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Microstructural investigation on an Al 6061 T6 alloy subjected to ballistic impact

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Abstract

Ballistic impact generates significant modifications in the microstructural patterns. High strain rate and local high temperature conditions work together in opposite way: the first causes strain hardening, while the second factor produces softening. Moreover, after the impact, the cooling process is responsible of other local modifications on the arrangement of dislocations and precipitates.
Therefore an experimental analysis on Al 6061 T6 cut from the edge of a component subjected to ballistic impact has been carried on in order to investigate on the microstructural modifications. Considerations about the influence on the mechanical behavior and on the fracture propagation are reported. The crystallographic textures and the misorientation featuring the grains play in fact a significant role in the fracture mechanism. The comparison between the texture situation before and after the impact can allow to evaluate the localized straining of the material and to point out its dissipation efficiency as a function of the distance from the damaged surfaces

Keywords: Al 6061 T6 alloy, EBSD analysis, texture and misorientation, areonautical rotor shaft, ballistic impact.

1. Introduction

Projectile impacts in the design of military aeronautic frames and components are critical for the structural assessment. In particular typical helicopter mission is a low altitude flight where wide variety hostilities can compromise the structural integrity. Light weapons are in fact "unfortunately" quite cheap and portable: 7.62 X 51 NATO ball 9.5 g projectiles are of widespread circulation and can be seriously dangerous both for human crew and helicopter parts. The assessment of such components in this extreme case is therefore a key task.

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Although numerical analyses are gaining importance also in this field, experimental tests remain fundamental. High velocity impact phenomena are in fact very complex especially as far as concern the mechanical behavior of the material involved. Large plasticity, high strain rate and local high temperature condition are aspects to be taken in account. The calibration of constitutive law able to replicate these entire features in a reliable way and the further application in a numerical model is still now a very complex challenge [1]. Therefore experimental tests still play a key role both in the structural assessment and especially in the phenomena awareness. As far as concern the characterization of the material behaviour one of the most popular is the Johnson-Cook model [2]. It was developed during the 80's and it has become very popular for ballistic penetration and explosive detonation problems, due to the simple relation of the constitutive equation and the availability of constants used in the equation for a number of materials. Most of the actual models are modification of J-C model. The great advantage of this model is to separate the contributions in the constitutive law. Plasticity, strain rate and temperature act in separate term in the model, therefore could be easy to calibrate the model with specific tests. However in the real case it could be difficult to separate the effects. High strain rate and local high temperature conditions for example work together in opposite way: the first causes strain hardening, while the second factor produces softening. Therefore, in order to investigate on the material modifications during impact an experimental analysis on Al 6061 T6 cut from the edge of a component subjected to ballistic impact has been carried on and presented in this paper. In particular the comparison between the texture situation before and after the impact can allow to evaluate the localized straining of the material and to point out its dissipation efficiency as a function of the distance from the damaged surfaces. The crystallographic textures and the misorientation featuring the grains play in fact a significant role in the fracture mechanism. The shaft under ballistic test consists of a thin-walled cylindrical tube with two TIG welded flanges that allow the positioning of the component in the desired condition (setting the offset and angle with respect to the projectile trajectory). The component is made of aluminium alloy 6061 T6, which is widely used in the aeronautical industry, since it is an excellent compromise in terms of welding technique, corrosion resistance and mechanical properties. Ballistic tests were performed in a dedicated shooting range. The gun used is a very precise tool with micrometrical controls in pitch and yaw that allows a correct and repetitive placement. 7.62 X 51 NATO ball 9.5 g projectiles have been used. Other important parameters that define the impact conditions are the offset and impact angle of the projectile.

- impact angle is defined as the angle between the trajectory of the projectile and the line normal to the generatrix of the tube (parallel to the longitudinal axis) in the impact point, where all the three object (line, generatrix and trajectory) lie in the same plane;
- offset is the distance between the longitudinal axis of the target and the trajectory of the projectile.

Based on preliminary considerations the theoretical worst condition, in terms of damage, has been identified for a shaft subjected to a torsional load. This worst condition, defined as "critical condition", is characterized by an impact angle of 45° and with the projectile surface tangent to the shaft surface: this condition generates a single hole almost elliptical in shape, with axis tilted at 45° and maximum size. More details about the ballistic test are reported in [3].

