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EXPERIMENTAL STUDY OF FATIGUE LIFE AND RESIDUAL STRESSES AFTER FRICTION STIR HOLE EXPANSION IN ALUMINUM ALLOY D16AT

Abstract: *This paper presents the outcomes from experimental study of fatigue life and residual hoop stresses after Friction Stir Hole Expasion (FSHE). FSHE is directed to fatigue life enhancement of structural components with holes in aluminum alloys. The object of study is high-strength aluminum alloy D16AT. The fatigue life has been estimated trough fatigue tests upon a testing machine Instron -1332. The residual hoop stresses after FSHE have been measured by non-destructive method X-ray diffraction. The outcomes obtained confirm that the FSHE process is more effective when it is implemented with a relatively smaller rotating speed with lubrication.*

Keywords*: Friction Stir Hole Expansion, experimental study, aluminum alloy D16AT; fatigue tests, residual hoop stresses*

INTRODUCTION

The damages and accidents caused by fatigue cracks around riveted and bolted holes are typical for the structural components in aircraft structures. Such natural stress concentrators are the numerous holes in the fuselage, wings and others. Due to the vibration, first-mode fatigue cracks are mainly propagated, as the crack tip grows in a radial direction with respect to the hole surface [1, 31]. Therefore the physical-mechanical state of the material around the holes, which are natural stress and strain concentrators, determines the strength resources of the structural elements. An effective approach to locally enhancement of the material quality characteristics is cold working. As a prevention against nucleation and propagation of first mode fatigue cracks, the conception “cold hole expansion” has been developed [3-10], which is implemented by means of several methods. A key point in the concept is the idea for performing of volume plastic deformation around the predrilled holes in order to generate residual hoop macro-stresses around these holes. After termination of the external impact, respectively after passing in the elastic equilibrium, the residual macro-stresses are equilibrated in the whole volume of the corresponding structural component. Because of that, the intensity of the internal forces in the new elastic equilibrium is assessed in terms of the mechanics of the continuous medium, i.e. of macro-level, although the actual interaction is of micro- and meso-level. In this aspect the so-called macro-approach to increasing fatigue life of metal structural members with holes is justified in [11]. In view of the nature of first-mode fatigue cracks, the effectiveness of the generated zone with beneficial residual stresses around the holes depends to a large extent on the residual stress distribution in qualitative and quantitative aspects. That is why the main contribution in the equivalent plastic deformation ε_{ekv}^{pl} $(4-5\,\%)$ has the hoop linear strain $\varepsilon_{t,0}$ in the points from the hole surface, which is numerically equal to degree of cold expansion (DCE):

$$DCE=\varepsilon_{t,0}=\frac{d_t-d_0}{d_0}=\frac{i}{d_0}\times 100,\% \qquad (1)$$

where i is the interference fit, d_t is the diameter of the tool working part, d_0 is the diameter of the previously drilled hole. The effectiveness of the macro-approach is determined by the intensity and depth of the field with residual hoop compressive stresses. If sufficiently intense compressive zone of relatively great depth (up to several millimeters) is created, it acts like a bracket and repeatedly slows the nucleation and propagation of the first-mode fatigue cracks (Fig. 1). In order to minimize the temperature factor, the process is fulfilled at a temperature lower than the temperature of re-crystallization of the respective metal and the strain velocity is limited up to $\dot{\varepsilon}=1\times 10^{-4}\div 1\times 10^{-3}, s^{-1}$ [11].

From the methods implementing the conception “cold hole expansion”, chronologically the methods Ball Cold Working and Mandrel Cold Working [12] have firstly arisen. At these methods the impact is directly on the surface of the previously drilled hole by means of spherical or conical-cylindrical mandrel passing thoroughly along the hole axis with ensured interference fit.

In the aircraft industry, the methods Slit Sleeve Cold Expansion [13-15] and Split Mandrel Cold Working [16, 17] have found largest practical implementation, since they require one-sided access to the hole being treated. Regardless of differences in the details, their practical implementation is generally subject to one and the same concept - special mobile devices with hydraulic drive are utilized and hole processing practically corresponds to a dimensional process. As a consequence, the manufacturing cycles consist a large number of operations and considerable part of them is operations for control of the previously drilled hole, as well as of the tool working parts. The large number of operations and the need for well-trained operators increases the cost of treatment. On the other hand, for all the methods in which the cold expansion is implemented by tool, passing through the hole end to end, support has to be used. The reason is the axial force flow that closes through the plate (detail) and the seat, which is part of the device [6, 11]. Thus, the cold expansion process is physically limited to a plastic deformation wave, which is moved along the hole axis together with the moving tool. Due to the tangential forces along the hole axis, the stress tensor for the points near the hole surface will contain tangential (shear) stresses in the plane rz (Fig. 2).

