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EXPERIMENTAL STUDY OF AXIAL FORCE AND TORQUE DURING THE PROCESS FRICTION STIR HOLE EXPANSION IN ALUMINUM ALLOY D16AT

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Purpose. This paper presents the outcomes from experimental study of the Friction Stir Hole Expasion (FSHE) method. **Methodology.** We have applied the mathematical simulation and construction of graphs by the received results. **Results.** 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 alteration of axial force and torque in real time depending on the rotating frequency, feed rate and interference fit have been studied in conditions of dry friction and lubrication. **Originality.** For the first time, i have carried out the integrated research of this problem. **Practical value.** The outcomes obtained have been proved the thermo-mechanical nature of the FSHE process.

Key words: Friction Stir Hole Expansion, experimental study, aluminum alloy D16AT, axial force, torque.

ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ ОСЬОВИХ СИЛ І КРУТНОГО МОМЕНТУ ПІД ЧАС ПРОЦЕСУ РОЗШИРЕННЯ ОТВОРУ ТЕРТЯМ З ПЕРЕМІШУВАННЯМ В АЛЮМІНІЄВОМУ СПЛАВІ Д16АТ

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Представлено результати експериментального дослідження процесу розширення отвору тертям з перемішуванням (FSHE). FSHE-процес спрямований на поліпшення опору втомленому руйнуванню конструктивних елементів з отворами в алюмінієвих сплавах. Об'єктом дослідження є високоміцний алюмінієвий сплав Д16АТ. Зміна осьової сили і крутного моменту в режимі реального часу в залежності від частоти обертання, швидкості подачі та натягу вивчалися в умовах сухого тертя і змащення. Отримані результати були доведені термомеханічною природою процесу FSHE.

Ключові слова: розширення отвору тертям з перемішуванням, експериментальне дослідження, алюмінієвий сплав Д16АТ, осьове зусилля, крутний момент.

PROBLEM STATEMENT. The fastener and structural holes are among the most frequent natural concentrators of strains and stresses in the machine and structural components. The strength resource of these elements depends primarily on the material condition around these holes as natural concentrators of deformations and stresses. This state is defined by the complex of geometric, physical-mechanical and crystallographic characteristics of the superficial layers, known as «surface integrity». When the structural elements are subjected to dynamic loading, the limiting factor to their strength resource is the fatigue in the areas around the holes. The damage and accidents caused by fatigue cracks around the rivet and bolt holes are typical for the bearing structural components in the aircraft. Such are the numerous fastener holes in the aircraft sheath, fuselagep wings and others. Due to the vibrations, first mode fatigue cracks are initiate and growth - cracks, whose tip propagates in radial direction with respect to the hole surface area [1].

For the prevention of nucleation and propagation of fatigue cracks, it is necessary the manufacturing process of processing these holes to provide an appropriate combination of qualitative characteristics in the surface layers around the fastener holes. The most important of these characteristics are: low roughness, high micro-hardness, useful residual compressive stress, high corrosion resistance and very fine microstructure. An effective approach in this direction is a technology based on finishing machining of holes by cold plastic deformation, i.e. under the conditions of room temperature. As a whole, the effect of the impact on the metal by means of plastic deformation depends on the basic characteristics of this impact – equivalent plastic deformation $\varepsilon_{ekv}^{pl},\%$, strain velocity $\dot{\varepsilon}, s^{-1}$, temperature field and the type of the contact between deforming element and the surface being treated – rolling contact or slide friction contact. The combination of the pointed out characteristics determines the scale in which the effect from plastic deformation is evaluated – in the entire volume of the corresponding structural component or a level of crystal lattice or even atomic level. In the first case the new material quality is due to the fact that the corresponding structural component passes in a new equilibrium state after its plastic deformation. In the second case the material modificationconsists in a change of the microstructure. This formulation allows to be investigated the state change of the material, undergoing of plastic deformation, from different points of view – according to the mechanics of deformable solid, according to the microstructure modification, or an approach which combines the two effects. Using this formulation, the basic approaches for enhancement of fatigue life of metal structural components with fastener holes are grounded and systematizedin [2–4]:

