium alloys processed by selective laser melting. Chou et al. [4] carried out a study to manufacture AlSi12 alloy
parts using a pulsed selective laser melting (SLM) process as opposed to continuous SLM process and showed that pulse SLM allowed for greater control over the heat input offering more optimization possibilities of the microstructure and hardness in the parts. Vora et al. [5] investigated the processing of AlSi12 parts using an anchor-less processing on SLM by pre-heating of the powder bed, which resulted in reducing the residual stress in aluminium parts. Wang et al. [6] analysed the fabrication of AlSi12 components using SLM process under various atmospheric conditions in the SLM chamber. They studied the effect of Ar, N₂, and He gases and found that the density and hardness of parts made were not affected by changing the atmosphere. However, Ar and N₂ were found to produce better ductility than He in the aluminium parts. Siddique et al. [7] investigated the effect of SLM process parameters and post-heat treatment on the microstructure and the resulting fatigue behaviour of AlSi12 parts. They reported that base plate heating affects the microstructure and mechanical behaviour of parts produced by SLM and mechanical properties are found to be better than those by conventional methods. In another study, Siddique et al. [8] conducted a very high cycle fatigue and fatigue crack growth behaviour of AlSi12 produced by SLM. They reported that the fatigue behaviour improved through base-plate heating and fatigue mechanism was controlled by micro-porosity. Prashanth et al. [9] studied the effect of heat treatment on tensile properties of AlSi12 alloys by SLM and reported that yield strength of SLM samples reduced from 260 MPa to 95 MPa and the fracture strain increased from 3% to 15% due to isothermal annealing. The microstructure after annealing became coarser. Li et al. [10] investigated the effect of solution heat treatment time on tensile strength of AlSi12 parts by SLM and found that the increase in tensile properties of AlSi12 parts in SLM could be attributed to the refined eutectic microstructure. They also observed an increase in ductility by 25% approximately.

Published literature reveals that no research seems to have been made to study the dynamic behaviour of aluminium parts processed by SLM process. In this paper, the focus is on the high strain rate behaviour as there are many practical applications such as high speed machining, mining machines, and situations such as automotive impacts, where strain rates can be as high as in the range of 10⁵/s to 10⁶/s subjected to various temperatures. Split Hopkinson Pressure Bar (SHPB) has been used in this study to characterise the dynamic compressive behaviour at high temperature of AlSi12 parts produced by ProX200 selective laser melting machine.

2. Material and Methods

2.1 Selective Laser Melting

The selective laser melting (SLM) machine used was ProX200, which was supplied by 3D Systems equipped with a fibre laser. The working principle of SLM has been described in [3]. The aluminium alloy AlSi12 powder was supplied by 3D systems, which was used to produce fully dense samples on the ProX200 for quasi-static compression tests and high strain rate compression tests. The process parameters used for preparing the samples in the SLM are: Laser power: 285 W, which is the 95 % of laser power, scanning speed of 1000 mm/s, and defocus distance of -4 mm. Along with other parameter, the layer thickness was 40 µm. Argon gas of high purity was used inside the SLM chamber in order to purge oxygen and to avoid possible contamination.

Cylindrical specimens of dimensions 010 mm × 10 mm were built horizontally in the SLM build plate and they were machined to Ø 8 mm × 8 mm size with an aspect ratio of 1.0 for quasi-static as well as dynamic tests. Necessary support anchors were built in order to maintain the mechanical stability of built samples. Also, the scan strategy followed was hexagonal pattern. The samples were polished using Auto-polisher, Struers Tegamin-25 and in order to reveal the microstructure, the etchant used was the sodium hydroxide and water, which had the composition of 10 gm of NaOH pellets and 90 ml of H₂O. Also, optical microscope of model Olympus BX61 was used to analyse the microstructure.

2.2 Quasi-static tests

A 50 kN MTS machine was used for quasi-static testing at the room temperature, and a 100 kN INSTRON machine with a heated chamber was used for a quasi-static testing at a high temperature. The rate of deformation was 1 mm/ min and the corresponding strain rate was 2 × 10⁻³ s⁻¹ for tests at
room temperature as well as at high temperature. ASTM E9 standard was followed for arriving at the sample standard with aspect ratio 1. A temperature of 200°C was maintained in the chamber for quasi-static studies at high temperature.

2.3 Split Hopkinson Pressure Bar

Figure 1 shows the schematic view of the split Hopkinson pressure bar (SHPB) apparatus used for high strain rate testing [11]. In general, the SHPB apparatus consists of five key elements namely two symmetrical pressure bars, a bearing and alignment fixture to allow free movement of the bars, a compressed gas launcher, generally a pair of strain gauges mounted on both input and output bars, a data acquisition system to mainly record the strain wave data. The test sample is sandwiched between incident bar and transmission bar. To minimize the effect of friction between the specimen and the bars, a thin layer of molybdenum disulfide lubricant is applied between the contacting surfaces. When the striker bar impacts the incident bar, it creates an elastic compressive pulse, referred to as an incident pulse. This incident pulse will propagate through the bar towards the sample. When the pulse reaches the sample, a portion of the pulse is reflected back into the incident bar due to the impedance mismatch between the incident bar and the specimen. The remaining portion of the pulse will be transmitted through the sample and into the transmission bar.