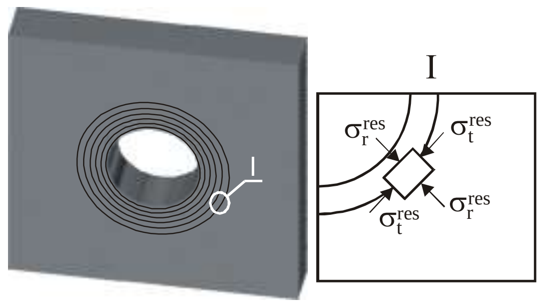


Fig. 1 – Effect of the zone with compressive residual macro-stresses around the holes

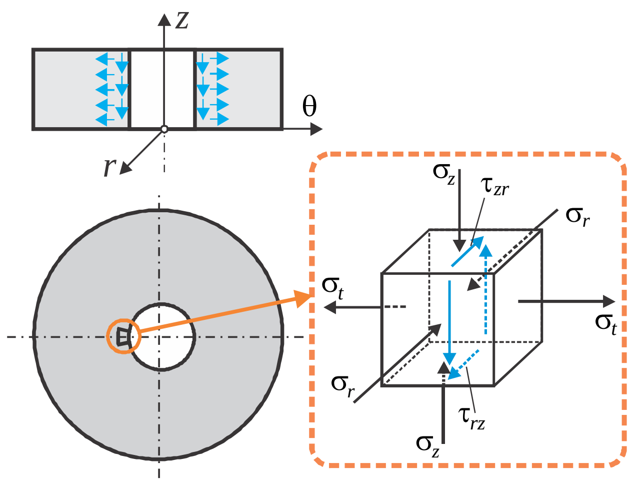


Fig. 2 – Stressed state for the methods, for which the cold expansion is carried on through translationally passing tool

As a result, axial gradient of the residual stresses is obtained in the axial direction and often on the entrance face around the hole (in terms of movement) undesirable ring of residual tensile stress is obtained. As a result, the likelihood of corner fatigue cracks significantly increased. The described disadvantage is typical and for the most common methods Split Sleeve Cold Expansion and Split Mandrel Cold Working.

As a counterpoint of the described shortcoming the patented Symmetric Cold Expansion method [18] has been developed, at which method the impact on the hole surface is only in the radial direction. As a result, a symmetric zone with beneficial residual compressive stresses with respect to the middle plane of the plate is obtained, i.e. the axial stress gradient is minimized [19-21]. Regardless of the shorter technological cycle and opportunities for control of the degree of cold expansion DCE, the method Symmetric Cold Expansion also requires hydraulic power device.

In this aspect the following idea is of interest: developing a method for increasing the fatigue life, which method to be implemented on conventional machine-building equipment, without requiring skilled technicians. Obviously, such an approach requires kinematics based on rotation of the corresponding tool. An appropriate basis for this is the modification of the Mandrel Cold Working method by means of including of an additional rotation of the tool (conical-cylindrical mandrel) around the axis of the previously drilled hole. In the presence of a guaranteed interference fit between mandrel working part and the predrilled hole, the treatment is implemented in conditions of tangential contact between the tool and the hole surface in axial and in circumferential direction as well. This formulation is appropriate for achieving of equivalent severe plastic strain ε_{ekv}^{pl} immediately around the hole surface, the formation of which the tangential (shear) stresses have major contribution. This conception is known as “Severe Plastic Deformation” [22]. Severe plastic deformation is a basis for achieving of beneficial modification of the material micro-structure, expressed in refining grains, reducing the pores in the material and homogenization of the structure. The refining micro-structure is physical basis for enhancement of material fatigue strength [23-25] and reaching of an exceptional plasticity (super plasticity) [26]. Because of that, this approach to enhancement of fatigue life is called in [27] “micro-approach”.