Macro-approach. The following idea leas in basis of this approach: plasticizing of the material around the existing or future hole in a depth in order to create around the hole a field with useful residual circumferential normal compressive stresses. When the created compressive field around the hole has a sufficient intensity and depth, it acts like a bracket which significantly retards the process of nucleation and propagation of first mode fatigue cracks [5–16]. The basic contribution in the equivalent plastic strain ε_{ekv}^{pl} (4–5%) is due to linear hoop strains $\varepsilon_{t,0}$ in the point from the hole surface. This strain is numerically equal to the 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.

Since the temperature factor neutralizes the compressive residual stresses, the process is implemented in cold condition – at a temperature lower than the temperature of re-crystallization of the corresponding metal. For the same reason, in order to eliminate the possibility of local increasing the temperature in the contact zone between the tool and the surface being treated, the strain velocity is limited: $\dot{\varepsilon} = 1\times 10^{-4} \div 1\times 10^{-3}, s^{-1}$ [2]. Because of that the methods, which practical implementation corresponds to the pointed out characteristics of the macro-approach, are called «cold working». Chronologically the first methods are accomplished through conical-cylindrical or spherical mandrel, which passes via the hole in the presence of interference fit – respectively Ball Cold Working and Mandrel Cold Working. For the needs of the aviation industrythe Split Sleeve Cold Expansion [17–19] and Split Mandrel Cold Working [20–21] methods have been developed. Their practical implementation is subordinate of one and the same conception – special mobile devices with hydraulic drive are used and the manufacturing process practically corresponds to «dimensional» process. A consequence of this, the technological process contain a large number of steps, most of which have operations for control of previously treated holes and the working parts of the tools. The large number of operations and the need for well-trained operators increase the treatment cost.

Micro-approach. The idea for the modification of the material microstructure in a direction of grain refining, reducing the pores in the material and homogenization of the structure, lies in the basic of this approach. A quantitative criterion for a useful modification of the microstructure are the size of grains - in the presence of grain refinement, their size is below $20 \div 50\ \mu m$. The result of this is increasing the mechanical properties, ductility, corrosion resistance and fatigue life of the material. The micro-approach is based on the requirement of very large plastic deformation, for which the shear stresses have a significant contribution. For that purpose, forces of friction between the tool and the metal with considerable intensity are needed, a phenomenon known as «Severe Plastic Deformation» [22]. A modern concept based on «Severe Plastic Deformation» is the Friction Stir Processing (FSP) concept [23]. The practical implementation of FSP is directed to aluminum alloys. The process has a thermo-mechanical nature since the heat generation in the contact zone between the tool and the surface being treated [4]. This heat is generated in two directions – due to friction forces between the tool and the metal being treated and due to the provoked severe plastic deformation. For this purpose, a compressive force has been applied to the tool, which is simultaneously moved along the hole axis. In FSP the material flow is characterized with complex gradient with respect to plastic deformation, temperature and strain velocity. The purpose is achieving Stir effect, i.e. intensive plastic deformation in condition of increased temperature. It is assumed that the transition toward high strain velocity is ensured, if $\dot{\varepsilon} \geq 1\times 10^{-2}\ s^{-1}$ is executed for the strain velocity. The outcome is the full material re-crystallization and the positive effect from this is the achieving grain refining microstructure. The latter leads to excellent mechanical properties, increased fatigue strength [24–26], exceptional plasticity (super plasticity) and better workability [27]. The scientific publications on the FSP technique, refer to commercial aluminum alloys with low mechanical properties ($\sigma_S = 25\ MPa$) [28].

