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EFFECTIVENESS OF DIFFERENT METHODS FOR FATIGUE LIFE ENHANCEMENT OF FASTENER HOLES IN D16AT ALUMINUM ALLOY

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ABSTRACT

An evaluation of the effectiveness of three different methods for enhancement of fatigue life of fastener holes in D16AT aircraft Al-alloy has been made. Objects of comparative analysis are the friction stir hole expansion (FSHE), solid mandrel cold working and symmetric cold expansion (SCE) methods. The results are generalized on the basis of fatigue tests, S-N curves obtained, X-ray diffraction and micro-structural analyses. Under the high-cycle fatigue performance, the SCE provides more than 66 times longer fatigue life as compared to solid mandrel method and more than 82 times greater fatigue life in comparison with FSHE method. Through X-ray diffraction analysis it has been found out that the higher efficiency of the SCE method is due to the symmetric distribution (with respect to the plate middle plane) of the introduced residual hoop stresses around the hole. On the other hand, the solid mandrel cold working method causes a significant gradient of the residual stress distribution in the thickness plate direction, which is a precondition for nucleation and propagation of corner fatigue cracks. It has been established that the FSHE method efficiency depends primarily on the heat generated and the equivalent plastic strain size. The combination of these factors determines the beneficial micro-effect of the microstructure modifying immediately around the hole and the useful macro-effect due to the introduced compressive residual stresses. It has been concluded that SCE method should be used for pre-stressing of fastener holes in the most loaded components in the D16AT aircraft structures - wings and fuselage, while FSHE method can be applied for processing of fastener holes in less loaded aircraft components.

1. INTRODUCTION

Aluminium alloys have enough strength at relatively low weight, big corrosion resistance and good workability. Because of that, they are widely used in responsible structures, due to their optimum combination of physical and mechanical properties. Said alloys display a wide range of application in airspace industry for various structural elements, more specifically those used in wing and fuselage structures. Despite the widespread use of composite materials, the skin of majority of contemporary aircraft is made of alclad aluminium alloys, such as D16AT; the latter being widely used in the Russian and Ukrainian aviation industries as analogous to 2024-T3. The subject of the present study is D16AT high-strength aluminum alloy.

A great variety of structural components in aircrafts, especially all wing and fuselage structures, are characterized by multitude fastener holes. Since the holes are natural stress concentrators, they appear to be a critical spot for initiation and growth of fatigue cracks. However, there are no particular studies on the application of methods for mechanical treatment of fastener holes in D16AT Al-alloy, which could possibly aim at increasing their fatigue life. In general, the investigations dedicated to D16AT aircraft components were focused on developing methods for fatigue and fracture processes prediction.

In order to reduce the possible corrosion process, D16AT is covered with a layer of pure aluminium, whose thickness is $(4 \div 7)\%$ from the total sheet thickness. Karlashov et al. have found that the coated layer thickness of 10 micrometers guarantees the greatest fatigue life and resistance against corrosion fatigue [1].

Troshchenko et al. have studied D16AT behaviour under regular and block loading in the presence of stress concentration and fretting-corrosion [2]. They have proved that the effective stress concentration factor increases with the number of cycles to failure and the stress ratio.

A comprehensive experimental study of the fatigue behavior of several aircraft Al-alloys was conducted by Nesterenko and Basov [3]. The experimental fatigue curves were obtained for both loading cases: regular (pulsating) and irregular (random), using flat specimens with central holes. However, the samples' holes were not pre-stressed. The authors have found out that relation between the fatigue life of 2024-T3 sheets and D16AT sheets lies within 1.25-3.85 range depending on the loading type and its level. For stress loading, typical of contemporary transport

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airplanes, the ratio of stage of macro-crack growth duration to the total specimen life to failure is 10-30 %.

The dependence between corrosion and fatigue life of D16AT aircraft structures has been a subject of a large number of studies over the last few decades. Many of these works have been motivated by situations in which the exploitation is in corrosion-promoting conditions, such as salt-containing sea spray and vapour. An extensive experimental study of D16AT specimens was conducted by Salimon et al. [4]. Sample specimens were cut from the fuselage skin, having long-term and real service conditions. The authors have realized that the degree of corrosion (the ratio of the corroded area to the entire area) is not a direct function of the operating time, but depends primarily on the exposure conditions (moisture, temperature regime and similar). In contrast with the degree of corrosion, maximum corrosion depth increases steadily during operation. The investigated D16AT alloy after 11 years of exploitation was subjected to both general non-uniform corrosion and local corrosion, namely pitting. After 20 years of exploitation, pitting corrosion, inter-crystalline corrosion and areas damaged by layer corrosion were observed. It was confirmed that the presence of corrosion damage in the specimens results in mechanical properties reduction. The authors have concluded that the rate of fatigue crack growth in corroded specimens is about 1.4 times greater than in the uncorroded specimens. The study of the mechanical properties in specimens without traces of corrosion confirms that the yield stress and tensile strength reach a peak after 15 years of exploitation and then start to decrease [4] On the basis of the microstructure studies, the authors have concluded that the exploitation in high-cycle fatigue conditions does not cause dramatic structural changes in the D16AT bulk material. In order to investigate the fatigue influence on the near-surface regions micro-structure, surface-sensitive methods of electrochemical testing and X-ray diffraction have been used. On this basis, the presence of a transition layer was grounded, where dramatic changes occur in both the electrochemical corrosion potential and the diffraction pattern parameters. The authors have suggested that the state of this transition layer corresponds to the interaction between the coating and the base material.

A wide range of fatigue tests on the D16AT riveted lap joint specimens were carried out by Kaniowski [5]. The specimen geometry represents the longitudinal joints in the aircraft pressurized fuselage. The author was studied the effect of the rivet size, its pitch and the thickness of the sheets on the fatigue behaviour of various rivet designs through fatigue tests. The microstructure change near the rivet holes in high tension conditions was registered through SEM analysis. The author has concluded that greater compressive force during riveting process provokes residual stresses around the holes, resulting in increased fatigue life. On the other hand, this force is related to the mechanism of damage due to the stress concentration and the fretting effect.

The statistics of defects, found in D16AT components of Tu-154 and Il-86 aircrafts, confirms that the fatigue as well as the corrosion is the most spread kind damages of the fuselage, wing and empennage of the aircrafts [6].

One of the approaches for fatigue performance prediction of D16AT Al-alloy is based on the surface deformation relief evolution as an indicator of accumulated fatigue damage [7]. The nucleation stage of fatigue is associated with formation and development of extrusions, intrusions, and persistent slip bands. For the quantitative assessment of the local damage a set of parameters of the surface deformation relief nearby the rivet hole was used. “Critical damage parameter”, corresponding to the fatigue crack origin, was proposed by Karuskevich [6]. On this basis relationships between the duration/rate of crack propagation and “critical damage parameter” were obtained by means of fatigue tests.

The fatigue sensor, made of D16AT Al-alloy, was developed by Ignatovich et al. for fatigue damage monitoring of aviation components [7]. A regressional model was proposed for the residual life prediction.