A contemporary conception based on “Severe Plastic deformation” is Friction Stir Processing (FSP) directed to aluminum alloys [28, 29]. FSP has a thermo-mechanical nature since due to friction forces and the provoked large volume plastic deformation, a heat is generated in the contact field between the tool and material being processed. A distinctive feature of FSP is the high strain velocity: $\dot{\varepsilon} \geq 1 \times 10^{-2}\ s^{-1}$. The purpose is achieving of Stir effect – intensive plastic deformation at high temperature which is physical basis for full material re-crystallization [28]. Apparently, because of presence of interference fit and tangential contact in circumferential direction, the modified Mandrel Cold Working method allows combining the positive effects of the macro- and the micro-approach. On this basis in [30] the combined method called Friction Stir Hole Expansion (FSHE) has been developed. This method is intended for finishing of holes in high-strength aluminum alloys. The effectiveness of FSHE method will depend on the effect of the microstructure modification and residual hoop stress distribution in quantitative and qualitative aspect. The first effect can be assessed indirectly – by means of fatigue tests, and the second – through residual stress measurement. For an evaluation of the residual stresses different methods [2, 31, 32] are applied, but the X-ray diffraction method is one of the most advanced non-destructive methods [33].

The main objective of the present study is an experimental assessment of the effectiveness of the FSHE method for enhancement of fatigue life of high-strength aluminum alloy D16AT widely used in aircraft industry. In order to evaluate the effectiveness, the outcomes obtained from fatigue tests and X-ray diffraction residual stress measurement have been utilized.

1. CHARACTERISTIC OF THE FRICTION STIR HOLE EXPANSION PROCESS

According to the FSHE method scheme (Fig. 3), the tool is moved by the machine spindle. The tool performs rotation around its own axis with frequency $n_e, tr/min$ and simultaneously performs rectilinear translation along hole axis with feed rate $f, mm/rev$. The working cycle includes primary and reverse strokes as the primary stroke terminates when the joint section of the conical and cylindrical sections passes with a few millimeters the hole output side. The reverse stroke is performed with the same direction of the tool rotation.

The taxonomy of the FSHE method is developed in [30]. Depending upon the ratio between the temperature factor, the amount of plastic deformation and the rate of deformation, three zones are defined: stir zone, transition zone and a zone with manifested macro-effect (Fig. 3). Due to the tangential stresses τ_{tr} a local increasing the temperature immediately around the hole is obtained which leads to so-called “softening effect” of the material. As a results the magnitudes of the axial force P_a and rotating moment T decrease in comparison with the case with only rectilinear translation. On the other hand the increased local temperature is necessary for obtaining of modified micro-structure, typical for the stir zone. The latter is characterized by large plastic deformation and high strain velocity in circumferential direction. In the transition zone in a natural way interference between the micro- and macro effect is obtained. In the zone with manifested macro-effect the temperature effect is slightly pronounced and the plastic deformation is significantly smaller. This is a precondition for introducing beneficial residual compressive macro-stresses after finalizing the FSHE process (Fig. 3).

The normal force magnitude in the contact field between the tool working part and hole surface is determined by:

$$N = \pi\, d_0\, a\, \sigma_r\,, \qquad (2)$$

Where a is the width of the contact area; σ_r is the average integral value of the radial stress in the contact zone.

In view of the thermo-mechanical nature of the fshe method and the dynamics of the tangential contact between the tool and the hole surface, σ_r and d_0 are variables. For this reason the normal force N and the friction coefficient alter. On the other hand, the temperature field around the hole is determinant for the micro-structure modification (micro-effect), as well as for the residual stress distribution (macro-effect). For a particular detail and material, the temperature field depends on the process manufacturing parameters n_e, f, initial interference fit i_{init} and the tangential contact conditions – dry friction or friction in the presence of lubricant.

