A Method For Determining The Residual Stresses Induced During A Modified Version Of Friction Tapered Plug Welding Process In Aluminium Alloys

Mohamed Harraz[1] Brando Okolo[2]
[1,2] Faculty of Engineering and Material Science
[1,2] German University in Cairo, Cairo, Egypt

Abstract— in this work a method for determining the residual stresses induced at the center and around a modified friction taper plug welding (FTPW) process in aluminium alloys is introduced. The strategy developed in this work depends on the principal idea of the hole-drilling method (HDM). Basically, the hole-drilling method relies on measuring the stress relaxation when material is removed by a hole that is drilled into the center of a rosette strain gauge. From the measured magnitude and direction of the strain relaxation, principal residual stresses can be calculated. In this approach the FTPW is modified such that the tapered plug is being removed by pushing it out from the other side after being friction welded into the material. The extent of the strain relief is monitored by three gauges placed around the welded plug during the push-out test and therefore the direction and magnitude of the principal stresses can be calculated. The result of the analysis of residual stresses induced during the FTPW shows a clear correlation to the result of the push-out test and therefore gives an in-depth understanding of the effect of the modified FTPW process on the material surrounded.

Key words: residual stresses, friction tapered plug welding, push-out test, aluminium.

I. INTRODUCTION AND STATE OF THE ART

Residual stresses are those stresses that remain in a material or body after manufacturing and processing in the absence of external forces or thermal gradients. In most of the thermal welding processes, the creation of residual stresses in and around the weld zones is obvious. Those stresses are noticed to influence the joints mechanical properties for example creep or fatigue. Although very few investigations were done to calculate the residual stresses of the joints resulting from novel friction welding processes, experimental studies on friction stir welding for example has shown that that like other welding processes, residual stresses also evolve and affect the fatigue life and other mechanical properties of the friction welded joints [1, 2].

Friction tapered plug welding (FTPW), which is also referred to as friction taper stud welding (FTSW) is a solid-state welding process developed by The Welding Institute (TWI) during the 90s from the concepts of friction hydro pillar processing (FHPP) [3]. The method was further developed as a repair welding technique, in which initial defective weld material is located, removed by drilling a tapered hole through the defect and replaced by a tapered plug, which is friction welded into place [4]. In all the former friction welding techniques the process is terminated by the sudden braking of the rotating stud or plug after complete welding is perceived, and then followed by a machining process to remove the rest of the stud or plug protruding from the weld. The current work focuses on a modified version of friction taper plug welding process which is relatively similar to the newly developed so-called filling friction stir welding (FFSW) [5], but is referred to as friction hole welding (FHW) in this manuscript. This process also entails driving a tapered pin into a tapered hole, to produce the frictional heat necessary for the welding process. The resistance built along the shaft of the tapered pin however causes breakage, leaving a portion of the pin in the hole. Here a notch is deliberately introduced at the neck of the tapered pin to assist the breakage process. The notch is precisely optimized to ensure that the pin rotates only long enough to induce a metallurgical bond before breakage at the surface of the defect component and that only the amount plastic flow needed to cause bond formation is realized. Fig. 1 is a schematic drawing showing the concept of the FHW process.