The combined approach for increasing fatigue life of structural components with fastener holes is based on combining between particular characteristics of the macro- and micro-approaches [4]. The basis of this approach is the idea for modification of Mandrel Cold Working method by means of an additional rotation of the conical-cylindrical mandrel around the axis of the previously drilled hole. For a such formulation, the following factors are determining: an impact on the hole surface in the presence of interference fit; tangential contact in radial and axial directions between the tool and the hole exists. The joint action of these factors allows to combine the macro-effect, expressed in generating a zone with beneficial residual compressive hoop stress in relatively large depth, with the micro-effect (Stir effect).

Applying the combined approach, the method's name Friction Stir Hole Expansion (FSHE) is grounded [4]. FSHE method can be considered as development of the conception FSP for finishing treatment of fastener holes in aluminum alloys. The basic advantage of the method is the possibility for implementation on conventional machine tools due to the «softening effect» of the material immediately the hole surface. On the other hand, in view of the widely application of the high-strength aluminum alloys in the airspace industry, an interest is the study of FSHE method in technological aspect with respect to such materials.

WORK GOAL of this study is to investigate the axial force and torque in the implementation of the FSHE method on the aluminum alloy D16AT which is widely used in aircraft.

MATERIAL AND RESULTS. In accordance with the FSHE method scheme (Fig. 1), the tool is set in motion by the machine spindle performing rotation around own axis with frequency n_e and simultaneously rectilinear translation along the axis of the previously drilled hole with a velocity determining by feed rate *f, mm/rev*. The working cycle includes primary and reverse stroke. The first of them finishes when the common section of thetapered and cylindrical sections overtakes with a few millimeters the hole output side. The reverse strike is performed with the same rotation direction.

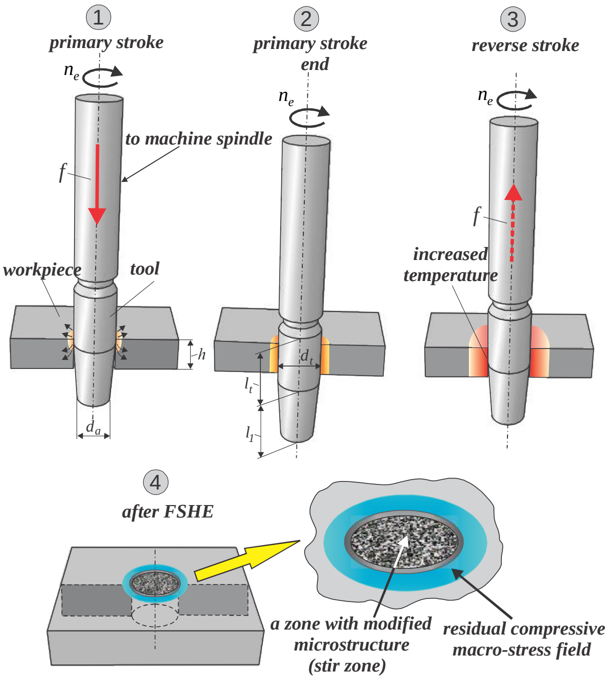


Figure 1 – Principle scheme of FSHE method

Depending upon the ratio between the temperature factor, the amount of plastic deformation and the rate of deformation of the following areas exist [4]:

Stir zone – a area with very small thickness immediately around the hole surface, having a modified microstructure due to the increased local temperature, a large plastic deformation and large velocity of deformation in circular direction;

Transition zone – a area in which the interference between micro- and macro effect is obtained;

Zone with pronounced macro-effect - a zone with very little temperature effect and significantly less plastic deformation, in which zone, after the finalization of the operating cycle residual useful macro compressive stresses are generated.

The instantaneous value of the friction coefficient is determined by:

$$\mu = \frac{F_f}{N} = \frac{2T_f / d_0}{N}, \qquad (2)$$

where F_f and T_f are respectively the friction force and the friction moment, acting in the contact zone between the tool and the hole surface; N is the normal force for which:

$$N = \pi\, d_0\, a\, \sigma_r \qquad (3)$$

where a is the contact zonewidth; σ_r is average integral value of the radial stress in the contact zone. In reality, σ_r and d_0 are variable quantities due to «softenenig effect» in the material as a result of the increased local temperature near the hole surface. Taking into account the thermo-mechanical nature of the FSHE method and the dynamics of the tangential contact between the tool and the hole surface, it is necessary to investigate the change of the power parameters of the process – axial force and the rotating moment.