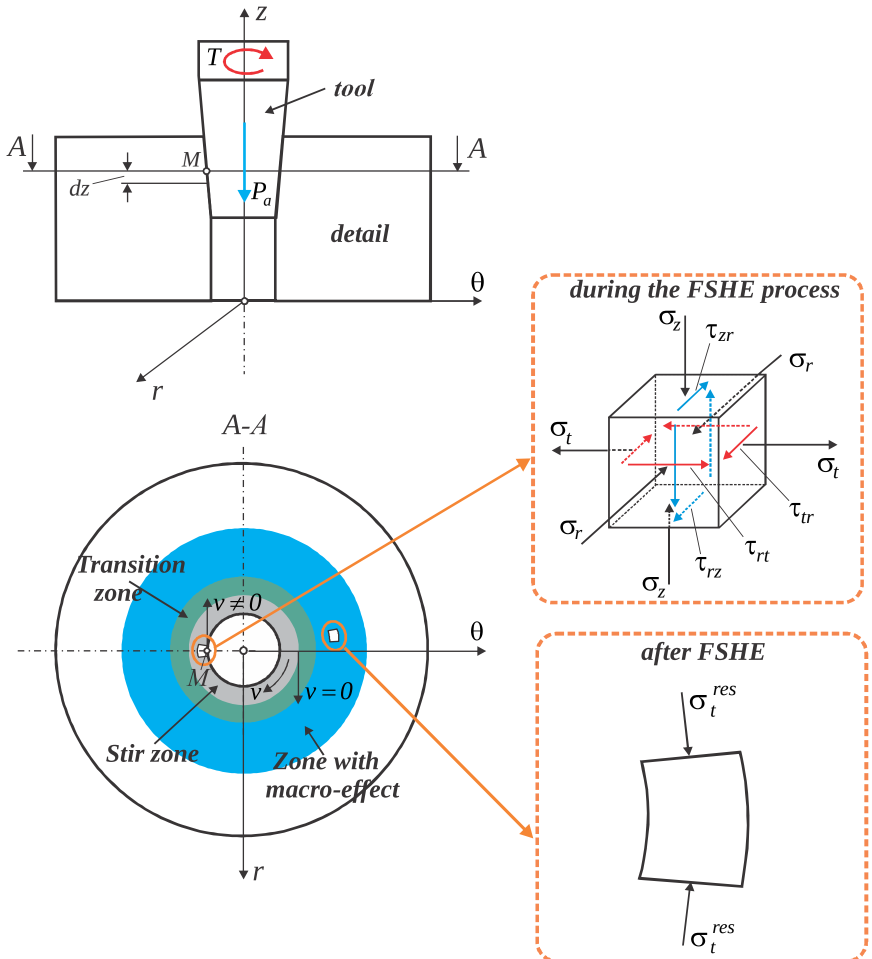


Fig. 3 – Areas with different effects after FSHE process

2. EXPERIMENTAL STUDY OF THE FATIGUE LIFE

2.1. Details of the experiment

The fatigue life after FSHE is evaluated on the basis of comparative analysis of the outcomes from fatigue tests of 13 specimens with holes treated in a different way. Specification of the experimental specimens and the corresponding number of cycles to fatigue failure are shown in Table 1. The specimen №1 is basic (the hole is only drilled and reamed). The holes in specimens with numbers 2-4 are subjected to Mandrell Cold Working with different interference fit. The holes in specimens with numbers 5-13 are processed through FSHE at different magnitudes of the initial interference fit, manufacturing parameters and conditions of friction.

For achieving of different interference fit, tools from the type of conical-cylindrical mandrel are manufactured, having geometry according to Fig. 4. Their geometrical parameters are depicted in Table 2.