Experimental procedures

The experimental procedure for the metallographic and texture investigations involves mechanical grinding followed by chemical electro-polishing or chemical micro-etching, in case of, respectively Electron Backscattered Diffraction (EBSD) analysis or Optical Microscopy (OM) observation. After the standard procedure for mechanical grinding, the samples are polished using an aqueous solution of colloidal SiO_2 (0.2 μm), while the electro-polishing is carried out using a Struers Movipol equipment using the following electrolyte composition (Tab. 1). Such treatment is designed to remove the surface oxide layer in order to enhance the backscattered signal emitted by the surface, a crucial requirement for the EBSD analysis. Concerning the chemical micro-etching the authors employ the so called Berker solution, whose composition is reported in the table above.

Table 1. Chemical composition of etchants [4]

Chemical composition of etchant solution				
	H_2O	C_2H_5OH	HBF_4	$HClO_4$
Electro-polishing sol.	500 ml	-	4-5 ml	-
Berker sol.	140 ml	800 ml	-	60 ml

The SEM instrumentation employed for the experimental work is a Carl Zeiss AG - EVO® 50 Series and the rolling direction, RD, taken during the measurement corresponds to the nominal trajectory of the bullets on the shaft (the 45° impact angle), as reported in images below. Moreover, in order to interpretate correctly the EBSD image reported in the following section it is worth to mention the resolution and other crucial parameters employed during the analysis. Specifically, the pixel area of the digital image for the texture corresponds to 7.02 μm^2, the magnification used is 500x, meaning that the EBSD picture includes 740x540 pixels and the working distance of the EBSD probe is 16.5 mm and 20 kVx1 nA is applied.
The Fig. 1 shows the damage configuration caused by the high speed impact produced by the bullet on the rotor shaft surface; the highlighted areas correspond to the sites where the investigated specimens are harvested. Sample #3 and #7 have been taken in the area adjacent to the exit zone of the projectile; this area is affected by compression residual stresses. While sample #4 and #6 have been taken in the area adjacent to the entry zone of the projectile; this area is affected by tensile residual stresses a [5]. Specimen #9 is selected such as reference zone in order to investigate the crystallographic configuration of healthy (far from damage) rotor-shaft.

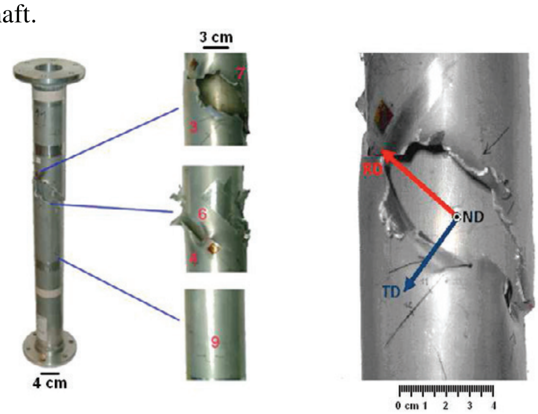

Fig. 1: Image of the whole rotor shaft studied and of the specific areas of interest (on the left), representation of the reference system employed for the EBSD analysis (on the right). RD=Rolling Direction, TD=Transverse Direction and ND=Normal Direction.

Results and discussion

The experimental work involved in this study consists mainly in an investigation concerning the metallographic and texture modifications associated to high speed impact phenomena. The case study considered corresponds to the worst case scenario mentioned in the introduction section, i.e. an impact angle of 45° and with the projectile surface tangent to the shaft surface. The authors wish to provide a thorough description of the deformation events taking place in the surroundings of the induced damage. Thus, the work collects a detailed analysis on the different parts of the rotor shaft under study by means of optical microscopy and SEM-EBSD (Scanning Electron Microscopy-Electron Back Scattered

Diffraction), followed by a observed textures comparison in order to define the deformation related exclusively to the damage in the zone affected by the bullet impact and passage.

The early stage of the work concerns microstructure investigations obtained by direct observation of the micro etched sample surfaces (Fig. 2). The microstructure on the edges of the damage features more elongated grains in the impact direction, while moving away from the fracture the grains appears to be randomly dispersed. Thus, it is safe to assume that such deformation is directly related to a dissipation phenomenon of the propagation stress, as the deformation is exclusively related to the rim of the damage. The comparisons among undeformed grain and the ones near the damage surfaces point out a significant deformation.

