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Anisotropy of impact toughness of Ti-6Al-4V alloy joints processed by linear friction welding

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Drop weight tear tests (DWTTs) of joints of Ti-6Al-4V alloy obtained by linear friction welding (LFW) were carried out. The specimens had a square cross-section with a U-shaped notch, which was set parallel (parallel notch) or perpendicular (perpendicular notch) to the direction of frictions during LFW (welding direction (WD)). The impact toughness and the fracture morphology were assessed. The specimens with the parallel notch have a 15% higher impact toughness than the ones with perpendicular notch. The widths of the side slopes of the fracture surfaces in specimens with the parallel notch were significantly larger greater than those in specimens with the perpendicular notch. A characteristic feature of the deformation diagrams for specimens with the parallel notch is the presence of two local maxima. This contrasts with the force change curve for the perpendicular notch specimens. The different types of fractures, the nature of the force change during DWTT, as well as the different impact toughness values of titanium alloy Ti-6Al-4V specimens obtained by the LFW method can be explained by the effect of textural hardening due to the formation of a sharp crystallographic texture of the α-phase in the weld. For the perpendicular notch specimens, the basal-plane texture strengthens the lateral surfaces. The latter leads to a decrease in local narrowing and plastic deformation of the overal bending. For the specimens with the parallel notch, the prismatic-type texture favors plastic deformation of the areas near the lateral surfaces. The basal-type texture in the notch center hinders plastic deformation.

Keywords: titanium, Ti-6Al-4V, linear friction welding, impact toughness, anisotropy.

1. Introduction

Impact tests for evaluating the properties of welded joints are widespread and belong to one of the main types of tests. The impact toughness is an important performance characteristic of welded structures. There are many publications on the study of the impact toughness of titanium alloy joints made by fusion welding [1–8]. However, the impact toughness of friction welded joints is less studied [9–12].

During LFW, two workpieces are fixed in clamping devices of a welding machine and pressed against each other with a certain force. One of the blanks is motionless, while the other carries out a reciprocating motion (vibration) of a certain frequency and amplitude (Fig. 1). In the process of close contact friction, intensive heating of the near-contact layers of the material of both workpieces occurs. The resistance to deformation of a metal decreases abruptly, and the plastic material is squeezed out of the joint with the formation of flash. Upon reaching the required degree of upsetting, the vibration is stopped, heat generation stops, and the final formation of a solid-phase bonding occurs [13–15].

The present paper aims at a study of the impact toughness of specimens of joints of Ti-6Al-4V alloys processed by LFW in order to understand the differences of this characteristic for different orientations of a notch.

2. Experimental procedure

The widely used titanium alloy Ti-6Al-4V was used as the material for specimens. Workpieces with a cross-section of 11.0 mm×11.0 mm and a length of 37 mm were welded on a laboratory LFW machine [16]. Four specimens were welded according to the following mode: frequency 35 Hz, amplitude 2 mm, welding time 4 seconds, welding force 2.4 kN.

After the welding of specimens was done, the side faces of specimens were deburred and grinded. The impact bending tests were conducted on specimens with a U-shaped notch (concentrator) made on the welded joint. The depth of the notch and the radius of its end were 2 mm and 1 mm, respectively. Before making the notch, the bonding zone was determined by macro-etching. On two specimens, the notch was oriented along the transverse direction (TWD), i.e. perpendicular to the direction of vibration (WD). On the other two, the notch was oriented parallel to the direction of vibration (WD) of the movable workpiece during LFW (Fig. 1).

The experiments were conducted on a vertically falling weight impact testing machine "Instron". The impact speed of the striker was 4.46 m/s, the mass of the striker was 15.078 kg, and the impact energy was 150 J.