The experimental study is based on the experimental setup for measuring the axial force and the torque in real time. The experimental setup is adapted for a universal milling machine (Fig. 2). The specimens are of type «sleeve» and have the following overall dimensions: outer diameter of 50 mm and high of 5 mm. After final reaming, the hole diameter is in the range d_0= 8,222 – 8,225.

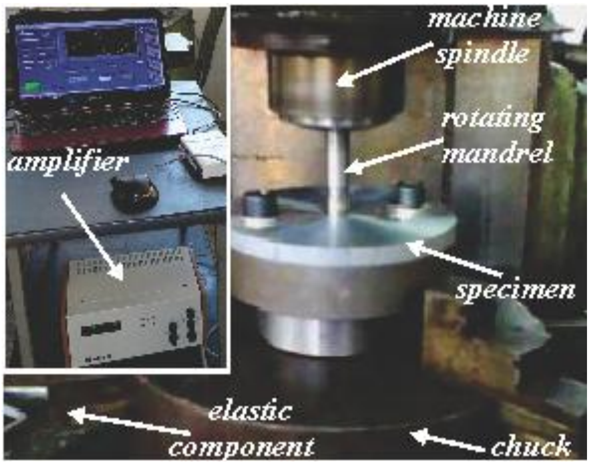


Figure 2 – Experimental setup

The material is aluminum alloy D16AT. For ensuring different interference fit, five conical-cylindrical mandrels are designed and manufactured. Their sizes are shown in Fig. 3 and Tabl. 1.

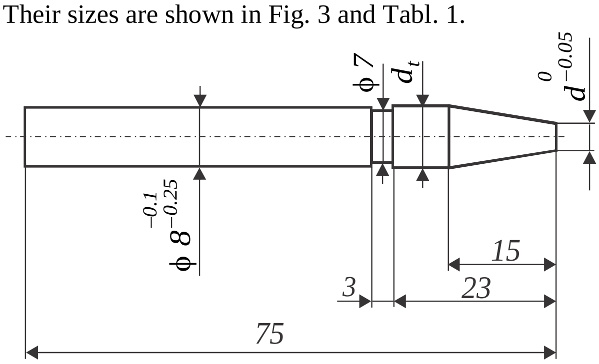


Figure 3 – Mandrel's geometry

The rotating moment (torque) and axial force, applied on the mandrel, have been determined experimentally trough a specially designed device (elastic component) (Fig. 2).

This device transforms the relative rotation of the sample, resulting from the torque, in displacement of the inductive sensor tip. This sensor signal is directed to an instrumental amplifier. The amplified signal is fed to the analog input of the USB DAQ – board. Similarly the device transforms the relative axial displacement, resulting from the axial force, in displacement of another inductive sensor tip, which has been situated in axial direction. A purposely created virtual tool through Labview is used for visualization and storage of the measured data. Simultaneously, the specimen's temperature is measured by a thermal imager FLIR E6.

Table 1 – 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	0,06	3,62	8,285	0,79
3	0,08	3,64	8,305	1,034
4	0,1	3,66	8,325	1,277
5	0,12	3,68	8,345	1,520

Experimental results and discussions.

1. Effect of rotating frequency.

The rotating frequency n_e, *tr/min* is a very important factor for the temperature local increasing immediately to the hole surface. The effect of n_e is studied in the condition of dry friction and with using of lubricant as well, for the constant values of the interference fit and feed rate: i_{init}*=0,08 mm*; 5 *mm*; *f=0,1 mm/rev*. The change of the axial force and the rotating moment in condition of dry friction is depicted in Fig. 4a and Fig. 4b respectively. The axial force depends on the change of the tangential contact along the axis of the hole being treated, respectively on the manufacturing resistance in axial direction. The graphs in Fig. 4a show significant variation range of the measured maximum values of the axial force in conditions of dry friction – 312 – 1157 N. As a whole, larger axial forces is observed at a smaller frequencies (the largest axial force is at n_e=160 tr/min) and vice versa – the axial forces are smallest at the largest frequencies.