The fatigue crack growth in D16AT specimens with multiple stress concentrators in the form of holes was experimentally studied by Ignatovich and Karan [8]. Although this kind of cracks have a relatively small size, for a sufficiently great number of damages an accelerated reduction in the residual fatigue life of structures is possible due to formation of a large leading crack in the riveted joint. A generalized kinetic fatigue growth curve was obtained and the Paris’ coefficients were determined for a great number of cracks. It was concluded that a general linear semi-logarithmic relationship exists between these coefficients. The experiment is time-consuming, as a digital camera has been used to quantify the process of nucleation and growth of the cracks, as each photo corresponds to a certain number of cycles.

The above-mentioned studies are focused on the residual life prediction of D16AT aircraft components, based on systematization of a large amount of empirical information. This approach to assessing the reliability of aircraft structures can be classified as a "passive" approach since it only registers the structure current state. There are known methods of preventing fatigue fracture based on the idea of mechanically treating the material around the fastener holes before introducing the corresponding component into operation. Unfortunately, there is no any information about the use of such methods for increasing the fatigue life of D16AT aircraft components with fastener holes.

Taking into account the effect of stress concentration around the multiple rivet holes in the aircraft components, the concept for fatigue life enhancement through locally modification of the material state around the fastener holes is fundamentally different. An effective approach for achieving such modification is the plastic deformation at room temperature. One of the main approaches for increasing the fatigue life of structural components with fastener holes is known as "cold working". Its essence is in achieving a new elastic equilibrium of the material around the hole after plastic deformation in a significant depth. The key point in this approach is creating a zone with residual compressive hoop macro-stresses after removing the tool from the hole. When a compressive zone with the sufficient intensity and depth is ensured, it acts like a bracket, which significantly retards the growth of first mode fatigue cracks. A measure of the hole deformation is the so-called degree of cold expansion (DCE):

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

where i is the interference fit, d_t is the maximum diameter of the tool working part, d_0 is the diameter of the previously drilled hole. Typically, it is equal to 4%. In order to minimize the temperature factor, the cold working process is fulfilled below the temperature of re-crystallization of the respective metal and the strain velocity is limited up to $\dot{\varepsilon} = 1\times10^{-4} \div 1\times10^{-3}, s^{-1}$.

The methods in which the tool acts on the surface of pre-drilled and reamed hole are most widely used: mandrel cold working methods [9] (ball or solid mandrel cold working), pre-stressing by tapered pin and tapered sleeve [10], split sleeve cold expansion [11], split mandrel cold working [12].

The split sleeve and split mandrel methods are the most popular in the aerospace industry as they are carried out as one-sided processes [13, 14]. From the point of view of the created residual stress zone, these methods have a significant disadvantage - a significant and non-symmetric gradient of the residual stresses with respect to the plate middle plane [15-17]. The reason is the significant axial force flow passing through the respective element due to use of a support during the hole pre-stressing. Both methods are based on one and the same concept: the degree of cold expansion depends only on the tool maximum diameter and the diameter of the drilled and reamed hole. This leads to a large number of control operations in the technological cycles of the two methods.

In order to eliminate this disadvantage, Maksimov and Duncheva have invented the symmetric cold expansion (SCE) method [18], which is also one-sided method. Another important advantage of the SCE method is the ability to control the DCE using one and the same tool. This allows holes with a relatively larger tolerance of their diametric size to be pre-stressed [19, 20].

Another approach to enhancement of fatigue life is based on the idea for modifying the structure of the material around the fastener holes. Physically, this transformation is expressed in grain refinement, reduction of the material pores and homogenization of the micro-structure. In order to achieve such significant transformation, severe plastic deformation (SPD) is required. Mandatory components of the SPD are tangential stresses with significant intensity due to the frictional forces between the tool and the hole surface [21]. The basic methods for SPD are torsion straining under high pressure and equal channel angular pressing [22]. These methods are inapplicable to fastener holes in aircraft structures. A perspective modern technique, aiming modified microstructure in aluminum sheet components, is Friction Stir Processing (FSP) [23]. FSP aims to obtain the so-called “stir effect”, localized in a zone with SPD and elevated temperature - greater than the temperature of the metal recrystallization (stir zone). As a result of the grain refinement microstructure, the fatigue strength is significantly increased [24, 25].

Adapting FSP for treatment of fastener holes in the aircraft structures, another surface modification technique called "rotating tool cold expansion" has been developed by Kumar et al. [26]. The interaction between the rotating mandrel and the hole surface, in the presence of interference fit, leads to a local SPD and heat generation in the material near the hole. The process combines the advantages of FSP with these of mandrel cold working methods due to two effects: micro-effect, expressed in hole surface modification, and macro-effect, expressed in introducing beneficial compressive residual macro-stresses. The generated heat, due to the significant friction, decreases the benefit from the macro-effect.

Taking into account the thermo-mechanical nature of the process, the name "friction stir hole expansion" (FSHE) is justified by Duncheva et al. [27]. The efficiency of the FSHE method with respect to the 2024-T3 Al-alloy was evaluated through fatigue tests and finite element simulations [27].

In regard to the D16AT aluminum alloy, the experimental studies of the FSHE method are incompleted. The FSHE process has been studied in terms of axial force and torque changes [28]. Based on fatigue tests and X-ray diffraction analysis, the macro- and micro-effects of the FSHE method were evaluated by means of a comparison with the solid mandrel cold working method [29]. At the same time, the question with the potential capabilities of the SCE and mandrel cold working methods in the conditions of wider range of DCE of fastener holes remains open, when it comes to D16AT Al-alloy.

In the known studies, dedicated to the D16AT aluminum alloy, there is no information about use of the methods described above for fatigue life enhancement. From the point of view of enhancement of fatigue life of D16AT aircraft components, the main idea in the present study is to justify the suitability of using different methods for treatment of holes, depending on the operating load intensity of the corresponding component.

The main purpose of this study is to compare the effectiveness of various methods for fatigue life enhancement of D16AT flat specimens with central hole with a view to their application in aircraft structures. To achieve the goal, an experimental approach based on combination of fatigue tests, X-ray diffraction analysis and microstructural analysis has been used. An object of comparative analysis is the efficiency of the mandrel cold working, FSHE and SCE methods.

2. EXPERIMENTAL PROCEDURE

2.1. Material and specimens

The GOST 21631-76 D16AT high-strength aluminum alloy was received as sheets with thickness of $5\,mm$. The sheets are covered with a pure aluminum with a coating thickness of about $0.3\,mm$. The chemical composition (Table 1) and mechanical characteristics (Table 2) were established in our laboratory “Testing of Metals” at Technical University of Gabrovo. The tensile tests were conducted on flat specimens.

The fatigue specimens were cut from a sheet so that their longitudinal axes are aligned in the sheet rolling direction. The specimen dimensions in accordance with ASTME 466-07 are shown in Fig. 1. The final nominal hole diameter for all specimen groups is 8.2 mm.