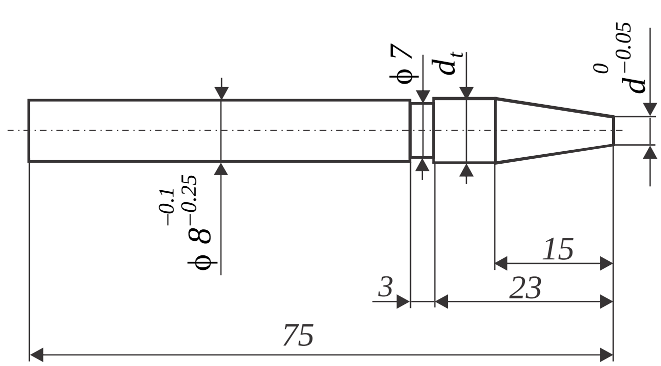


Fig. 4 – Mandrel's geometry

Table 1

Specification of the specimens subjected to fatigue tests

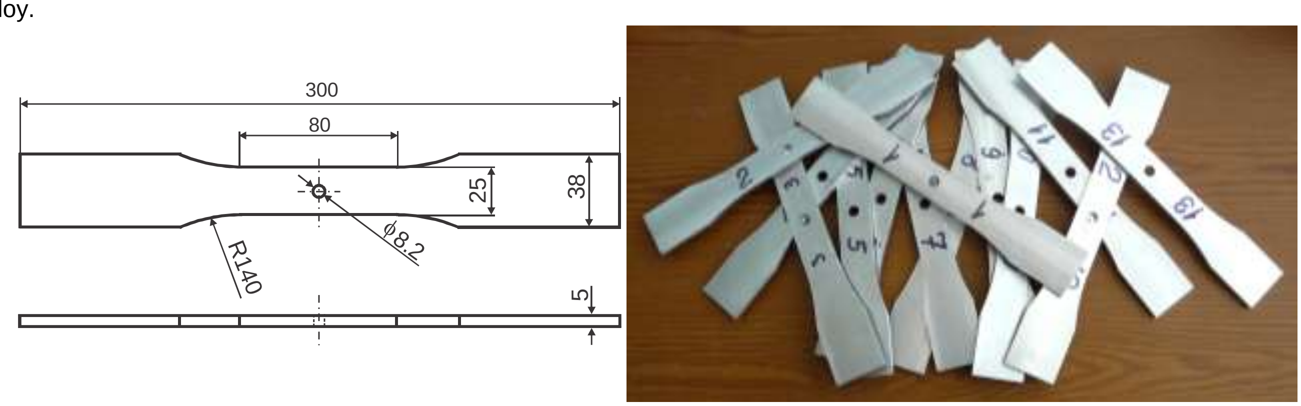
№	Treatment oh the hole	Friction conditions	Interference fit $i\,(i_{init}),mm$	Rotating frequency $n_e,tr/min$	Feed rate $f,mm/rev$	Number of cycles to failure N
1	Basic specimen (only drilled and reamed)	-	-	-	-	63307
2	Mandrel Cold Working	with lubrication	0.04	-	-	66971
3	Mandrel Cold Working	with lubrication	0.08	-	-	83698
4	Mandrel Cold Working	with lubrication	0.12	-	-	49984
5	FSHE	with lubrication	0.04	80	0.1	78020
6	FSHE	with lubrication	0.08	80	0.1	104017
7	FSHE	with lubrication	0.12	80	0.1	37946
8	FSHE	with lubrication	0.04	160	0.1	70246
9	FSHE	with lubrication	0.08	160	0.1	28592
10	FSHE	with lubrication	0.12	160	0.1	26170
11	FSHE	dry friction	0.04	80	0.1	34099
12	FSHE	dry friction	0.04	160	0.1	43857
13	FSHE	dry friction	0.04	315	0.885	28992

Table 2

Geometrical parameters of the mandrels

№	i_{init},mm	d,mm	d_t,mm	$\varepsilon_{t,0},\%$
1	0.04	3.6	8.265	0.547
2	0.08	3.64	8.305	1.034
3	0.12	3.68	8.345	1.520

The specimens geometry is shown in Fig. 5a, and their appearance – in Fig. 5b. The material is D16AT aluminum alloy.



a. ***b.***

Fig. 5 – Specimens for fatigue tests

The cold working (Mandrell Cold Working) is carried out in the laboratory Testing of Metals at Technical University of Gabrovo on testing machine *ZD 10* set to slow speed. The fatigue test are accomplished on testing machine *Instron – 1332* in the laboratory VSB at Technical University of Ostrava, Czech Republic (Fig. 6) with the following parameters of the cyclic loading: coefficient of symmetry of the cycle $r = F_{min} / F_{max} = 0$; frequency $10\ Hz$; maximum force $F_{max} = 14500\,N$. The maximum force is chosen so that the operating equivalent stress at a critical point in the hole periphery reaches the yield strength of the material.

The FSHE process is implemented on universal milling machine (Fig. 7).

Fig. 6 – Testing machine Instron 1332

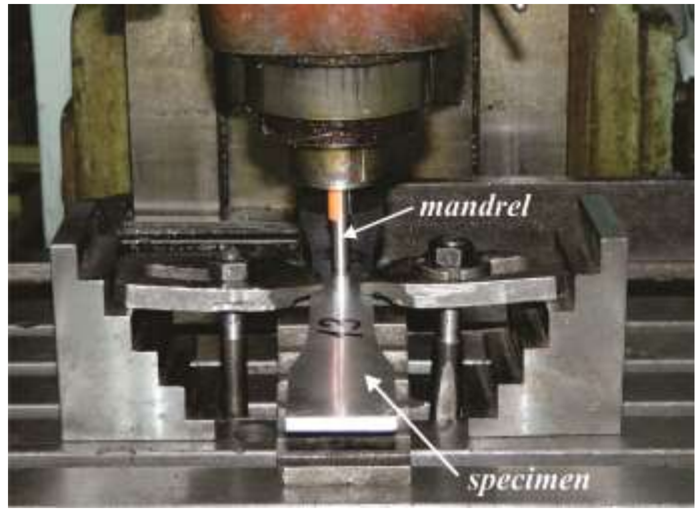


Fig. 7 – FSHE process

2.2. Fatigue tests results and comments

The fatigue test outcomes are generalized in Fig. 8.