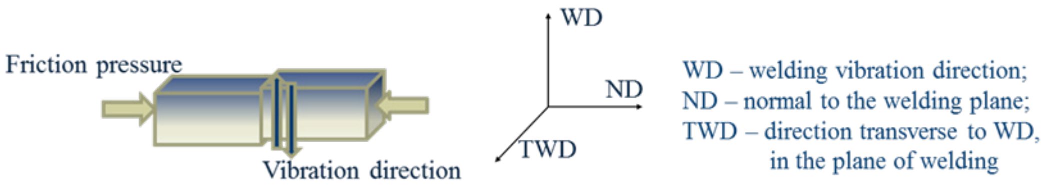


Fig. 1. Scheme of linear friction welding.

3. Results and Discussion

Table 1 shows the values of the impact toughness of joints determined by DWTT.

Table 1. Impact toughness values of specimens.

Specimen no	1	2	3	4
Notch orientation	|| WD	⊥ WD	|| WD	⊥ WD
a_k, J/cm^2	71	60	68	60
Plastic deflection, mm	1.9	1.3	1.8	1.1

Specimens with the parallel notch (see specimens No. 1 and No. 3) have 15% higher impact toughness values a_k than with the perpendicular notch specimens (see specimens No. 2 and No. 4).

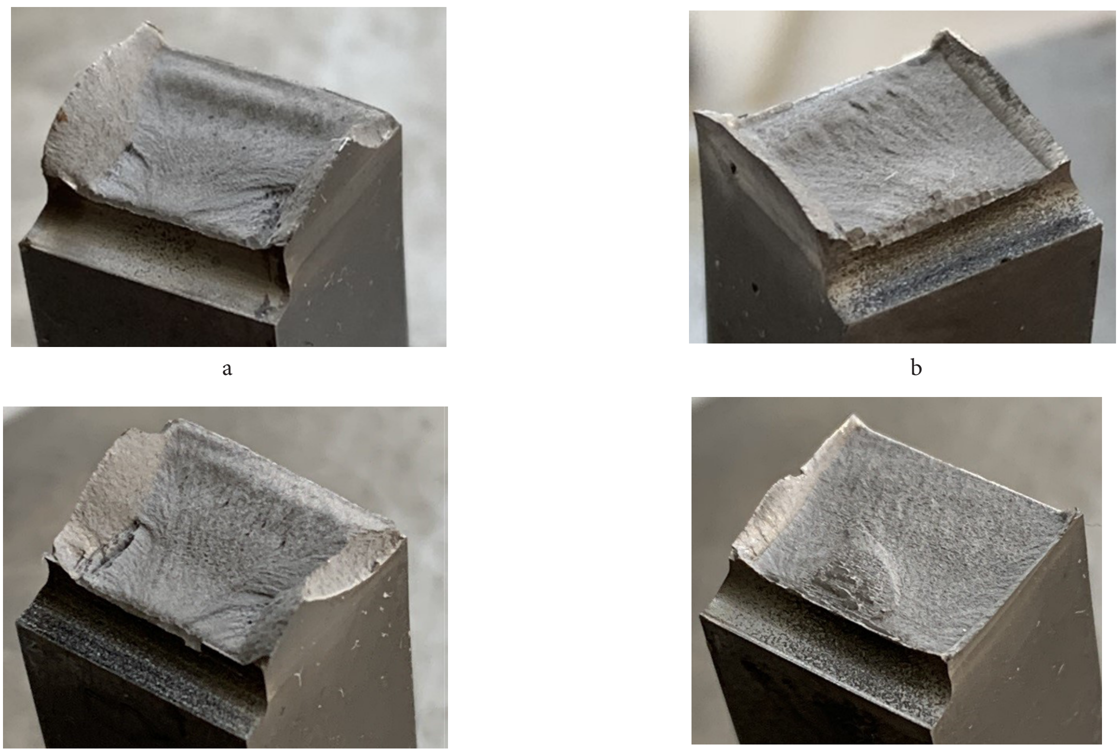
The views of fracture surfaces of the broken specimens are shown in Fig. 2.