Depending on the way the holes are treated, the experimental specimen groups are denoted as follows:

A – basic specimen: the hole is drilled and reamed;

B – the hole is successively drilled, reamed and subjected to FSHE;

C – the hole is successively drilled, reamed and cold worked by means of solid mandrel;

D – the hole is successively drilled, reamed and cold expanded through SCE method.

2.2. FSHE and solid mandrel cold working methods – tool setup and implementation

Conical-cylindrical mandrels were manufactured (Fig. 2) in order to achieve different interference fit. For a given interference fit, one and the same tool was used for the holes in the B and C groups. The geometric parameters of the mandrels and the diameters of the pre-treated holes, depending on interference fit, are shown in Table 3.

The specimen preparation and the holes treatment were made in laboratory Testing of Metals at Technical University of Gabrovo. According to the FSHE method kinematics [27], the tool is driven by a machine spindle, performing simultaneous rotation around its axis with angular velocity ω and a rectilinear translation along the hole axis with feed rate f. The working cycle includes a primary and a reverse tool strokes, as the primary stroke ends when the intersection between the conical and cylindrical sections passes with a few millimeters the exit side hole. The reverse stroke is performed with the same direction of the tool rotation. The machining of holes by FSHE method is performed on conventional milling machine (Fig. 3). The manufacturing parameters are shown in Table 4.

Table 1. *Chemical composition of the tested aluminum alloy D16AT*

Element	*Cu*	*Mg*	*Fe*	*Si*	*Mn*	*Zn*	*Sn*
wt%	*1.53*	*0.738*	*0.491*	*6.42*	*0.215*	*1.01*	*0.023*
Element	*Bi*	*Pb*	*Ti*	*Ni*	*Cr*	*Al*	
wt%	*0.005*	*0.052*	*0.035*	*0.027*	*0.015*	*Balance*	

Table 2. *Mechanical characteristics of the tested aluminum alloy D16AT*

Young's modulus	*Yield limit*	*Ultimate stress*	*Elongation*	*Transverse contraction*
0.7×10^{11} *Pa*	355×10^{6} *Pa*	472×10^{6} *Pa*	*15.5%*	*36%*

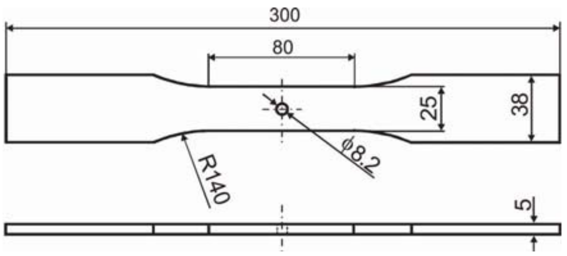

Fig. 1. Specimens geometry

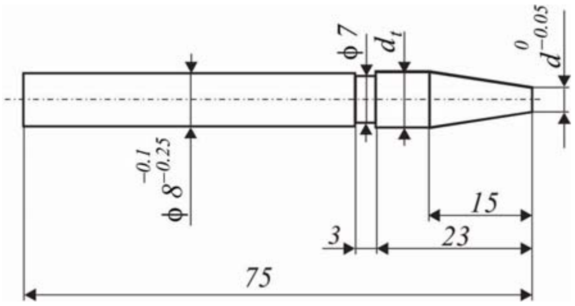

Fig. 2. Mandrel's geometry

Table 3. *Geometrical parameters for specimen groups B and D*

i, *mm*	$\varepsilon_{t,0}$, *%*	d_0, *mm*	*Employment (specimen groups)*	*Mandrel's parameters*	
				d, *mm*	d_t, *mm*
0.04	*0.5*	*8.22*	*B and C*	*3.6*	*8.265*
0.08	*1*	*8.22*	*B and C*	*3.64*	*8.305*
0.12	*1.5*	*8.22*	*B and C*	*3.68*	*8.345*
0.32	*4*	*7.94*	*C*	*3.6*	*8.265*

Table 4. *Specimen specification*

Specimen groups	*Hole treatment*	*DCE, %*	*Tool rotating frequency* n_e, *tr / min*	*Tool feed rate* f, *mm / rev*	*Number of cycles to failure* N
A	*Basic specimen*	*-*	*-*	*-*	*63307*
B	*FSHE*	*0.5*	*80*	*0.1*	*78020*
		1	*80*	*0.1*	*104017*
		1.5	*80*	*0.1*	*37946*
		0.5	*160*	*0.1*	*70246*
		1	*160*	*0.1*	*28592*
		1.5	*160*	*0.1*	*26170*
C	*Solid mandrel cold working*	*0.5*	*-*	*-*	*66971*
		1	*-*	*-*	*83698*
		1.5	*-*	*-*	*49984*
		4	*-*	*-*	*45595*
D	*SCE*	*0.5*	*-*	*-*	*74518*
		1	*-*	*-*	*154574*
		1.5	*-*	*-*	*193765*
		4	*-*	*-*	*318932*

It was established that FSHE process is effective in the presence of lubricant [28]. Thus, the adhesion of particles of the processed material to the tool due to sticking friction phenomenon is avoided. At the same time, the temperature factor is crucial for both micro-effect and macro-effect. The friction in the circumferential direction between the hole surface and tool has a main contribution to the generated heat. The elevated temperature locally around the hole is necessary in terms of the beneficial stir effect, and on the other hand, it leads to softening of the material. Namely softening effect allows the FSHE process to be implemented on conventional machine tools. For the same interference fit, the tool rotation frequency and feed rate are decisive for the amount of heat generated.

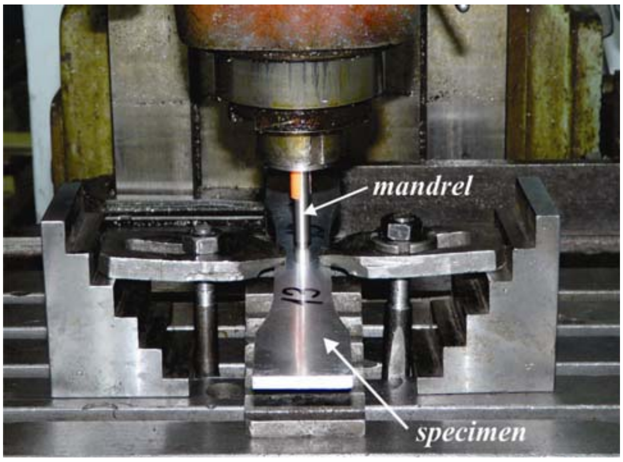

Fig. 3. FSHE process implementation

The effectiveness of the cold working methods depends primarily on the intensity and depth of the introduced residual compressive hoop stresses around the holes. In the present study solid mandrel cold working method was implemented with DCE in the range of $(0.5 \div 4)\%$.

