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Procedia Structural Integrity 46 (2023) 24–29

Structural Integrity Procedia

www.elsevier.com/locate/procedia

5th International Conference on Structural Integrity and Durability

Residual stress modelling and analysis of a 7075-T6 hourglass specimen after foreign object damage

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Abstract

Foreign Object Damage (FOD) is a major cause of fatigue failure in aircraft engine components. The impact of objects is responsible for the introduction of defects and residual stresses which influence the fatigue life. 7075-T6 aluminum alloy is commonly used for manufacturing of aerospace components due to its high strength-to-density ratio. In this paper the effect of FOD on the integrity of 7075-T6 alloy was investigated experimentally and by Finite Element (FE) analysis. In the experiment a steel ball was fired at a 7075-T6 hourglass specimen at its middle cross section by using a compressed-air gun device, which caused plastic deformation in the shape of a crater. After the impact, the specimen was subjected to rotating bending fatigue test until it failed. In order to simulate the ball impact on the hourglass specimen, a FE analysis in Abaqus Explicit was conducted, by means of which the plastic deformation and residual stress state were assessed. The maximum tensile residual stress in the middle cross section appeared at the locations where the crack initiation was observed in the experiment.

Peer-review under responsibility of ICSID 2021 Organizers

Keywords: FOD; residual stresses; 7075-T6 aluminum alloy; experimental testing; FE analysis

1. Introduction

FOD is an expression typically used in the aerospace industry to designate the damage to engine components caused by the impact of foreign objects (Nicholas, 2006). FOD can introduce micro- and macro-structural damages and stress

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2452-3216
Peer-review under responsibility of ICSID 2021 Organizers
10.1016/j.prostr.2023.06.005

concentrations that can alter fatigue strength. In the case of high speeds of impact, FOD is also responsible for piling up and removing material (Peters and Ritchie, 2000). Due to a mechanism similar to shot peening (Baragetti et al., 2000), FOD can induce residual stress states (Boyce et al., 2001). Residual stresses can affect the fatigue life as demonstrated for example in the case of coating deposition (Baragetti et al., 2005, 2020; Baragetti and Tordini, 2007) and ion-implantation (Voorwald et al., 2019).

Under fatigue loading in structures and components cracks may initiate at locations of stress concentration (Božić et al., 2014; Mlikota et al., 2017, 2018, 2021a, 2021b). Initiated fatigue cracks can further propagate under service load (Božić et al., 2010a, 2010b, 2011, 2012, 2018; Baragetti et al., 2019c; Vučković et al., 2018), which can bring to fracture at a critical load (Pastorcic et al., 2019; Vukelić et al., 2020).

To achieve high performance in the aerospace industry, the components are made of light and resistant alloys, due to their high strength-to-density ratio. Some of the most commonly adopted light alloys are 6060-T6 and 7075-T6 aluminum alloys and Ti-6Al-4V titanium alloy. The integrity of these alloys in various loading and environmental conditions has been investigated by Baragetti (2013), Baragetti and D'Urso (2014), Baragetti and Arcieri (2018) and Baragetti et al. (2009, 2018, 2019a, 2019b).

The numerical modelling and prediction of the fatigue life of structural components plays a strategic role to avoid unforeseen disasters, reduce the needed experimental research time, and the product development time and costs (Babić et al., 2018, 2019, 2020; Cazin et al., 2020; Solob et al., 2020; Braut et al., 2021a; Papadopoulou et al., 2019).

In this paper FE analysis and experimental testing were carried out to analyze the impact of a steel ball on a 7075-T6 hourglass specimen surface at its middle cross section. After the impact, the specimen was subjected to a rotating bending fatigue test. An analysis by Abaqus Explicit was conducted to simulate the impact and to assess the introduced residual stresses. The location of high tensile axial stresses determined in the numerical simulations agrees well with the location of crack initiation observed in the experiment.

Nomenclature

d	diameter
E	Young's modulus
m	mass
UTS	ultimate tensile stress
YS	yield stress
μ	coefficient of friction
ν	Poisson's ratio
ρ	density

2. Experimental analysis of impact and fatigue in the hourglass specimen

The experimental analysis consists of two stages: (i) impact of the steel ball on the 7075-T6 hourglass specimen; (ii) rotating bending fatigue test. The ball and the specimen are shown in Fig.1a and the geometry of the specimen is given in Fig. 1b. The mass of the steel ball was m=0.51 g and its diameter was d=5 mm. The mechanical properties of the specimen material are as follows: ρ =2810 kg/m^3, E=71700 MPa, ν =0.33, YS=598 MPa, UTS=650 MPa.