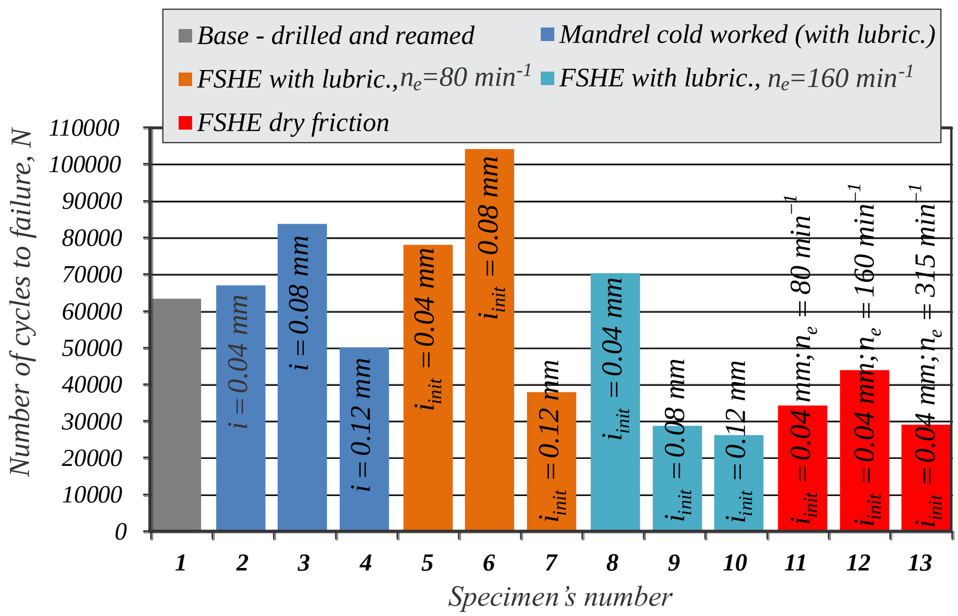


Fig. 8 – Fatigue tests results

As a whole, the fatigue test results show that the crack tesistance of the alu,inum alloy D16T subjected to dynamic loading depends largely by the characteristics of the influence through plastic deformation: the equivalent plastic deformation ε_{ekv}^{pl}, velocity of deformation $\dot{\varepsilon}$ and temperature field around the hole. A proof of this is the significant scattering of the number of cycles to failure of the studied methods for finishing machining of holes (Fig. 8). The results warrant the following comments:

- The larger degree of plastic deformation ($DCE = 1.46\,\%$ за $i_{init} = 0.12\,mm$) does not lead to enhancement of fatigue life after *Mandrel Cold Working* as well as after *FSHE*. Moreover, for samples with numbers 4, 7 and 10, treated with interference fit $0.12\,mm$, less fatigue life is registered compared to the baseline sample treated only by cutting;

● One and the same tendency is observed for the alteration of the number of cycles to failure depending on the interference fit of the samples, treated by *Mandrel Cold Working* (with numbers 2, 3 and 4) and for the samples (with numbers 5, 6 and 7), treated by *FSHE* with the lowest frequency $n_e = 80\, tr / min$. Simultaneously, the largest fatigue life is obtained for the specimen № 6, treated by *FSHE* under following conditions: utilization of lubricant, interference fit $i_{init} = 0.08\, mm$ and frequence of rotation $n_e = 80\, tr / min$. This results proves the potential of the *FSHE* with respect to the studied aluminum alloy;

● The implementation of the *FSHE* method with relatively larger interference fit and frequency of rotation decreases the fatigue life of the treated holes (specimens with numbers 9 and 10);

● It is not appropriate to apply the *HSHE* in conditions of dry friction and small interference fit (samples with numbers 11, 12 and 13). This results can be explained with the deposition of particles from the material being processed on the working part of the mandrel, which cause significant deterioration of the roughness obtained of the hole surface.