2.3. SCE process implementation

SCE realizes the idea of homogenization in axial direction of the generated residual compressive hoop stresses [18]. Thus, principle novel process of cold expansion is performed ensuring ‘‘pure’’ radial hole expansion. The tool consists of a pin having external conical working part situated in a longitudinally slotted sleeve of multitude of sectors (Fig. 5a). The cold expansion process is carried out through preliminarily assigned axial stroke of the pin, driven and controlled by a hydraulic or another type of system. When the pin moves, it interacts through its conical working edge with the respective internal conical surfaces of the sectors. As a result simultaneous displacement of sectors is provoked whereat each sector moves in radial direction in its plane of symmetry. Thus, radial expansion is exerted simultaneously on the whole hole surface, and the DCE is a function of the axial stroke of the pin. The obtained residual compressive stress distribution is symmetric with respect to the plate middle plane and practically uniform in axial direction [13].

A special SCE device [18] (Fig. 5b) was used for pre-stressing the holes of group D specimens. The longitudinally slotted sleeve contains four sectors. For comparison with FSHE and solid mandrel cold working methods, four DCE were used: $0.5\%, 1\%, 1.5\%, 4\%$. Similarly to split sleeve and split mandrel methods, after hole pre-stressing, final reaming is required in order to efface the traces, which are a result of the longitudinal cuts in the tool working part. The reamer diameters, used before and after SCE, were respectively $7.9\ mm$ and $8.2\ mm$.

It was established [28] that FSHE process is effective when DCE is limited to $DCE \le 1.5\%$. The larger interference fit leads to undesired large torque and axial force, generation of considerable heat, poor quality of the treated surface, degraded conditions of lubrication, unwanted adhesion effect on the tool [28].

In view of the above, in the present study the FSHE is carried out with DCE of $0.5 - 1.5\ \%$.

Solid mandrel cold working is carried out on testing machine ZD 10 with slow speed (Fig. 4). Both processes are carried out in conditions of lubrication with a consistent lubricant.

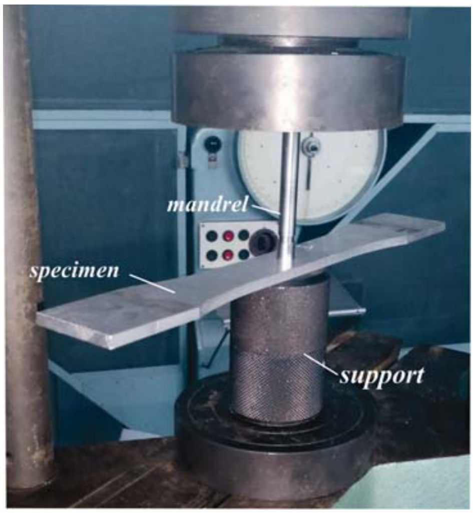

Fig. 4. Solid mandrel cold working process

3. FATIGUE TESTS

Experimental study of the fatigue behavior of D16AT specimens (see Fig. 1) was conducted. Two types of one-dimensional cyclic tension fatigue tests were carried out: 1). fatigue tests under conditions of constant amplitude; 2). fatigue tests to obtain S-N diagrams.

The specimen groups (A, B, C and D) were subjected to one-dimensional cyclic tension on Instron-1332 testing machine in VSB laboratory at the Ostrava Technical University. For each specimen group and for each DCE, the final result for number of cycles to failure is arithmetic mean from three specimens. The fatigue test conditions for the two types experiments were: regime – pulsating cycle, i.e. sinusoidal loads with a ratio $R = P_{min} / P_{max} = 0$; frequency - $10Hz$. In order to find the dependence between the stress in a remote cross section from the specimen and the equivalent stress in the critical point from the hole periphery, FEM simulation of the tensile test was carried out. Because of the symmetry, one eighth part (Fig. 6) was modeled from the portion of the specimen with sizes $60 \times 25 \times 5\,mm$ (see Fig. 1). The dependence obtained is shown in Table 5.

On this basis, the maximum tensile force of $14500\,N$ was applied for the fatigue tests under constant amplitude conditions. Thus, the amplitude of the cyclical stress in a remote cross-section, having a area of $125\ mm^2$ (see Fig. 1) was $\sigma = 116 MPa$. The maximum value of tensile force was chosen so that the working equivalent stress in the critical point from the hole periphery reaches the yield stress for the specimens from group “A”. Thus, the heavier variant for the specimens was obtained – conditions were near to low cycle fatigue.

The S-N curves were obtained for five amplitude values of the cyclical stress σ in a remote cross section in accordance with Table 5, respectively 116, 108, 100, 92 and 84 MPa. It should be noted that for mandrel cold working and SCE methods DCE was 4%, while FSHE was implemented with DCE of 1% and with optimal manufacturing parameters $n_e = 80\ min^{-1}$ and $f = 0.1\ mm/rev$, obtained from the fatigue test under constant amplitude condition.

4. RESULTS AND DISCUSSIONS

The experimental specimen specification and the corresponding number of cycles to fatigue failure in the conditions of low-cycle fatigue performance are shown in Table 4. The experimental results obtained from the fatigue tests for all specimen groups are summarized in Fig. 7.

The results for samples processed by FSHE with various interference fit i and mandrel frequency of rotation n_e, confirm the thermo-mechanical nature of this process (Fig. 7a). When the interference fit i and feed rate f are constant, the heat amount depends on the mandrel frequency of rotation n_e. The temperature factor has contrary effect on the micro- and macro-effect. The generated heat reduces the zone with useful residual stresses, but at the same time it favours modifying the material micro-structure immediately around the hole.

When the FSHE is implemented with smaller frequency of rotation ($n_e = 80\ min^{-1}$), the fatigue life increases, since a more favorable combination between the stir effect and the beneficial residual stresses is obtained. At the same time, the combination from higher frequency of rotation ($n_e = 160\ min^{-1}$) and larger DCE leads to a smaller fatigue life compared with that of the basic specimen. The reason is the favorable conditions for manifestation of the so-called sticking friction [23]. The latter is manifested by introducing defects in the treated surface due to separation of micro-particles from the aluminum alloy and adhesion to the tool.

Fig. 7b and Fig. 7c show repeatedly the greater efficiency of the SCE method compared to the solid mandrel method for the entire range of DCE. Unlike the solid mandrel method, the positive effect of the SCE increases with the increase of DCE - for $DCE = 4\,\%$ the largest value for N is registered: $N_{max} = 318932$.