In the impact test the ball was fired to the 7075-T6 hourglass specimen from a distance of 180 mm, at a speed of 100 m/s, by using a compressed-air gun device. The specimen holder is shown in Fig. 2. The two cylindrical parts of the specimen placed in the holes of the holder were fixed by screws in the experimental setup. The impact was perpendicular to the specimen surface at its middle cross section. As a consequence of the impact a crater was created due to the occurred plastic deformation in the specimen. After the impact, the damaged specimen was subjected to a rotating bending fatigue test by using a four-point bending testing machine ItalSigma X2TM412. The test was performed in air environment with an angular velocity of 2500 rpm. The specimen was tested by using a step loading procedure (Nicholas, 2002). In this procedure several load blocks are implemented sequentially, similarly to the Locati method (Locati, 1955; Braut et al., 2021b). In the first load block, the specimen was subjected to 200000 cycles with a starting load which corresponds to a bending moment of 1 Nm. The load was incrementally increased in the next load blocks until the specimen failed. The applied increase in the load corresponds to an increment of 0.2 Nm in the bending moment. The procedure was repeated until the specimen failed at the bending moment 2 Nm.

The failure surface of the specimen after the fatigue test, shown in Fig. 3, was observed with a trinocular 7–45× zoom stereo microscope ZENITH SZM-4500. The final fracture area is rather small compared to the fatigue crack propagation area and it occupies less than 15% of the whole middle cross section area of the failed specimen.

a) b)

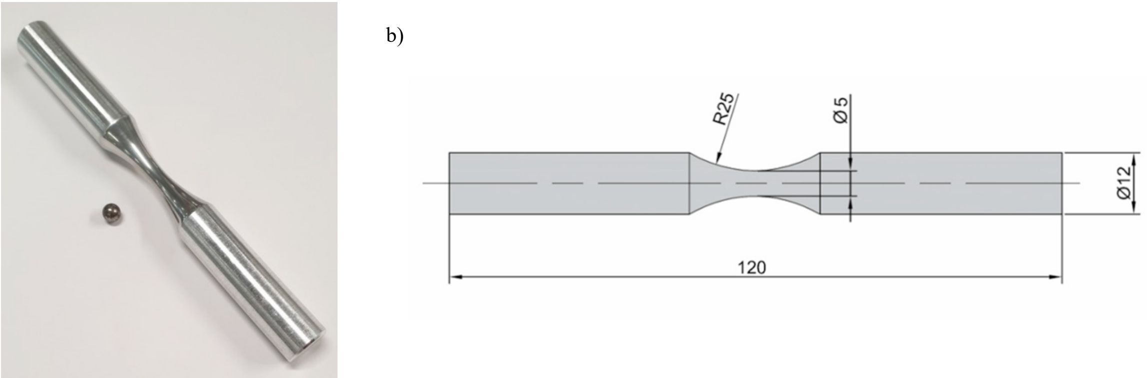

Fig. 1. Impact test: (a) steel ball and 7075-T6 hourglass specimen; (b) 7075-T6 hourglass specimen.

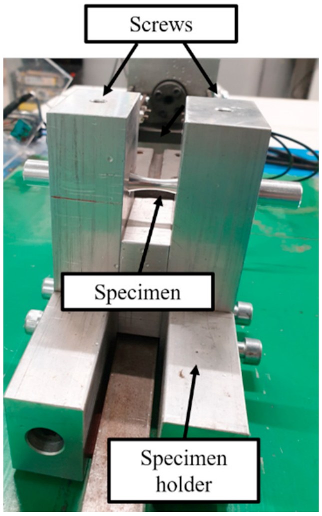

Fig. 2. Specimen holder.

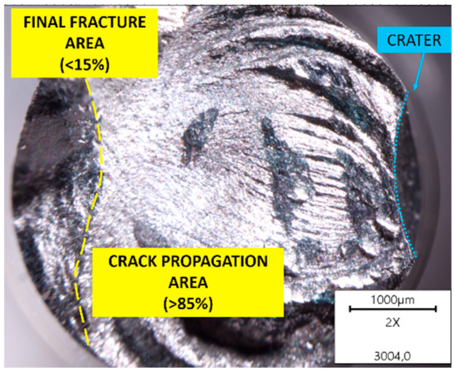

Fig. 3. Failure surface.

3. Numerical modelling and analysis of the residual stresses in the hourglass specimen

The FE model and procedure for the analysis of an impact on an hourglass specimen was developed in a previous work on Design of Experiments applied to FOD on 7075-T6 aluminum alloy (Arcieri et al., 2021). The residual stresses in the specimen after impact were simulated by using FE Abaqus Explicit software (2017). The explicit integration scheme is normally used in problems involving impacts (Baragetti and Arcieri, 2020).