This alteration can be explained through the softening effect of the material due to the local temperature increasing when the process is carried out for more time for small values of the frequencies (Fig. 4a).

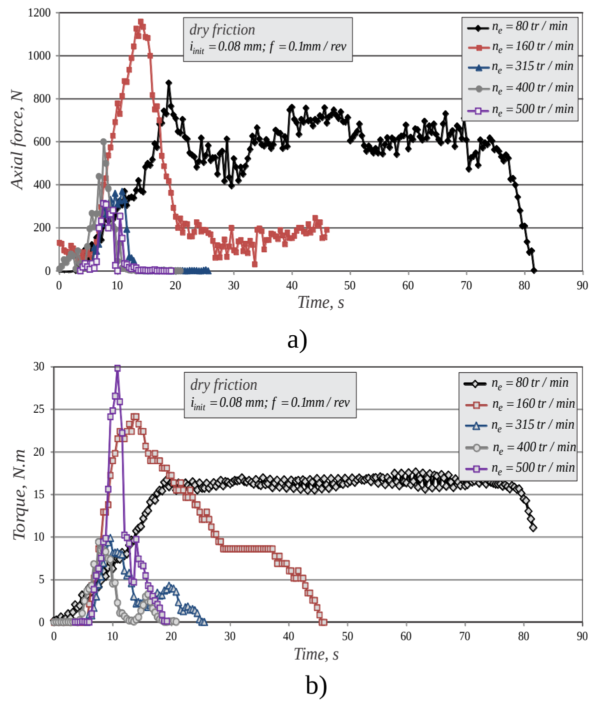


Figure 4 – Alteration of axial force and torque depending on rotating frequency in dry friction condition

The alteration of the rotating moment is determined by the change of the manufacturing resistance in hoop direction. Fig. 4b shows significant influence of n_e on the rotating moment alteration – for the studied frequency range the measured maximum values of the moment is changed in the range of 9,5 – 30 Nm. Despite that for n_e=500 tr/min the largest rotating moment is measured, a trend for decreasing the moment is observed, when n_e increases. The reason is the same as for the amendment of the axial force – the effect of the localizedtemperature which practically leads to smaller interference fit.

From the other hand, the physical mechanism of the sticking friction phenomenon reflects in the separation of micro-particles from the workpiece, some of which adhere to the tool, and another part wedges in the treated surface [3]. Thus, the friction coefficient and the interference fit are changed during the working cycle. In this way the maximum measured values of the moment for the largest studied frequency (n_e=500 tr/min) can be explained.

Fig. 5a–5f gives a opportunity a comparison to be made between the axial forces and the rotating moments, measured in conditions of dry friction and with using of lubricant. For the whole studied range of frequencies (n_e=315 – 500 tr/min), larger maximum values of the axial force are measured when a lubricant is used in comparison with the case of dry friction.

In the presence of a lubricant, the local temperature around the hole is smaller and as a result bigger manufacturing resistance arises in axial direction. At the same time, very close nature of change of the axial forces in qualitative aspect is observed. With exception of the case of n_e=500 tr/min, larger rotating moments are measured when a lubricant is used in comparison with the case of dry friction.

2. Effect of the interference fit.

The power parameters of the FSHE process are studied in conditions of dry friction for 5 values of the initial interference fit i_{init} in accordance with Table 1.

The experimental outcomes for the measured values of the axial force and the rotating moment are generalized in Fig. 6a and Fig. 6b respectively.

Apparently, for one and the same values of the manufacturing parameters n_e and f the axial force is changed to a lesser extent depending on the nominal interference fit, without a clear tendency to be observed. The smallest axial force is measured for i_{init}=0,08 *mm*. The biggest rotating moment is measured for i_{init}=0,1 *mm*, which most likely is due to the sticking friction effect. For the remaining values of the interference fit, relatively small scattering of the maximum values (10 – 12 N.m) of the rotating moment is observed.