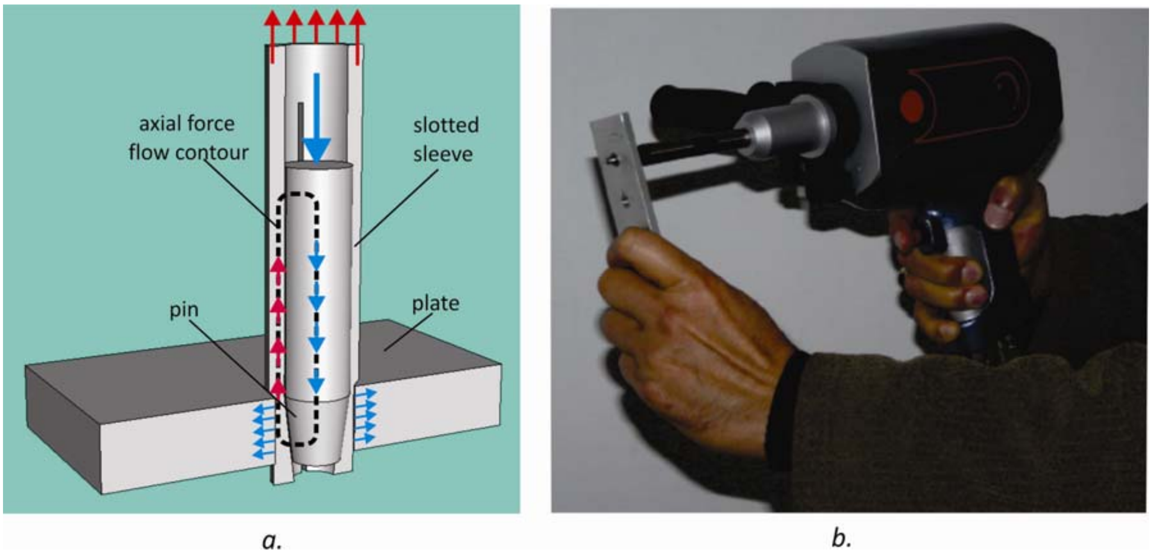

Fig. 5. SCE process implementation: a. scheme of the method; b. SCE device

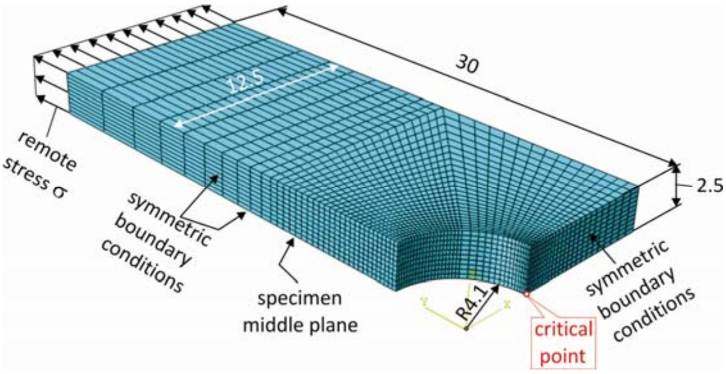

Fig. 6. FEM model of the tensile test

Table 5. *Dependence between remote stress and equivalent stress in the critical point*

Remote stress, MPa	*Equivalent stress in the critical point, MPa*
116	*356*
108	*355*
100	*332*
92	*305*
84	*279*

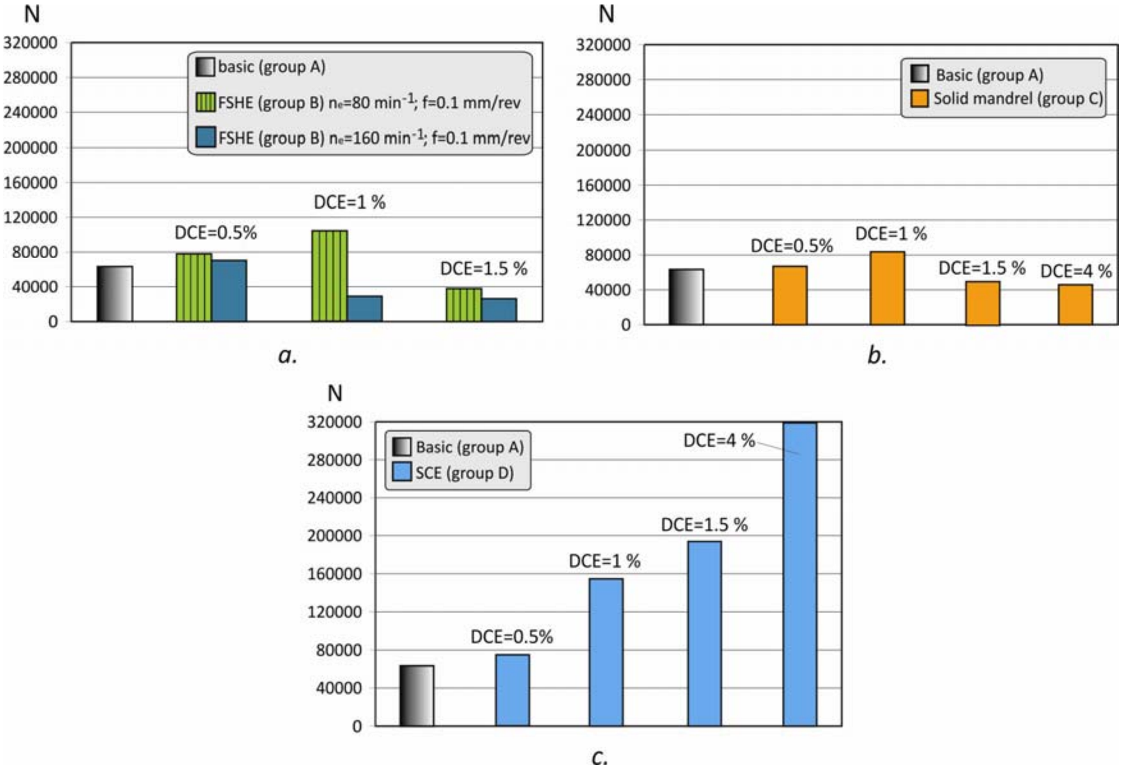

Fig. 7. Fatigue tests results

Fig. 8 evaluates the efficiency of the FSHE and Solid mandrel cold working methods under low fatigue cycle performance (remote stress $\sigma = 116 MPa)$. The larger fatigue life for both methods is obtained for $DCE = 1\%$. For a relatively small value of DCE ($DCE = 0.5 \div 1\,\%$), FSHE method shows larger (with $16 \div 24\,\%$) fatigue life in comparison with solid mandrel cold working, when the FSHE is implemented with manufacturing parameters $f = 0.1\, mm/rev$ and $n_e = 80\ min^{-1}$. Obviously, this trend changes when $DCE \geq 1.5\,\%$. Therefore FSHE is most effective in terms of enhancement of fatigue life when it is implemented with $DCE = 1\%$ and with technological parameters: $n_e = 80\ min^{-1}$ and $f = 0.1\, mm/rev$. Fig. 9 shows a comparison of the outcomes from the fatigue tests (with maximum remote stress of $116 MPa$) for solid mandrel cold working and SCE methods. Obviously, SCE is much more effective than the solid mandrel cold working method for all values of DCE. The effectiveness of the SCE increases with increasing DCE, unlike the solid mandrel method. It should be noted that this bad result for the solid mandrel method is valid for this material and only for low-cycle fatigue performance.

The results from this study confirm the great potential of the SCE method with respect to D16AT Al-alloy.