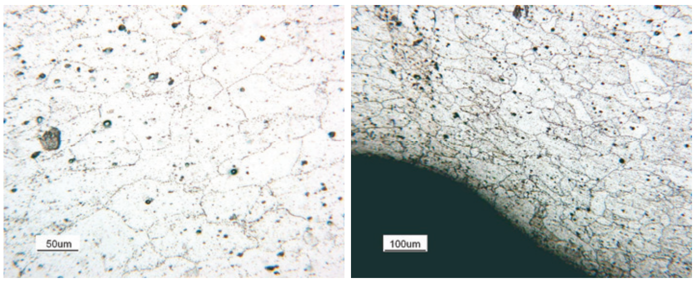

Fig. 2: Micrographies of (a) undeformed structure (#9) and (b) edge of damaged area (#3)

Further analysis by means of EBSD provides a closer look to the actual grains distribution allows to explore the orientation distribution and the specific misorientations for the grains related to the different parts of the rotor shaft. Specifically, the EBSD investigation includes a survey and elaboration of the diffraction, ODF and polar images retrieved from the experimental analysis. The following EBSD images reports the observed textures for both undeformed areas (far away from the damage) and edges of the damage.

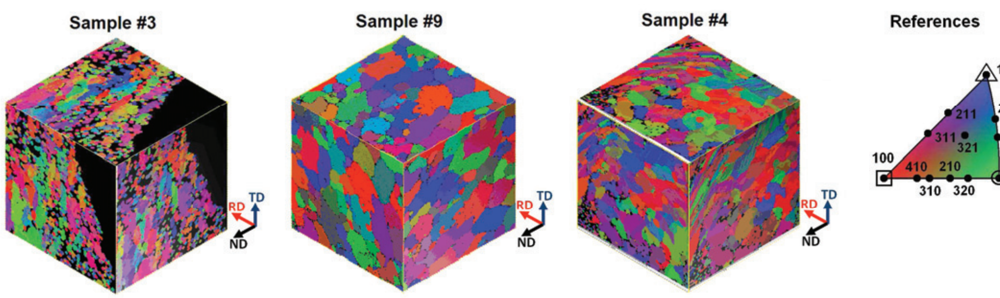

Fig. 3: Diffraction images along the three directions, normal, rolling and transverse of samples #3,#9,#4.

As evident from comparing the images for the different conditions, the areas not affected by the ballistic damage differ quite a bit from the edges of the fracture (Fig. 3). Specifically, the specimens harvested from areas distant from the damage indicates a quite isotropic orientation distribution, i.e. the diffraction images shows a wide dispersed range of orientation and the inverse polar pictures do not indicate any preferential direction (Fig. 3,#9 and Fig. 4, #9). On the other hand, the EBSD analysis on the area close to the damage produces diffraction images where the grains on the rim presents a quite precise and intensive rotation along the propagation axis (see the grains featured by a purple and brown colours on Fig. 3, #3 along RD direction). This observation is further confirmed by the inverse polar images, which describe a structure featuring few defined orientations (Fig. 4, #3). Therefore, it is safe to conclude that, as observed by means of optical microscopy, the damage causes a transition from an isotropic dispersion to a narrower range of preferential directions aligned along the damage surface, i.e. <$\underline{1}$13>, <$\underline{1}$15>, <$\underline{1}$17> and <001>. There is a significant difference between the strong orientation of the larger grains pointed out by EBSD maps and the smaller ones that show a more heterogeneous situation: this is due to the fact that the small grains are produced by the recrystallization process that takes place in presence of high strain, strain rate and temperature interesting the fracture region. Moreover, it is worth to highlight the rapid decrease in deformation extent detected by the EBSD analysis as the distance from damage increases. Such phenomenon is directly related to the specific failure modality occurred on the shaft, in fact the high speed impact of the bullet involves intensive, but localized stress field, which determine a strong, but narrow deformation extent. Thus it is possible to conclude that the alloy show a good ductility and is very prone to deformation in the impact region, but it is also interested by very high deformation gradient, because the grains of the fracture surface have been reoriented strongly while at about 200μm form the surface the deformation seems to disappear.

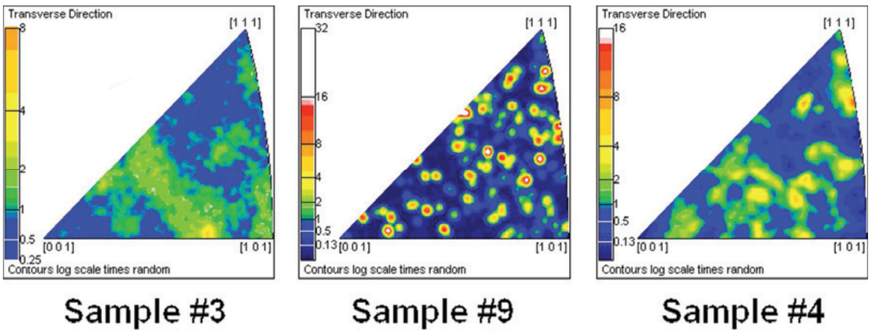

Fig.4: Inverse polar figure, respectively in the region undergoing tensile stress, undeformed region, then the one undergoing compression one.