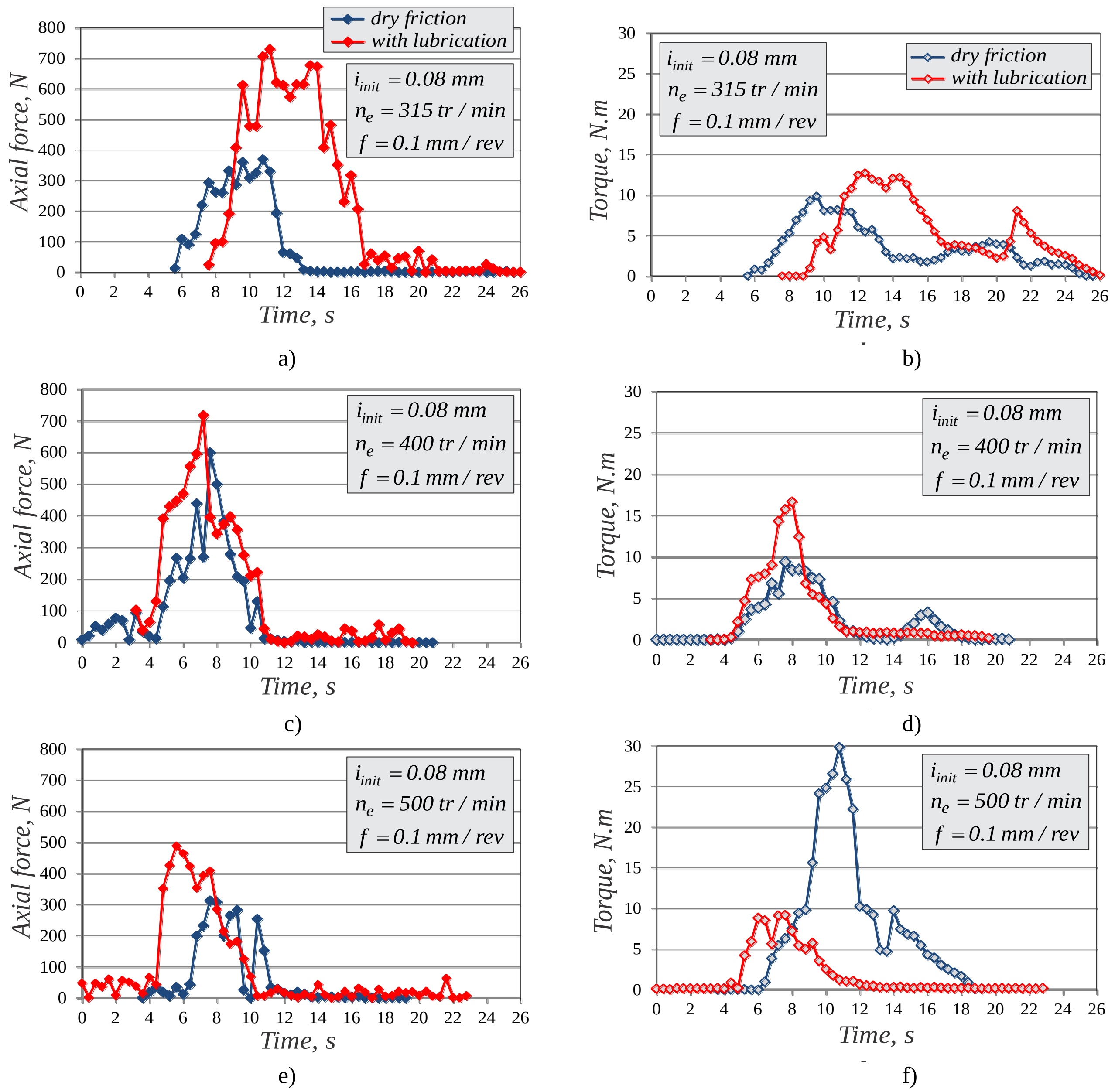


Figure 5 – Comparison between axial force and torque in conditions of dry friction and with lubrication for different rotating frequencies