The S-N curves are shown in Fig. 10, comparing the reference conditions (RC) (the holes are drilled and reamed) with FSHE, mandrel cold working and SCE methods. As can be expected, the reference condition S-N curve shows smallest fatigue life in comparison with the other studied methods. The S-N curves, obtained for FSHE, mandrel cold working and SCE methods, confirm the significant advantage of SCE method. This advantage increases with decreasing the amplitude of the pulsating load. When $\sigma = 84\, MPa$, the SCE method ensures 1×10^7 cycles fatigue life without specimen destruction. The obtained fatigue life is more than 66 times in comparison with the mandrel cold working and more than 82 times compared to FSHE. On the other hand, no significant difference was observed between the S-N curves obtained from FSHE and mandrel cold working methods. As a whole, the solid mandrel cold working method ensures slightly larger fatigue life. However, this results for solid mandrel method was obtained when $DCE = 4\%$, while FSHE was carried out with DCE of 1%. An advantage of the FSHE method is that conventional machine-building equipment can be used for its practical implementation with the specified parameters.

In order to explain the results obtained by the fatigue tests, the residual stresses were measured after treatment by the three compared methods. The object of measurement is the residual hoop stress distribution around the holes in rectangular specimens. The holes were treated through FSHE, Solid mandrel cold working and SCE methods. The specimen sizes are $65 \times 40 \times 5\ mm$ as the largest size is aligned in the sheet rolling direction. The residual hoop stresses were measured on the front surfaces in the net section which is determined by the smaller specimen size after removal of the pure aluminum coating. This section coincides with the smallest cross-section of the fatigue test specimens (see Fig. 1).

Depending on the holes processing, the samples are denoted as follows:

- Specimen №1 - the hole is successively drilled, reamed and subjected to FSHE with the following parameters: $n_e = 80\, min^{-1}$, $f = 0.1 mm/rev$, $DCE = 1\%$;
- Specimen №2 - the hole is successively drilled, reamed and subjected to FSHE with the following parameters: $n_e = 160\, min^{-1}$, $f = 0.1 mm/rev$, $DCE = 1\%$;

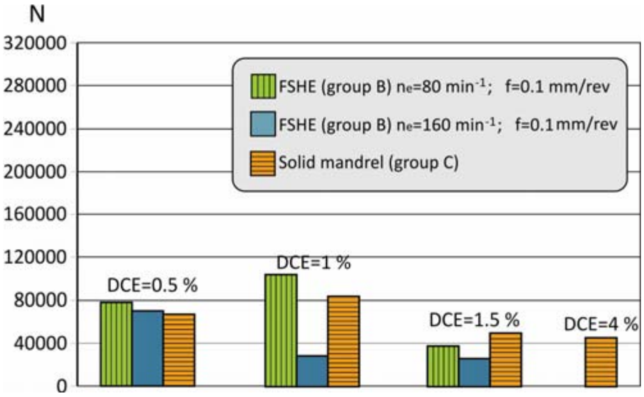

Fig. 8. Comparison between the FSHE and Solid mandrel cold working methods

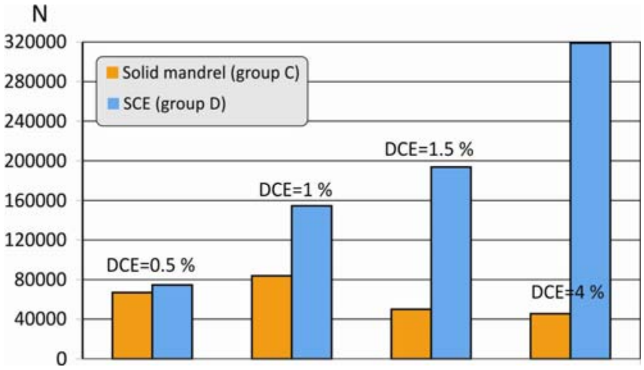

Fig. 9. Comparison between solid mandrel cold working and SCE methods

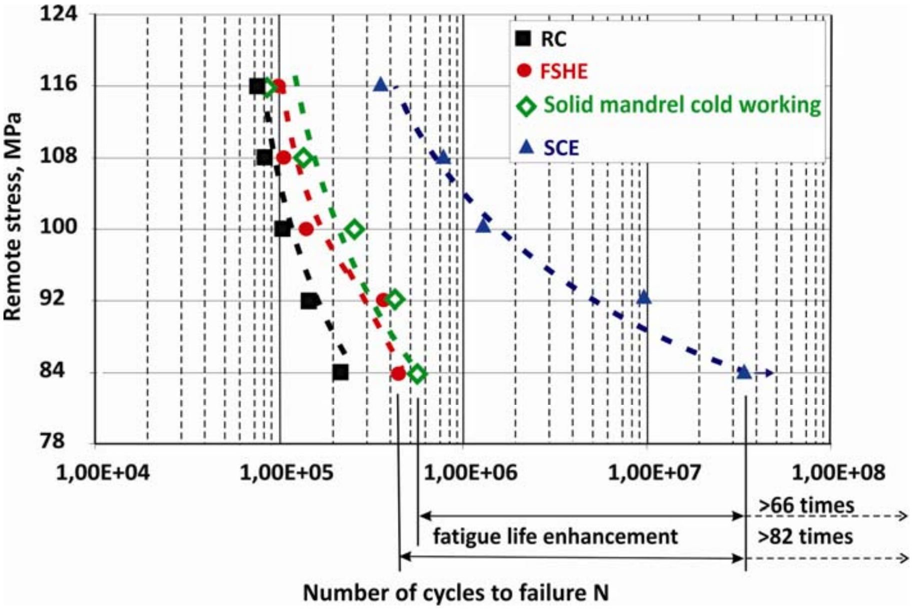

Fig. 10. S-N curves

- Specimen №3 - the hole is successively drilled, reamed and cold worked by means of solid mandrel with $DCE = 4\%$;
- Specimen №4 - the hole is successively drilled, reamed and cold expanded through SCE method with $DCE = 4\%$;

The residual stresses in base material (under the pure aluminum coating layer) of the specimens were measured using the X-ray diffraction technique. For that purpose the layers with coating were gradually removed by electrolytic polishing. Residual hoop stresses were measured by means of X-ray diffraction method. Diffraction measurements were carried out on a vertical θ/θ X'Pert PRO MPD diffractometer with a pin-hole collimator 0.5 × 1.0 mm² in the primary beam. Positioning of the measured sample to the required locations was done by combining versatile positioning system with six degrees of freedom and laser triangulation for precise surface position determination with accuracy of approximately $5\ \mu m$. Since the effective penetration depth of used $CrK\alpha$ radiation into the investigated alloy is only approximately $8\ \mu m$, a biaxial state of stress was assumed, and the „$\sin^2\psi$" method with least squares fitting procedure was used to evaluate residual stresses. The measured diffraction profile of Al {311} planes has for the used filtered CrKα radiation; its maximum at 2θ ≈ 139.5 °. Diffraction profiles were fitted by Pearson VII function, and lattice deformations were calculated. In the generalised Hooke's law, Winholtz&Cohen method and X-ray elastic constants $s_1 = 4.89\times10^{-6}\ MPa^{-1}$ and $\frac{1}{2}s_2 = 19.05\times10^{-6}\ MPa^{-1}$ were utilised. Moreover, the diffraction profile corresponding to Al {311} planes parallel with the surface was characterized by FWHM (Full Width at Half Maximum) profile parameter which could be interpreted as „degree of plastic deformation", because the diffraction profile broadening relates to such materials characteristics as grain size, microscopic residual stresses or dislocation density whose evolution is closely connected with plastic deformation.