3. EXPERIMENTAL STUDY OF THE RESIDUAL STRESSES

3.1. Specimens

The specimens are type of bushings with sizes: outer diameter of $50\, mm$ and high of $5\, mm$. After final reaming the hole diameter is in the range of $d_0 = 8.222 - 8.225\, mm$. The chosen shape of the specimens eliminates the influence of the non-circular boundaries on the residual hoop normal stress distribution. For the stress measurement X-ray diffraction analysis is carried out [33]. The measurement was conducted in Czech Technical University of Prague. Five specimens, treated in different manner but with one and same interference fit - $i_{init} = 0.08\, mm$ in accordance with Table 3, are measured.

Table 3

Specification of specimens for X-ray diffraction analysis

Indication of specimens	*Treatment oh the hole*	*Friction conditions*	*Rotating frequency* $n_e, tr / min$	*Feed rate* $f, mm / rev$
Basic specimen	*Mandrel Cold Working*	*with lubrication*	-	-
L	*FSHE*	*with lubrication*	*630*	*0.05*
I	*FSHE*	*dry friction*	*630*	*0.05*
N	*FSHE*	*with lubrication*	*400*	*0.125*
K	*FSHE*	*dry friction*	*400*	*0.125*

The residual stresses are measured in radial direction from the hole edge along lines AB and CD on the entrance and exit faces of the specimens – respectively side "a" and side "b" (Fig. 9).

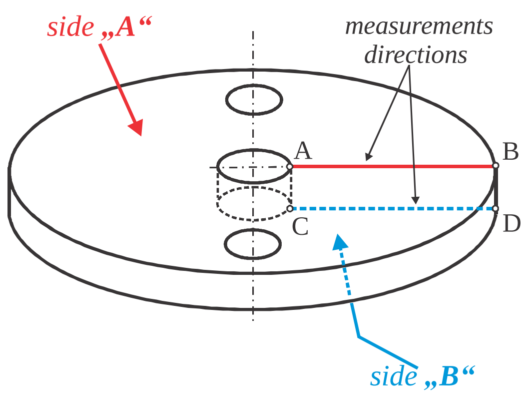


Fig. 9 – Scheme for X-ray diffraction measurement

3.2. X-ray diffraction measurement

The residual hoop stress distribution along measured lines for each specimen is depicted in Fig. 10.