The above described procedure is implemented in this paper to simulate the impact of the ball on the hourglass specimen studied experimentally, as described in Section 2. The units used in the dynamic FE analysis in this study are as follows: mm for length, kg for mass and ms for time. The hourglass specimen was modelled with 8-node linear brick elements, with reduced integration and hourglass control, C3D8R in Abaqus element library. In the impact area on the specimen, a mesh size of 0.25 mm was adopted. An elastic perfectly plastic material law was assigned to the hourglass specimen in the nonlinear dynamic analysis. The mechanical material properties of the specimen are given in the part describing the experimental analysis in Section 2. The impact ball was modelled by using 4-node 3D bilinear rigid quadrilateral elements, R3D4 from the Abaqus element library. The mesh size of the ball was 0.25 mm, the same as the hourglass specimen, to achieve the convergence of the contact analysis. A coefficient of friction μ=0.47 was defined for the contact between the ball and the specimen (Serway, 1995). The inertial properties of the ball were assigned to the Reference Point (RP) placed at its center. To reduce computing time, a minimum distance between the ball and the specimen of 0.1 mm was implemented. The impact velocity was 100 m/s as implemented in the experiment and it was defined in the RP of the ball as a predefined field, according to the Abaqus manual. The implemented boundary conditions reproduced the experimental setup of the specimen placed in the holder shown in Fig. 2. To simulate the fixation of the hourglass specimen described in Section 2, all the degrees of freedom of the nodes on the specimen part inside the holder were fixed. These areas are marked with red lines in Fig. 4, which shows the residual axial stresses in the specimen and at the middle cross section after impact. The stresses are symmetric with respect to the horizontal line on the cross section. The maximum residual axial stress in the section is 184 MPa and it is located at 72° from the direction of the impact. The maximum tensile residual stresses occur at the locations where the crack initiation was observed in the failure surface of Fig. 3. Due to the impact, stress concentrations also occur on the surface of the created crater. According to the legend attached in Fig. 4, the blue area between the center of the section and the crater is subject to compressive stresses. This area corresponds with the area where the discontinuity was observed in the failure surface of Fig. 3.

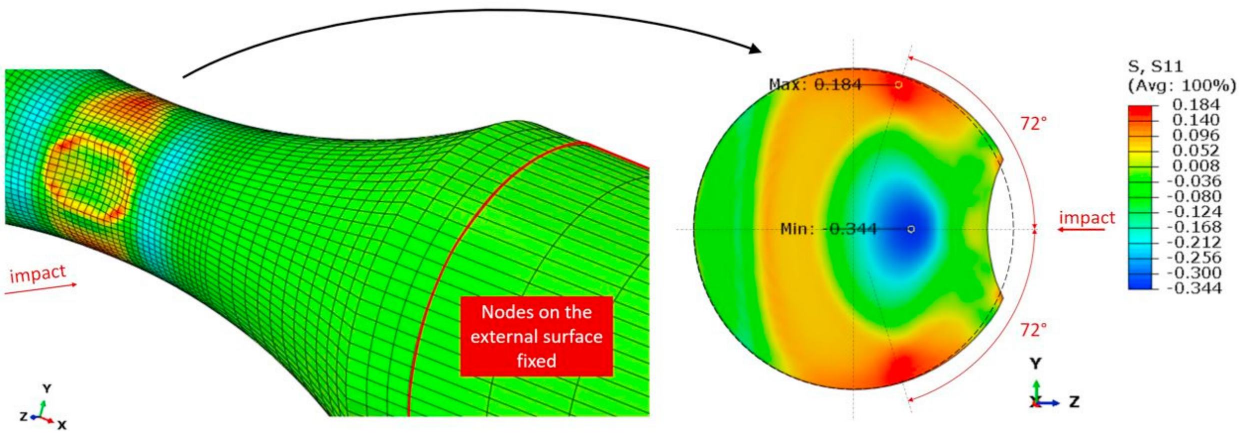

Fig. 4. Residual axial stresses [GPa].

4. Conclusions

The impact of a steel ball on an hourglass specimen was studied experimentally and by FE analysis in order to study the stress distribution in 7075-T6 alloy after FOD. In the experiment the ball was fired perpendicularly to the external surface of the specimen at its middle cross section. Due to the plastic deformation induced by the impact a crater was formed in the specimen. After the impact test, the damaged specimen was exposed to a rotating bending fatigue test until failure. The residual stresses in the specimen introduced by the impact were modelled by using Abaqus Explicit FE code. The locations of high tensile axial residual stresses determined in the numerical analysis correspond to the crack initiation sites observed in the experiment. In the future work, the superposition of bending stresses due to fatigue loading and residual stresses introduced by the impact can be modelled and analyzed. This will enable to identify the areas of crack initiation more precisely.

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