X-ray diffraction outcomes for the residual hoop stress distribution on the specimen entrance and exit faces are depicted in Fig. 11. The results obtained for FSHE method confirm its thermo-mechanical nature. Obviously, the larger velocity (Specimen №2) leads to more generated heat and as a result tensile stresses arise around the hole edge (Fig. 11b). Conversely, the less pronounced temperature effect in Specimen №1 (Figure 11b) is a prerequisite for creating a wider zone with compressive residual stresses, respectively for larger fatigue life. Fig. 11c confirms the strongly expressed axial gradient in the residual hoop stress distribution, which is characteristic of solid mandrel method. The reason is in the principle scheme of the method - the process is carried out layer after layer, as the plastic deformation wave is moved in the hole axis direction together with the moving mandrel. As a result a significant axial force flow passes through the specimen thickness. This causes more intensive compressive field on the exit side (Fig. 11c).

This nature of residual stress distribution is a prerequisite for development of dangerous angular fatigue cracks arising from the entrance side in terms of the tool movement. To counterbalance that, the SCE method provides a homogeneous distribution of the residual hoop stresses through the specimen thickness (Figure 11d). At the same time, the created residual stress zone is almost symmetrical with respect to the specimen middle plane. The explanation is that the SCE method ensures “pure” radial impact on the hole surface, which results in a minimum axial gradient of the introduced residual stresses [19, 20]. Therefore, the significant advantage of the SCE in terms of fatigue life (see Fig. 9 and Fig. 10) is due to the almost symmetrical and homogeneous distribution of the beneficial compressive hoop stresses around the pre-stressed holes.

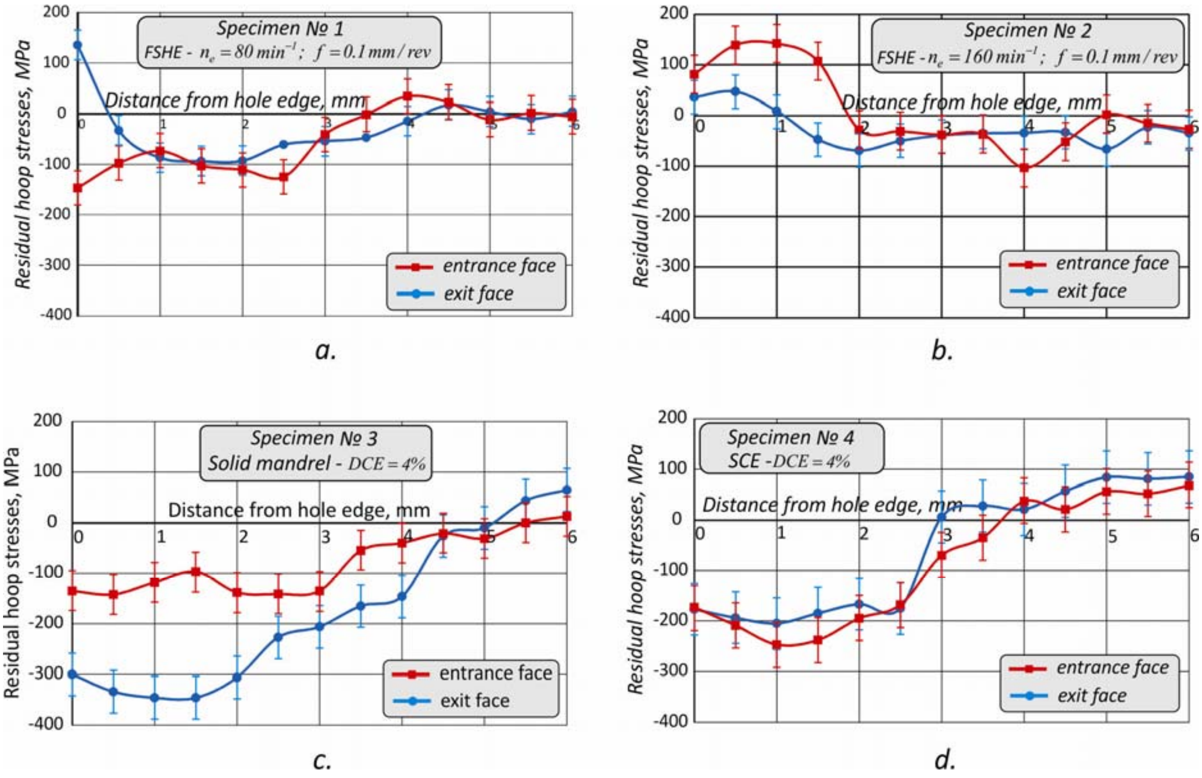

Fig. 11. Residual hoop stress distribution

For a qualitative evaluation of the useful micro-effect, expressed in the modification of the microstructure around the hole due to the FSHE process, the micro-structural analysis was performed. In accordance with the nature of FSP, the stir effect occurs as a result of severe plastic deformation and temperature higher than the recrystallization temperature. The result is microstructure modification, expressed in grain refining, homogenization and reducing the material pores. The temperature field in the material immediately around the hole and the size of the plastic strain are due to the following main factors:

- the contact type between the tool and the hole surface in axial and circumferential directions (normal contact, tangential one or a combination of the two);
- the plastic strain rate in axial and circumferential directions.

In this aspect, the difference between the FSHE and SCE methods is greatest, and therefore the object of microstructure analysis are two specimens whose holes are treated through these methods. The specimens preparation for optical micrographs is illustrated in Fig. 12.

The hole, subjected to SCE, was cold expanded with $DCE = 4\%$. The hole, subjected to FSHE, was processed with the established optimum parameters: $DCE = 1\%$, $n_e = 80\ min^{-1}$, $f = 0.1\ mm/rev$.

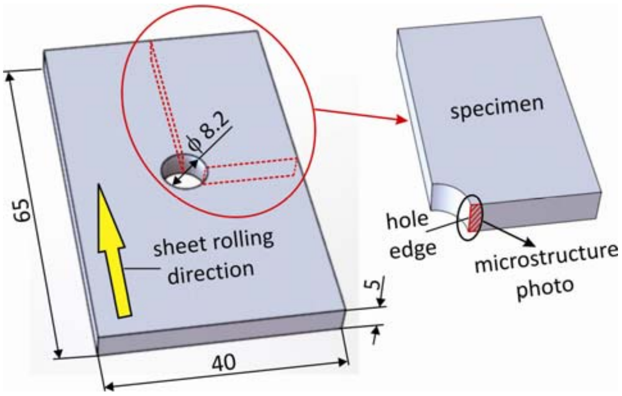

Fig. 12. Specimen preparation for optical micrographs

The obtained optical micrographs are shown in Fig. 13. The investigated D16AT alloy due to the large amount of alloying elements has a multiphase structure. As a consequence of heat treatment and subsequent aging, hardening phases are obtained in the solid solution. The main hardening phases are $CuAl_2$ and $Al_{12}CuMg$. Much of the grains have the form of secondary dendrite branches and the grain sizes vary within relatively wide limits. This structure is observed in the base material in a depth greater than $0.1\ mm$ from the hole edge (Fig. 13).

