ARTICLE IN PRESS

Thin-Walled Structures xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

Ballistic impact response of high strength aluminium alloy 2014-T652 subjected to rigid and deformable projectiles

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ARTICLE INFO

Keywords:
High strength aluminium
Failure modes
Ballistic tests
Constitutive modeling
Numerical simulations

ABSTRACT

Experimental and numerical studies were conducted to determine the impact response of 15 mm thick AA2014-T652 forged plates in the velocity region from 800 m/s to 1300 m/s. Spherical projectiles (10 mm diameter) of hardened steel and soft iron were launched from propellant gun of 30 mm bore diameter and their impact and residual velocities were measured by capturing the impact phenomena with a high speed camera. Residual velocities of projectiles were in good agreement with Recht-Ipson analytical model, when kinetic energy of the fragments ejected from the target was accounted for in the energy balance. Failure in target plates occurred due to a combination of failure mechanisms such as hydrodynamic flow, spalling, ductile hole growth and scabbing. A comprehensive material characterization program was executed to study the plastic flow and failure of the material. Tensile tests were carried out on target and projectile materials at different stress triaxialities, strain rates and temperatures. The experimental data of stress-strain curves were used to calibrate the material parameters of Johnson-Cook constitutive model, which relates the flow stress of the material to effective plastic strain, strain rate and temperature. Fracture strain values were used to calibrate the material parameters of Johnson-Cook failure model, which relates the fracture strain of a material to stress triaxiality, strain rate and temperature. Finite element analyses of all the impact experiments were carried out using a two dimensional axisymmetric model. Numerical results overestimated the ballistic limit velocities as the quasi-brittle fracture of target could not be captured using Johnson-Cook failure model. Limitations of Johnson-Cook failure model were analyzed and numerical simulations were repeated using hydrostatic tensile stress failure model. A non-linear equation of state was also introduced in the model for more accurate calculations of hydrostatic stress. These modifications resulted in an excellent correlation between experimental and numerical results.

1. Introduction

The technological advancements in the field of armaments have led to tremendous increase in demand for lightweight armour materials. Aluminium alloys have emerged as a strong candidate material for defence and aerospace applications due to their low density, high strength and high corrosion resistance [1,2]. The impact behaviour of high strength aluminium targets is quite complex as the perforation takes place due to combination of different failure mechanisms like spalling, ductile hole growth, plugging, petalling etc. [3].

Analytical solutions are unable to capture multiple failure mechanisms and do not provide accurate solutions. These mechanisms can be incorporated more easily in numerical codes which are therefore more commonly used to analyze failure due to ballistic impact. The accuracy of numerical simulations depends heavily on the constitutive and fracture models used to represent the dynamic mechanical behaviour of the material. Although a number of physically based and phenomenological constitutive models have been proposed in the last few decades, but only a few of them have been found practically usable in computational codes due to difficulty in the calibration of model parameters. One of the most popular constitutive models for metals was proposed by Johnson and Cook [4], which has five material parameters representing the effect of strain, strain rate and temperature. The material parameters of Johnson-Cook model are available in open literature for some of the aluminium alloys like AA1100 [5–8], AA2024 [9,10], AA5083 [11–13], AA6005 [14], AA6061 [15], AA6070 [16], AA6082 [17], and AA7075 [18].

No material data is available on the high strain rate behaviour of AA2014 in open literature. AA2014 is one of the strongest available aluminium alloys with very good machinability. It is primarily used for complex and highly stressed structural components in aerospace, defence and automobile applications. The present study was aimed at

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http://dx.doi.org/10.1016/j.tws.2017.05.014
Received 5 February 2017; Received in revised form 10 May 2017; Accepted 12 May 2017
0263-8231/

Table 1
Chemical composition (wt%) of AA 2014 T652.

Cu	Mg	Si	Fe	Mn	Cr	Zn	Ti	Others	Al
4.2	0.5	0.8	0.7	0.6	0.1	0.2	0.1	0.1	Balance

investigating the dynamic fracture behaviour of AA2014 using an integrated approach encompassing ballistic impact tests, dynamic material characterization, constitutive modeling and numerical simulations.

