Materials Science & Engineering A 701 (2017) 226–236

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Investigation on crashworthiness of ultrafine grained A356 sheets and validation of Hall-Petch relationship at high strain-rate deformation

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ARTICLE INFO

Keywords:
High strain-rate deformation
Crossbow test
Ultrafine grained material
Cryorolling
Hall-Petch relationship

ABSTRACT

High crushing force and good energy absorption are the essential requirements for structural materials subjected to dynamic loading. In the present work, commercial A356 material is subjected to cryorolling and post-cryoroll annealing to produce sheets of different grain sizes and the influence of microstructural change on dynamic behavior of the material is studied. Dynamic tests are done in a crossbow test equipment at an average strain rate of 250 s^{-1}. Quasi-static tests are done at an initial strain rate of 0.005 s^{-1} to compare the dynamic performance of the material with its static/quasi-static behavior. It is found that strength and ductility of cryorolled material at dynamic loading condition is lesser than that in quasi-static loading. Upon annealing, the material performance of the material is found to be better at high strain-rate deformation than that at quasi-static condition. A detailed analysis on the deformation behavior and fracture mechanism of the material at high strain-rate is carried out. Further, the existence of Hall-Petch relationship at high strain-rate deformation is evaluated. The material's strengthening factor is found to hold good agreement to the Hall-Petch relationship with a grain boundary strengthening coefficient of 112 MPa at dynamic loading.

1. Introduction

Ultrafine grained (UFG) materials fabricated by various severe plastic deformation methods have been successful in demonstrating excellent mechanical properties [1,2]. UFG sheets are gaining more importance in the recent years, as they show superior mechanical behavior over the coarse-grained conventional sheets [3–7]. This makes them, a suitable alternative for exterior structures and many other applications predominantly in automotive and aerospace industries.

Cryorolling is found to be an effective processing route to get ultrafine grained sheets with less amount of strain imposed. As demonstrated originally by Wang et al. [3], the cryorolling process involves rolling the material at liquid nitrogen temperature. The low processing temperature suppresses dynamic annihilation of the generated dislocations, thereby enhancing the rate of grain refinement [8]. In particular, cryorolling is a suitable process required to enhance dislocation density and hinder recovery effectively in aluminium and its alloys due to their high stacking fault energy. Extraordinary improvement in material's strength by cryorolling has been demonstrated by various researchers [3–8] which makes cryorolled materials a suitable alternative in high strength applications. However, in application areas such as automobile, defense and aerospace industries, many of the structural components are subjected to a wide range of loading rates. In those application areas, other than the static load-bearing ability, the material must be capable of withstanding sufficient load at high strain rates which is termed as its crashworthiness [9].

The deformation behavior of the materials at high strain rate (i.e. impact loading) is not as same as that at conventional low strain rate (i.e. quasi-static loading). While the low strain-rate deformation behavior is controlled by the dislocation motion, deformation at high strain-rate involves the influence of inertial waves generated during the deformation process [10]. Since the behavior of the material to the external load is microstructure driven, it is essential to understand how the microstructural features affect the materials performance at high strain rate loading. Though grain refinement leads to strength enhancement as per the Hall-Petch relationship, its validation in the high strain-rate regime is not completely understood because of the complexity involved in the deformation process at high strain-rate. Also, a large number of research work has been carried out in understanding the high strain rate deformation behavior of materials with conventional microstructure [10], but the deformation behavior of ultrafine-grained materials at high strain-rate is rarely reported [11–13]. Most of the published work on high strain-rare deformation pertains to compression loading. However, in the case of sheet metal applications,

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http://dx.doi.org/10.1016/j.msea.2017.06.080
Received 28 April 2017; Received in revised form 17 June 2017; Accepted 19 June 2017
Available online 22 June 2017
0921-5093/

understanding their dynamic behavior by compression testing is difficult and the research work on tensile loading at high strain-rate remains scanty. Moreover, the effect of cryorolling on the material's dynamic behavior has not been studied till date.

It is established from our earlier work [8] that cryorolling leads to enhanced strength in A356 material because of the uniform distribution of hard silicon particles and the dominating dislocation-strengthening mechanism. However, any material which is used in external structures should have the ability to withstand impact loads and stay crashworthy. This is the motivation behind the present study and with this background, our present research work is formulated to study the crashworthiness of ultrafine grained A356 alloy sheets developed by cryorolling. The cryorolled sheets are subjected to post-cryoroll thermal treatment to generate microstructure with different grain sizes which enable us to understand the effect of grain size on the high strain-rate deformation behavior of the alloy. The objectives of the current work are: (i) To understand the deformation behavior of ultrafine grained A356 alloy at high strain rate; (i) To study the influence of grain size on dynamic deformation behavior and (ii) To analyze the existence of Hall-Petch relationship at high strain-rate.