The widths of side slopes of fracture surfaces in the parallel notch specimens No. 1 and No. 3 turned out to be significantly larger than those in the perpendicular notch specimens No. 2 and No. 4. In specimens No. 2 and No. 4, fracture initiated adjacent to the notch in its central part. The ridges resulting from shear failure are parallel to the direction of the notch. Specimens No. 1 and No. 3 have two clearly expressed corner centers of fracture, located on the border between the lateral slope and the "fragile square". Here, the shear ridges are oriented almost perpendicular to the notch. There is also a third focus of destruction adjacent to the notch between these two corner foci.

We note that the centers of destruction in all tested specimens are in the central zone of the weld.

Fig. 3 displays the curves of the force change depending on the deflection during the DWTT for specimens No. 2 and No. 3 (the diagrams for specimen No. 1 is similar to the one for specimen No. 3, and the diagram for specimen No. 4 is similar to the one for specimen No. 2).

The initial stage of the deformation diagram of specimen No. 2 (as well as of specimen No. 4) displays a rapid change in the force within the elastic deformation range. Then the plastic flow begins. During this stage, the nucleation of the main crack occurs. Next, the crack displays stable growth and rapid breakthrough with further fracture and shearing of the side slopes.



a b c d

Fig. 2. (Color online) Fracture surfaces of welded specimens with different orientations of the notch relative to the direction of vibration of the LFW: spec. No. 1 (a); spec. No. 2 (b); spec. No. 3 (c); spec. No. 4 (d).

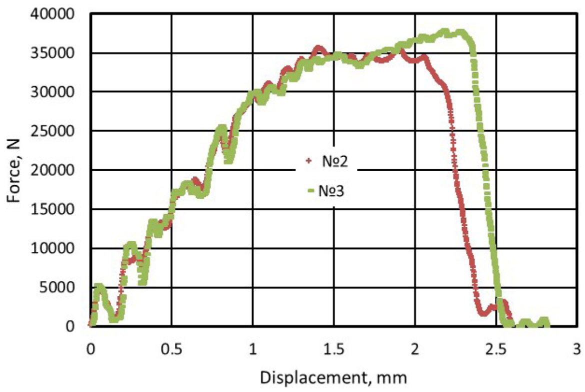


Fig. 3. (Color online) The force change depending on the deflection during DWTT. Curve No. 2 — the notch is perpendicular to the direction of vibration (WD); Curve No. 3 — the notch is parallel to the direction of vibration (WD).

A characteristic feature of the deformation diagrams for specimens No. 1 and No. 3 is the presence of two local maxima. After the first maximum of about 35 kN, which corresponds to a deflection of approximately 1.5 mm in Fig. 3, the force starts slightly decreasing. Then an almost linear increase in the force to 37.5 kN occurs followed by a small section with little changing and further decreasing force. Finally, there is a sharp drop of force (breakdown).

The difference in results for different orientations of the notch can be explained as follows. It is known that a sharp texture of the α-phase is formed in the weld zone during LFW of titanium alloy Ti-6Al-4V [17,18]. In the plane perpendicular to the transverse direction (TWD), the texture is characterized by the predominance of the component $(000\bar{1})\langle 11\bar{2}0\rangle$ (Fig. 4). The origination of a crack is preceded by plastic deformation, which manifests itself as a local narrowing of the sample near the bottom of the notch. Plastic deformation during bending is distributed unevenly and is concentrated mainly in the surface layers [19]. The notch creates a multiaxial stress state. It is biaxial near the lateral surfaces of the sample and triaxial in the central zone. Biaxial tensile yield strength is higher than uniaxial one. In addition, for metals with a hexagonal close-packed lattice, the effect of textural hardening is characteristic when the basal plane is parallel (or close to being parallel) to the plane of principal tensile stresses [20]. This leads to an increase in the yield stress, since slip deformation in the direction of the "c" axis of the hexagonal lattice is difficult.