Figure 1. Schematics of SHPB [11].

Axial resistive strain gages are attached on the surface of the incident and transmission bars at the midpoint of the bars. These strain gages provide time-dependent strain pulses of the bars. In one of the oscilloscopes, the velocity is recorded. Both the incident and the transmission bars are made of maraging steel, whose nominal yield strength and elastic modulus are equal to 2310 MPa and 190 GPa respectively. Their diameter and length are 14.5 mm and 1200 mm, respectively. The striker bar, incident bar and transmission bars are of identical diameter and made of same steel. However, the striker bar length of 300 mm has been used. The sample temperature was increased to 200 °C by heating only the specimen, while keeping the incident, transmission and striker bars at room temperature. Essentially, the bars were brought in to contact with the specimen just a fraction of second before an impact of the striker bar. The sample mounted between incident bar and transmission bar is assumed to have a dynamic stress equilibrium and the sample undergoes constant strain rate while deformed [12]. The signals from the strain gauges are amplified and recorded by high speed digital oscilloscope. The relative magnitudes of these incident, reflected and transmitted strains are combined to generate the dynamic stress strain curve for the specimen [13]. Figure 2 shows the voltage magnitudes of incident, reflected and transmission pulse obtained from the incident and transmitter bars for an AlSi12 specimen. From this data set the strain rate vs. strain is calculated.
3. Results and discussion

Figure 3 shows stress-strain curves for the quasi-static and dynamic (SHPB) compression tests at room temperature for AlSi12 parts made by SLM. Two test samples were tested for each case. The strain rate for quasi-static stress was $2 \times 10^{-3}$ /s and the maximum strain rate for dynamic curves was 750/s. A negative strain rate effect is observed in Figure 3, where the flow stresses are larger for the quasi-static stresses when compared to dynamic curves. This effect was due to micro-cracks observed in the microstructure as shown in Figure 4 as well as due to the thermal softening caused by adiabatic heating.

In Figure 3, the quasi-static as well as dynamic flow stresses are found to be consistent, as the same applied forces in terms of quasi-static tests and the velocity for SHPB tests were maintained.
Figure 4. Microstructure of AlSi12 tested samples at room temperature for (a) dynamic studies; and (b) quasi-static studies.

In Figure 4(a), dynamic studies shows that lesser number of pores and no cracks were observed. However, in Figure 4 (b), more oval shaped pores and cracks propagating along the grain boundaries were observed. Also, coarse grains were found along the grain boundaries compared to grains found inside the laser tracks in both the dynamic and quasi-static studies.

Figure 5 True stress vs true strain at 200°C for quasi-static and dynamic tests.

Figure 5 shows stress-strain curves for the quasi-static and dynamic (SHPB) compression tests at 200°C temperature for AlSi12 parts made by SLM. The positive strain effect was observed in Figure 5 where the maximum strain rate attained for the dynamic flow stress was 1500/s and the quasi-static stress was $2 \times 10^3$ /s. The dynamic flow stress at 200°C was found to increase significantly when compared to the quasi-static flow stress.
In Figure 5, it is noted that a positive strain rate occurred due to the rate controlling mechanism, which was also mentioned as a thermally activated diffusion [14]. The strain rate sensitivity with respect to an increase in strain rate was found to be higher, which could be due to the nature of AlSi12 produced by SLM. Also, both the temperature and strain rate affect the strength and deformation characteristics that was influenced by dynamic recrystallization [15]. Figure 6 shows the microstructure corresponding to the positive strain rate effect, which reveals that no pores are found and grain boundary was well defined. The microstructure revealed that the grain boundaries became narrow in a horizontal orientation after quasi-static testing. The pores observed in all the cases were observed to have closed after dynamic testing, as the applied force was compressive by nature.

4. Conclusions

The quasi-static stress strain as well as dynamic stress strain curves at high strain rate compressive loads conducted at room temperature and at a high temperature for SLM built AlSi12 parts were found to be repeatable and consistent. The effect of strain rate on the flow stress at room temperature and high temperature at 200°C was analysed. From the quasi-static and dynamic stress strain curves, negative strain rate effect was observed for specimens tested at room temperature and positive strain rate effect was observed for specimens tested at high temperature. These studies are supported by microstructure. Results also show that for the high strain dynamic testing, lesser number of pores and no cracks were observed. Further studies are planned to study the effect of build orientations on the quasi-static and dynamic behaviour of SLM aluminium parts.

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