2. Materials and methods

2.1. Material

Commercially available A356 ingots are procured from Sargam Metals, India, and the elemental analysis is done using optical emissive spectroscopy (OES) which shows the percentage composition of various elements present in the alloy as presented in Table 1.

2.2. Processing

The as-procured ingots are sliced into plates of 8 mm thickness and subjected to solutionizing heat treatment in a muffle furnace at 540 °C for 8 h followed by cold water quenching. The solution treated plates are soaked in liquid nitrogen for 15 min and then rolled in a rolling mill with a roll diameter of 110 mm at a speed of 8 rpm. A final thickness reduction of 87.5% is obtained in multiple passes with a 2.5% of thickness reduction per pass. Between each pass, the sample is soaked in liquid nitrogen in order to maintain uniform rolling temperature. To generate different grain sized microstructure, post-cryoroll annealing is done in the muffle furnace at 200 °C, 300 °C and 400 °C followed by air cooling. The designation of different material conditions which will be used throughout the manuscript along with its description is given in Table 2.

Table 1
Elemental composition (weight %) of A356 obtained from OES.

Si	Mg	Mn	Fe	Cu	Ti	Zn	Others	Al
6.62	0.357	0.092	0.324	0.0783	0.0329	0.0233	0.03	Bal.

Table 2
Designation of material subjected to various processes.

Material condition	Designation
As-cast material solution treated at 540 °C for 8 h	ST
ST material subjected to cryorolling up to 87.5% thickness reduction	CR
CR material annealed at 200 °C for 1 h	CR – 200
CR material annealed at 300 °C for 1 h	CR – 300
CR material annealed at 400 °C for 1 h	CR – 400

2.3. Testing

The crashworthiness of the material is evaluated by testing the material in a cross-bow test apparatus (Fig. 1(a)). Samples for the dynamic tests were made with both length and width of 10 mm in the gauge area. A specially designed fixture as shown in Fig. 1(b) is used to test the sample under tensile loading mode. Elastic ropes are used to propel the projectile along the mass guide to strike the test material. When the elastics held at tension is released, the potential energy stored in the elastics is converted into kinetic energy, generating the necessary impact velocity for testing.

The strain gauges are fixed on the receiver bar which holds the test specimen. The receiver bar deforms elastically when the impact mass strikes the sample attached to the bar. From the elastic strain values obtained from the strain gauge and the diameter of the receiver bar, the stress induced in the work material is calculated based on the Hooke's law. A FastCam APX high-speed camera is used to measure the impact velocity (strain-rate) and the strain values with respect to time. The strain field at the material surface is captured using a digital image correlation software ICASOFT. The strain values obtained from the high-speed camera images and the stress values obtained from the receiver bar are synchronized to plot the stress-strain curves. Testing is carried out at an average strain rate of 250 s^{-1} to understand the dynamic performance of the material.

To compare the deformation behavior of the material at high strain rate with that of quasi-static deformation, tensile test at an initial strain rate of 0.005 s^{-1} is done in a universal testing machine on samples with gauge area similar to that used for crossbow test.

2.4. Characterization

Optical microscopy is used to reveal the microstructure before testing and to examine the lateral surface near the fractured edge in the tested samples. In both the cases, the samples under study are mechanically polished using emery of 2000 grit size and final polishing is done with colloidal diamond suspension of 1 µm size. In case of post-tested samples, the gauge area is sectioned from the test sample using a low-speed diamond cutter across the cross section near the gripping area. The sectioned piece is then molded into cylindrical molds using cold-setting epoxy mixture to help retain the fractured edge.

Field emission scanning electron microscopy (FE-SEM) is used to observe the fractographs (i.e. fractured surface) of the tested samples. Electron backscattered diffraction (EBSD) analysis attached with the FESEM is used to characterize the microstructure of CR-400 material. For EBSD analysis, samples were polished by the technique provided above and then electro-polished using the electrolyte containing 80% perchloric acid and 20% Methanol at an operating voltage of 25 V.

Transmission electron microscopy (TEM) is used to observe the pre-test microstructure of CR, CR-200 and CR-300 materials. Samples for TEM analysis were mechanically ground to a thickness of 500 µm using emery sheets of 600 grit and then the thickness is reduced further to 80 µm by polishing using emery sheets of 2000 grit size. Discs of 3 mm diameter were punched out of the thinned sheets and then electro-polished using a twin-jet polisher with an electrolyte containing 80% methanol and 20% nitric acid maintained at −20 °C.

3. Results

3.1. Microstructural characterization

The optical microstructure of the solution treated material is shown in Fig. 2. The material is composed of dendritic microstructure with eutectic phases filling the inter-dendritic space. An inhomogeneous distribution of the dendrite size is also observed along with the non-uniform distribution of the second phase particles.

The microstructure of cryorolled material (CR) and post-cryoroll