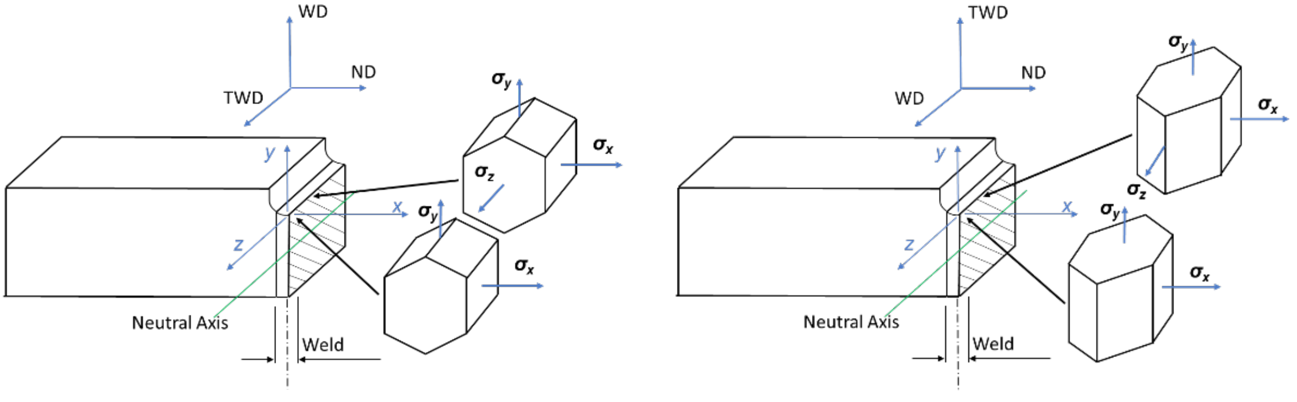
The different types of fracture surfaces, the nature of the force change during DWTT, and the different impact toughness values of titanium alloy Ti-6Al-4V specimens obtained by the LFW method can be explained by the crystallographic texture of α-phase.

For the specimens with the perpendicular notches (Fig. 4a), the basal-plane texture strengthens the lateral surfaces. The latter leads to a decrease in local narrowing and plastic deformation of the overall bending and the initiation of the main crack occurs near the center of the notch.

For the specimens with the parallel notches (Fig. 4b), the prismatic-type texture favors plastic deformation of the areas near the lateral surfaces. The basal-type texture in the notch center hinders plastic deformation and crack initiation due to textural hardening. This largely explains the nature of the change in the force during DWTT. The first local maximum of the force corresponds to plastic deformation and the initiation of two internal semi-elliptical cracks near the side surfaces. However, these cracks have an orientation unfavorable for their growth: the semi-minor axis is directed along the notch. In addition, plastic deformation in these zones reduces the stress concentration with a redistribution of stresses to the center of the notch. Therefore, these cracks do not develop further. An increase in the force occurs that leads to plastic deformation and the initiation of the main crack now in the central part of the specimen under the notch. The latter further leads to the destruction of the specimen. This manifests itself in the form of a second maximum in the force change diagram during DWTT.

Thus, the anisotropy of the impact toughness of joints obtained by LFW is mainly associated with the texture-related difference in the stress of the yield point in different zones of the specimen under the notch.

A comparison of the macro-fractures (Fig. 2) and the nature of the deformation curves (Fig. 3) after DWTT also indicates that the parallel specimens are characterized by a harder to achieve the main crack initiation, that easily propagates.



a b

Fig. 4. Scheme of the relationship between the deformation and the α-phase crystal texture of the welded joint near the notch during bending. the perpendicular notch (a), the parallel notch (b).

4. Conclusions

The joints of Ti-6Al-4V alloy processed by LFW exhibit an anisotropy of impact toughness. Specimens with a notch parallel to the welding direction have a 15% higher impact toughness than the specimens with perpendicular orientation of the notch.

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