The comparison between Fig. 13a,b and Fig. 13c,d shows visibly microstructure evolution near the edge of the specimen hole which is treated by the FSHE method. The modified microstructure zone has a small thickness - approximately $0.06\,mm$ and is localized immediately to the hole edge (Fig. 13a,b).

The microstructure modification is expressed in the grains refining, the material homogenization and the pores reduction. With other words the so-called stir effect is manifested in this area. This effect is mostly caused by tangential stresses with considerable intensity due to the friction forces between the tool and the hole surface in circumferential direction in the presence of interference fit. The FSHE process provokes an increased local temperature, a large plastic deformation and a high strain rate. These factors, in accordance with the FSP concept, are the physical basis for modifying the microstructure [23, 27]. This modified microstructure provides increased fatigue strength, despite the absence of a zone with residual compressive hoop stresses around the hole on the exit face (see Fig. 11a). Unlike the FSHE, the SCE method excludes tangential contact between the tool working parts and the hole surface, since a pure radial cold expansion process is fulfilled [19]. The presence of a normal contact only between the tool and the hole at room temperature conditions and the final reaming practically does not alter the microstructure of the investigated aluminum alloy (Fig. 13c, d). This confirms that the high efficiency of SCE method is entirely due to the macro-effect.

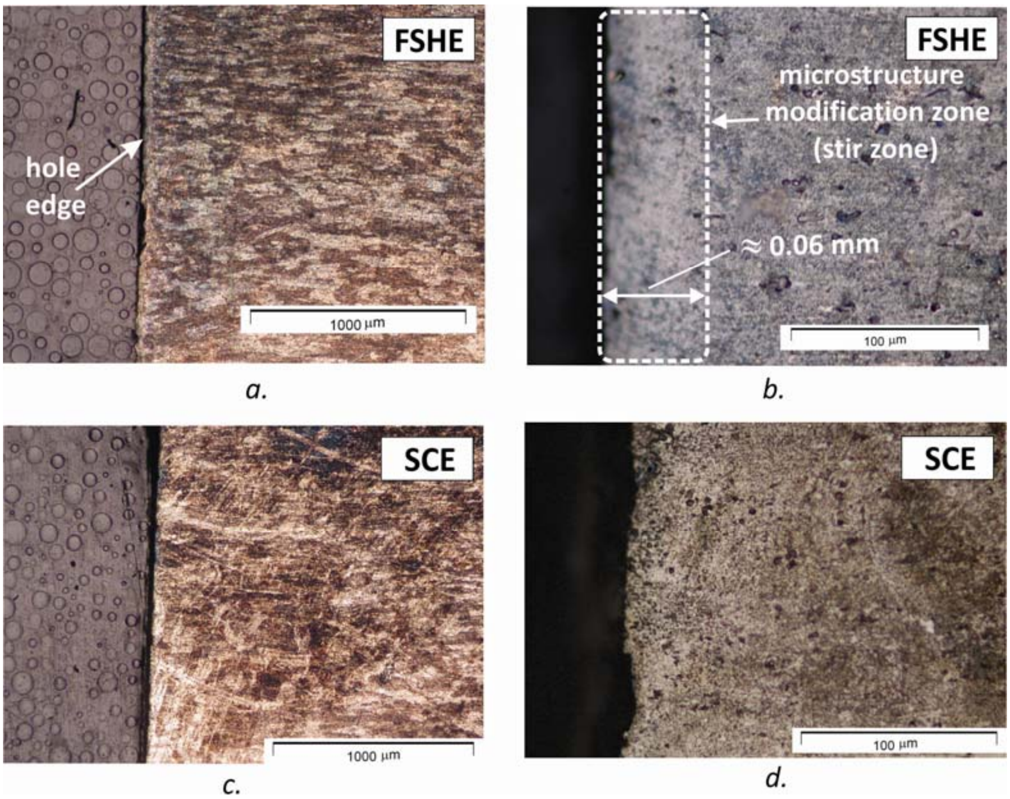

Fig. 13. Optical micrographs

5. CONCLUSIONS

In the present study, for the first time, the effectiveness of different methods for enhancement of fatigue life of D16AT aircraft components with fastener holes has been studied. A comparative analysis of the efficiency of FSHE, Solid mandrel cold working and SCE methods is made. On the basis of the results obtained from comprehensive experimental study, including fatigue tests, X-ray diffraction and microstructure analyses, the following conclusions are made:

- From the three studied methods, SCE method ensures largest fatigue life of D16AT Al-alloy specimens. For remote stress of $84MPa$, the specimens reach 1×10^7 cycles fatigue life without any destruction. This is more than 66 times in comparison with solid mandrel method and more than 82 times compared to FSHE method. The SCE method is most effective when is performed with $DCE = 4\%$. The main reason for the high efficiency of the method is the symmetrical and homogenous in regard to the middle plane area with beneficial residual hoop stresses. Therefore, the SCE method should be used for pre-stressing of fastener holes in the most loaded components in the aircraft - wings and fuselage.
- In accordance with the obtained $S-N$ curves, the solid mandrel method provides significantly less fatigue life as compared to the SCE for the same DCE of 4%. This difference is due to the strongly expressed axial gradient of the residual hoop stress distribution. By X-ray diffraction analysis it was found that generated residual stresses on the exit face were with about $200\,MPa$ greater in absolute value compared to the residual stresses on the entrance face. This gradient is a prerequisite for the nucleation and propagation of corner fatigue cracks, which significantly reduce the fatigue life.
- Due to the thermo-mechanical nature of the FSHE method, its effectiveness depends on the ratio between the heat generated and the size of the plastic deformation, respectively between the micro-effect from the microstructure modification immediately around the hole and the macro-effect from the introduced residual stresses. The conducted fatigue tests and X-ray diffraction analysis confirm the correlation between the mandrel rotation

velocity, generated heat, and residual hoop stresses distribution. The carried out micro-structural analysis reveals the presence of a thin layer of material with a thickness of about $0.6\ mm$ immediately around the hole with a modified micro-structure (stir effect). This effect is a physical basis for increasing the fatigue strength of structural components made of D16AT Al-alloy. The FSHE method is most effective when it is performed with relatively small values for interference fit, the rotation velocity and axial feed rate: $DCE = 1\%$; $v \approx 2\, m/min$; $f = 0.1\ mm/rev$. Implemented with these optimal parameters, FSHE method provides slightly less fatigue life compared to the solid mandrel method. However, its advantage over the solid mandrel method is the possibility of implementation on conventional machine tools without a special hydraulic power device. The FSHE method should be applied for finishing processing of fastener holes in less loaded aircraft structural components. Thus, the FSHE method not only reduces labour and time consumption, but it also decreases the overall cost for processing a large number of holes in D16AT aircraft structures.

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