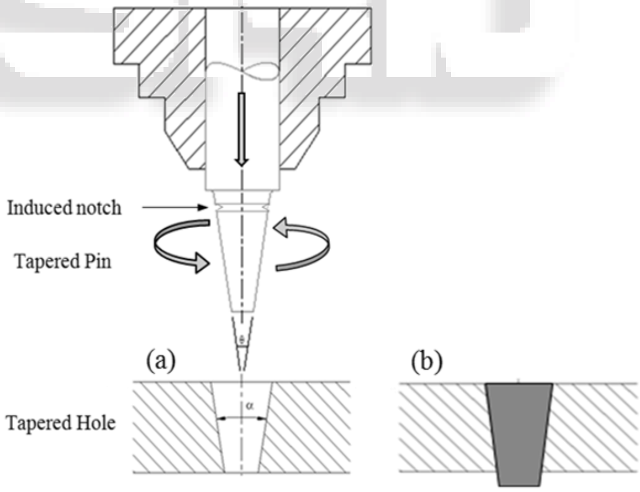

Fig. 1: Schematic drawing of FHW process before (a) and after (b) welding

Existing studies on friction hole welding shows that there are correlations between the welding parameters and material state on the one hand and the quality of the welded zone on the other hand [6]. The rotational speed of the tapered pin and the size of the induced notch, for instance, directly influence the structural integrity at the pin interface [7]. Apparently, many studies were conducted to analyses the microstructure as well as temperature distribution of the former friction welding processes , but the residual stresses associated with this new friction welding approaches are still barely understood [8,9]. In this investigation the hole-drilling method is being used to calculate the residual stresses evolved during the novel modified version of the FTPW. Hole-drilling strain-gage method of stress relaxation is one of the most widely used modern techniques for measuring residual stress. It is relatively simple and has been standardized in ASTM Standard Test Method E 837 [10]. Here the introduction of a hole (of a very small diameter) into a residually stressed body relaxes the stresses at that location. This occurs because every perpendicular to a free surface (the hole surface, in this case) is necessarily a principal axis on which the shear and normal stresses are zero. The elimination of these stresses on the hole surface changes the stress in the immediately surrounding region, causing the local strains on the surface of the test object to change correspondingly. This principle is the foundation for the hole-drilling method of residual stress measurement, first proposed by Mathar [11]. The measurement of the stress relaxation is done through a special type of rosette strain gauge like the one shown in Fig. 2. The geometry of such rossette conforms to the early Rendler and Vigness design [12].

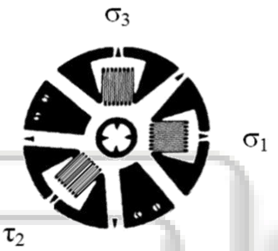

Fig. 2: Residual stress strain gauge rosette

II. EXPERIMENTAL PROCEDURE

Experimental investigations were carried out to test and verify the method for calculating the residual stresses induced during the modified version of the FTPW. Before beginning with the tests six samples of aluminium plates AW-2007 10 mm thick were cut out with the dimension 50x50 mm each. These samples are divided into two sets with three samples each. For each two samples the pin is welded exactly at the center with 500, 630 and 800 RPM respectively and with the same welding conditions. Table 1 shows the types of tests performed on each set of samples.

Set	Type of Test performed	Welded pin speed [RPM]		
		S1	S2	S3
Set A	Residual stress calculated at the center of the welded pin by HDM	500	630	800
Set B	Residual stresses calculated around the pin during push-out test	500	630	800

Table. 1: Types of tests performed on each sample

The tapered pins which are made of wrought aluminium AA6061 were prepared with a taper angle of 8° and were 15 mm long with a 0.2 mm notch placed at a distance of 12 mm from the bottom of the pin to allow a protrusion distance of at least 2 mm at the lower surface of the aluminium plate after welding. Fig. 3 shows a schematic drawing of the shape and size of the tapered pin.

During the first investigation the strain relaxation is measured and thus the residual stresses calculated at the center of each pin after being friction welded at the centers of the first set of samples. The other three samples are welded with the same experimental conditions for the second investigation. Three strain gauges are placed during a push-out test using the same design orientation of gauge rosette shown in Fig. 2.

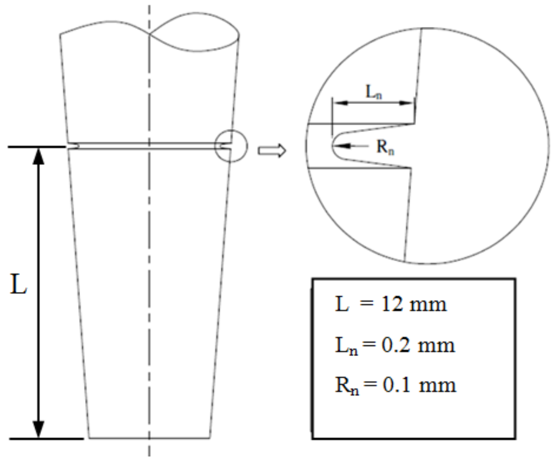

Fig. 3: A schematic drawing of the shape and size of the tapered pin.

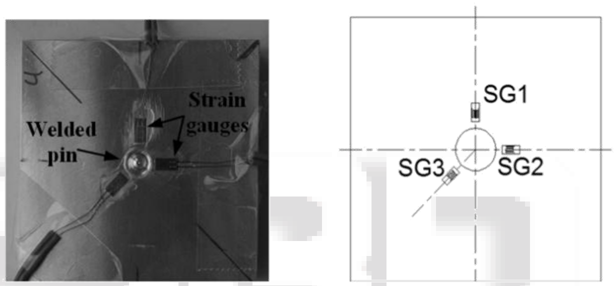

Fig. 4: Samples preparation with strain gauges around the welded pin

The strain gauges are fixed at a radius distance of 5 mm from the center of the welded pin. Fig. 4 shows the orientation of the strain gauges placed at equal distance to the center of the welded pin. After that the samples are turned upside down, and the welded pins are pushed from the other side while monitoring and measuring the material relaxation concurrently during and after the push out test. From the data obtained, the size and direction of the residual stresses can be precisely calculated [13]. Fig. 5 shows an illustration of the push-out test as performed during this experimental study.