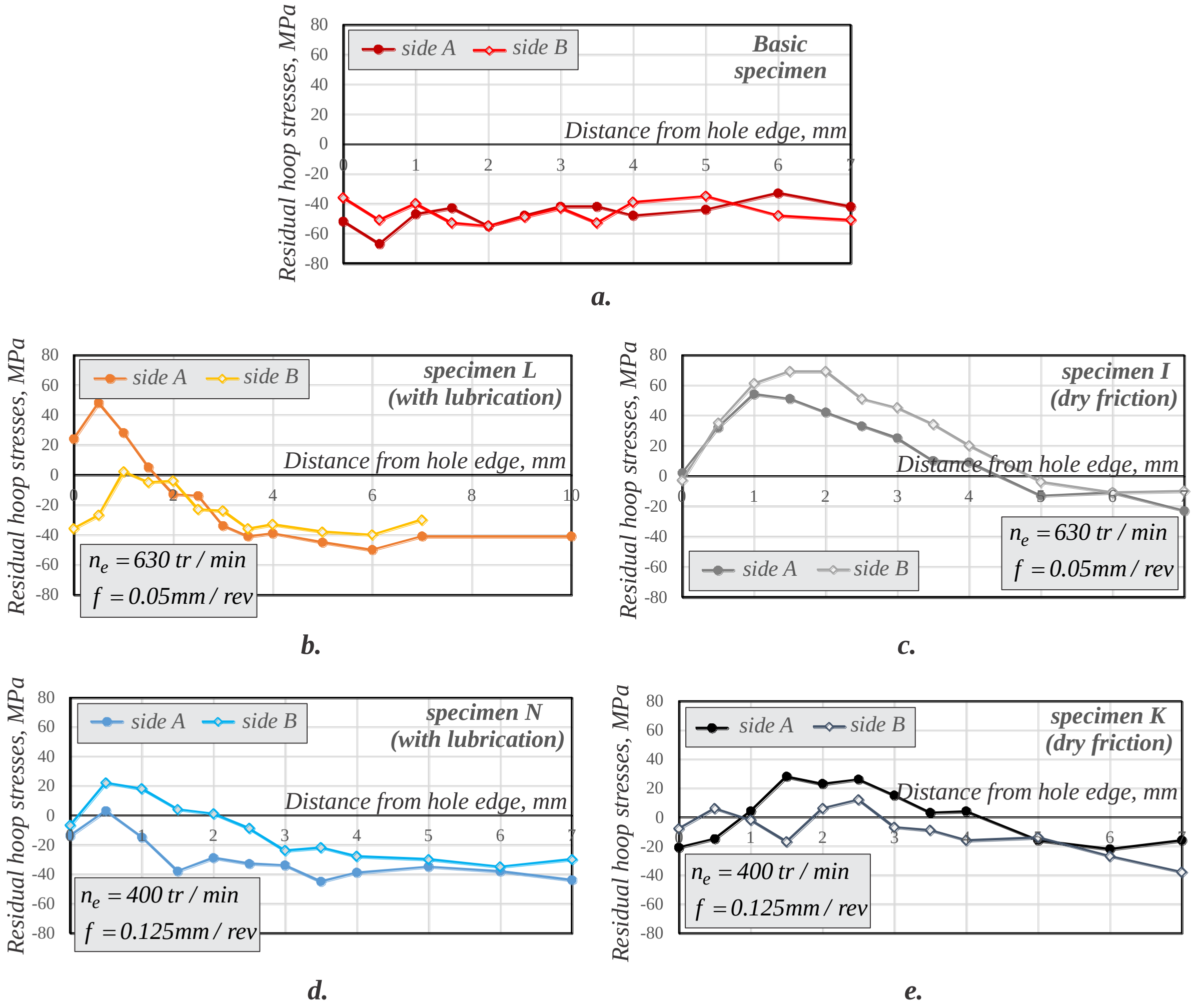


Fig. 10 – Distribution of residual hoop stresses in radial direction

The results from The X-ray diffraction analysis can be generalized in the following manner:

- The influence of the temperature factor on the distribution of the residual regional tensions is confirmed – expectedly, the largest in absolute value residual compressive stresses were measured in the base sample – mainly in the range of $(-60 \div -40)\ MPa$ (Fig. 10a). At the same time, the distribution is uniform on the entrance and exit faces. This can be explained with the larger width of the mandrel working part ($8\ mm$) in comparison with the samples thickness ($5\ mm$) – at this condition moving plastic wave along hole axis does not practically arise.
- The FSHE process implementation in conditions of dry friction with larger frequency of rotation and smaller feed rate leads to formation of a zone with residual tensile stresses with large depth - $\approx 5\ mm$ (Fig. 10c). On the other hand relatively larger frequency of rotation ($n_e = 630\ tr/min$) even with utilization of lubricant, leads to a zone with residual tensile stresses near to hole surface. For the case of dry friction, the width of this zone is much larger on both sides of the specimen in comparison with the case with a presence of lubricant - $4.4 - 4.8\ mm$ (фиг. 10c). The process implementation with the same manufacturing parameters but with a presence of lubricant, significantly reduces the width of the tensile zone – especially on the exit face - $1\ mm$;
- The smaller frequency of rotation in combination with larger feed rate leads to a less generated heat and thus, the zone with residual tensile stresses is less pronounced. On the other hand, different distribution of the residual stresses on the entrance and exit faces is observed. In the presence of lubricant, a tensile ring is created on the exit face near the hole (Fig. 10e), whereas in condition of dry friction the residual tensile stresses are more pronounced on the entrance face (Fig. 10d). As a whole, the implementation of the FSHE process in conditions of dry friction leads to less pronounced zone with useful residual compressive stresses.

COCLUSIONS

By experimental way the effectiveness of the FSHE method is evaluated in aspect of fatigue life with respect to aluminum alloy D16AT. The experimental results can be generalized with the following conclusions:

♦ The carried out fatigue tests in conditions of low cycle fatigue show larger effectiveness of the FSHE method in comparison with the case of Mandrel Cold Working method, where only translation exists. For achieving of larger fatigue life, it is appropriate the process to be implemented with relatively small values of rotational speed and initial tightness in the range $i = 0.06 \div 0.08$;

♦ The outcomes form X-ray diffraction analysis confirm the correlation between the temperature factor and residual hoop stress distribution. Therefore, for a given initial interference fit the beneficial effect can be optimized by means of manufacturing process parameters. For ensuring more intensive zone with beneficial residual compressive stresses, it is appropriate smaller values of the frequency of rotation and relatively larger feed rate to be chosen. Thus, optimal combination between macro- and micro-effect can be achieved.

♦ In order to achieve greater fatigue life and elimination of the harmful effect from violating the integrity of the surface of the processed holes, it was necessary the process FSHE to be implemented by lubrication.

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