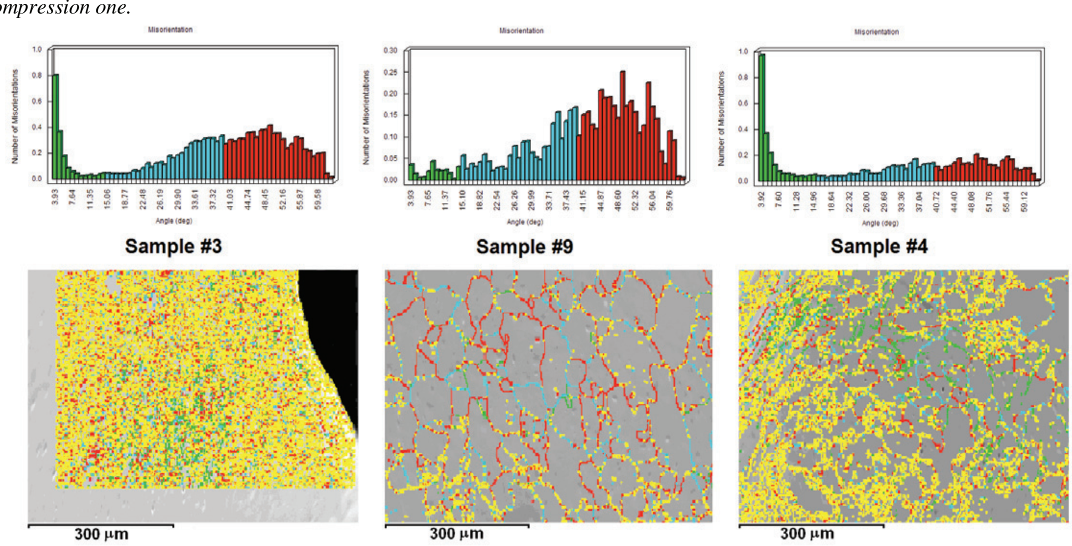

Fig. 5: Misorientation distribution of the different areas of the rotor shaft examined.

The comparison among the grain boundary misorientation featuring undeformed region and the one deformed by bullet impact points out that after the impact the angle of misorientation between the different grains is strongly lowered toward low boundary angles (lower than 15°) (Fig. 5). The increase of

the number of boundary featured by low misorientation (Fig. 5, #3 and Fig. 5, #4) constitutes a very favourable pattern for the successive propagation of a fatigue crack, because it is known that fatigue cracks do not recognize low angle of misorientation as grain boundaries that can constitute obstacle to surface propagation [5,6]. Fatigue crack can nucleate and growth on the edge of the damage during application of spectrum load representative of a recovery mission of the helicopter after the damage [7].
The zone interested by tensile residual stresses, #4, shows a more distributed textural situation (Fig. 4, #4) indicating that a higher number of deformation pattern have been activated as shown by less intense alignment of the grains along particular fibre, while the grains of the region subjected to compressive stress, #3, tend to concentrate in a narrow textural pattern (Fig. 4, #3). This implies that during an eventual successive loading the compressive residual stresses regions, #3, are featured by a lower attitude to dissipate the provided work. This conclusion is further confirmed by another EBSD analysis conducted by the same authors on mechanical test specimens subjected to different load conditions [8].

Conclusions

As stated previously, the work deals with an EBSD survey on a helicopter rotor shaft subjected to the ballistic impact. From the experimental results it has been possible to draw the following conclusions:

- ✓ the fracture process determines a strong orientation along the propagation direction of the grains close to the edges of the ballistic damage;
- ✓ the high deformation gradient observed moving away from the damage can be referred to the ballistic dynamics and to a significant ductility featured by the material. Moreover, also the larger orientation distribution of the smaller grains detected on the edges of the damage can be pin on the high strain, strain rate and temperature associated to the impact of the bullet, which triggered a recrystallization of the lattice.
- ✓ parallel to this, the comparison of the misorientations featured by the undeformed areas and the ones interested by the ballistic impact yields a decrease in boundary angles values (lower than the 15° limit), allowing an eventual crack (nucleated on the edge of the ballistic damage) to proceed undisturbed through the grains boundaries.
- ✓ the bullet inlet and outlet, to which correspond respectively, a compressive and tensile residual stress field, show different deformation features. Specifically, the compression determines a narrower orientation dispersion than the tension, implying a lower energy dissipation efficiency for successive loadings.

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