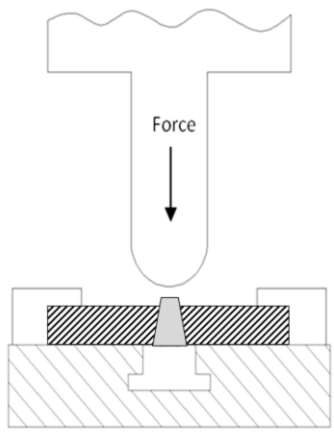

Fig. 5: Push-out test as performed during this study

III. RESULTS AND DISCUSION

Although the rotational speed had proven to have a direct influence on the quality and therefore the bonding integrity of the weld produced [6], there was no big difference in stress analysis between the three samples investigated. For this reason and for convenience the analysis shown here is for one sample only as the rest of the samples have shown similar results for strain measurements. For calibration measures the hole-drilling method was first performed on the aluminium plate in a location far away from the zones affected by the friction hole welding process. Fig. 6 shows the result of the stress analysis outside the welding zone on the base material. For practical reasons the first strain gauge readings for 0.2 mm depth can be conveniently ignored due to surface error of the drilling tool of the hole-drilling method [10]. It is clear from the stress calculations that are based on the strain gauge readings that the values of the stresses are so low ranging from -2 to 7 MPa which is considered stress free material.

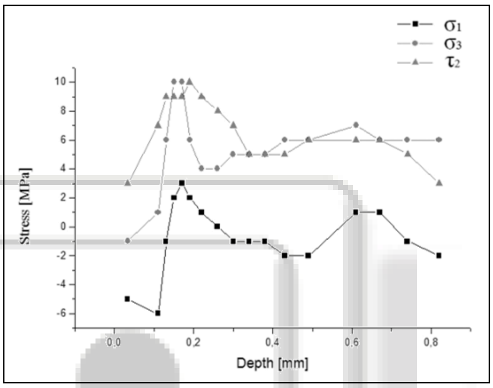

Fig. 6: Stress analysis outside the weld-zone on the base material

Secondly the results of samples prepared in such a way as shown in Fig. 4 have proven a correlation between the stresses calculated during the push-out test and the stresses induced at the center of the three samples investigated. During the push-out test the three strain gauges which are placed around the welded pin read a relaxation of +260.7µm/m, +253.8µm/m and +170.4µm/m respectively. As first indication this can be interpreted to a negative stress value which indicates a compressive stress value of 29.5 MPa. During further calculations it is implicitly attributed that this value of compressive stress is increased when moving towards the center until reaching a maximum value of about 120 MPa at the center of the welded tapered pin.

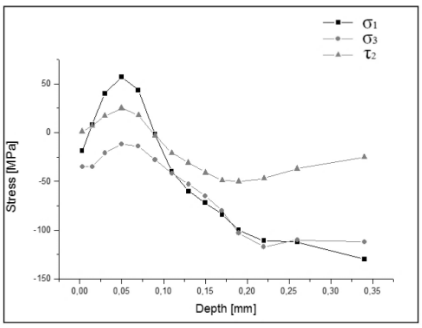

Fig. 7: Stress at the center of a welded pin

On the other hand Fig. 7 shows the results of stress analysis at the center of a welded pin that is being friction welded with the same welding conditions of the previous sample used in the push-out test.

It is clear from the calculated measurements and after ignoring the readings of the first 0.20 mm depth, that the pin is subjected to compressive stresses that is varying with the depth and ranging from 100 to 125 MPa.

IV. CONCLUSION

The welded pin is mainly subjected to compressive stresses, which increases with the depth ranging between 100 to 125 MPa. The rotational speed did not have a big influence on the size nor the type of residual stresses induced. The reaction of the strain gauge here gives an indication of the previous residual stresses present around the pin. The positive reading of the strain gauge indicates that base material was exerting compressive stresses on the pin after the friction hole welding process. As the pin is removed the material has more space to relax causing tension towards the centre of the pin. The difference in the strain gauges readings for the same sample indicates that the material behaves anisotropically, and is also attributed to the human error in fixing the strain gauges at exactly the same center distance to the pin. However, the results obtained during the push-out test match the previous results of calculated residual stresses using the hole-drilling method. This investigative methodology reiterated its validity for calculating and analysing the values and type of residual stresses induced during and after the friction hole welding process and therefore gave an in-depth understanding of the effect of FTPW process on the material surrounded.

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