2. Material description

2.1. Target

15 mm thick forged plates of AA 2014 T652 aluminium alloy were used as target material. Wrought aluminium alloys are divided into seven major classes as per their major alloying elements. The 2xxx series aluminium alloys have copper as their main alloying element and these alloys are heat treatable. These alloys are used in aerospace industry due to their high specific strengths. The composition of AA 2014 T652, the subject of present study, is given in Table 1. T652 denotes the tempering condition of the alloy which means that the alloy was solution heat treated, stress-relieved by compressive deformation and artificially aged.

2.2. Projectiles

10 mm diameter spheres were used as projectiles. Commercially available ball bearings were used as rigid projectiles (hardness 830 HV10). Deformable projectiles were made of soft iron (hardness 165 HV10). The major alloying element in soft iron is Manganese (Mn), which is added to reduce the hot shortness of the material. Hot shortness is caused due to local melting of the material due to the presence of sulphur, which has much lower melting point than iron. Manganese reacts with this sulphur and forms Manganese Sulphide (MnS), which has a much higher melting point than sulphur. The detailed chemical composition of soft iron is given in Table 2.

3. Ballistic tests

3.1. Experimental set-up

Ballistic tests were conducted using a smooth bore propellant gun with 30 mm bore diameter (Fig. 1). Since the diameter of the projectile (10 mm) was less than the bore diameter of the gun, a two-piece polycarbonate sabot was used to launch the projectile (Fig. 2). The projectile is placed in the spherical cavity provided inside the sabot. The sabot is fitted into the cartridge, which is filled with required quantity of propellant (single base nitrocellulose based) depending on the projectile velocity to be achieved.

Upon firing, the sabot, along with projectile, gets separated from the cartridge and two parts of the sabot opens up due to air drag. These two parts of the sabot are trapped at sabot catcher plate (Fig. 1), which is placed ahead of the actual target. Sabot catcher plate is a steel plate (500 × 500 × 25 mm) with a 100 mm hole in the center so that only the projectile can pass through it. Projectiles were recovered after perforation of the target with the help of cardboard racks, which were placed behind the target.

Table 2
Chemical composition (wt%) of soft iron.

C	Mn	Si	S	P	Fe
0.006	0.43	0.05	0.013	0.005	Balance

Fig. 1. Smooth bore propellant gun.

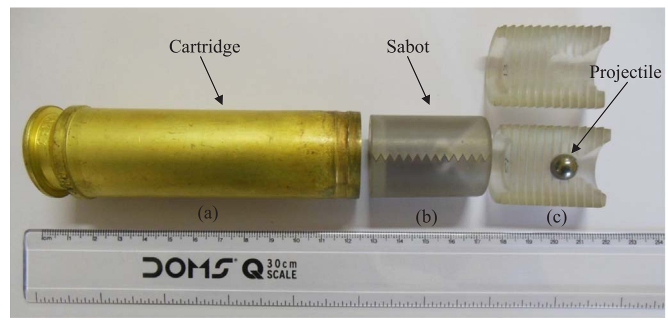

Fig. 2. (a) Cartridge, (b) sabot and (c) projectile inside sabot.

Target plate of size 500 × 500 × 15 mm was placed at a distance of 10 m from the muzzle end of the gun. A minimum distance of 76 mm was maintained between the point of impact and edge of the target. Minimum inter-shot distance of 51 mm was maintained between two successive impact points on the target. These distances are prescribed as per the fair hit criteria defined by National Institute of Justice; United State Department of Justice [19].

The interaction between projectile and target was recorded with Photron Fastcam-APX RS high speed video camera system for accurate measurements of impact and residual velocities. The camera can capture images at maximum frequency of 2,50,000 frames per second with picture resolution of 128 × 16 pixels. In the present study, the perforation process was captured at 10,000 frames per second to get better resolution pictures (512 × 512 pixels).

3.2. Ballistic test results

3.2.1. Impact with hardened steel projectiles

Fig. 3 shows the schematic diagram of target cross-section after perforation.The results of the ballistic impact tests are summarized in

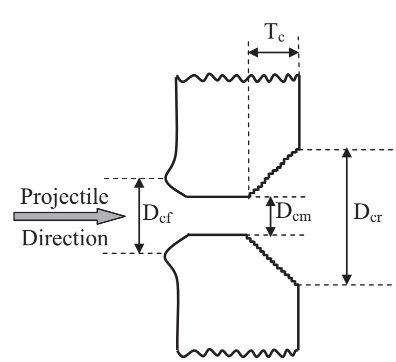

Fig. 3. Schematic of the perforation channel in the target.