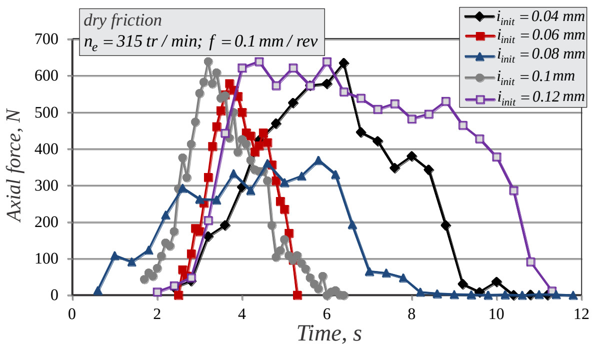
Fig. 7 a, b shows a comparison between the axial forces and the rotating moments for the cases of dry friction and utilization of lubricant for two values of the interference fit: i_{init}=0,06 *mm*, i_{init}=0,1 *mm*.

For the investigated values of the interference fit, the axial force is bigger when the FSHE process is implemented in the condition of dry friction (Fig. 7a, c). At the same time, the difference between the maximum values of the axial force for the two cases (with and without utilization of a lubricant) decreases when the interference fit increases (Fig. 7c).

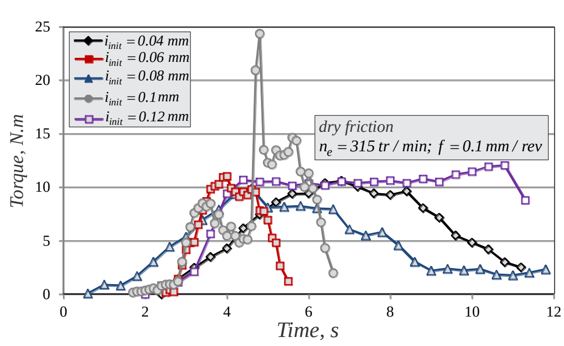
In regard to the effect of the interference fit on the maximum values of the rotating moment the following phenomenon is observed (fig. 7b, d): a larger moment for smaller interference fit in conditions of lubricant, while a bigger moment is necessary for dry friction. This fact shows that the tangential contact in hoop direction is significantly changed at relatively small difference in regard to the nominal interference fit and different conditions of friction.

3. Effect of the feed rate.

The experimental outcomes for the alteration of the axial force and the rotating moment depending on the feed rate *f, mm/rev* for dry friction are generalized in Fig. 8 a, b. The alteration of the feed rate ceteris paribus leads to a different processing time and hence affects on the generated heat in the vicinity of the hole being treated. When the feed rate *f* increases the axial force grows, since the process is fulfilled for smaller time, respectively larger manufacturing resistance in axial direction has to be overcome. As a whole, a clear trend is not observed in the change of the rotating moment – the largest moment is measured when the feed rate is the smallest (Fig. 8b).

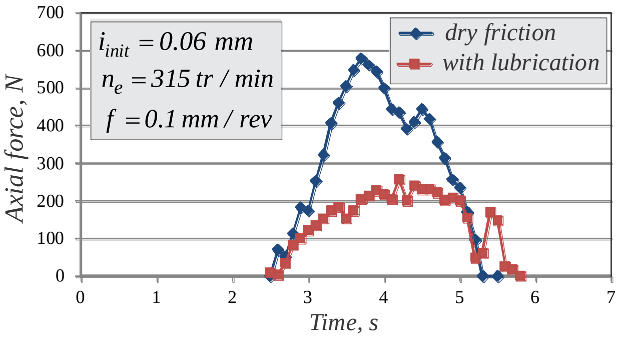


a)



b)

Figure 6 – Alternation of axial force and torque depending on tightness in condition of dry friction



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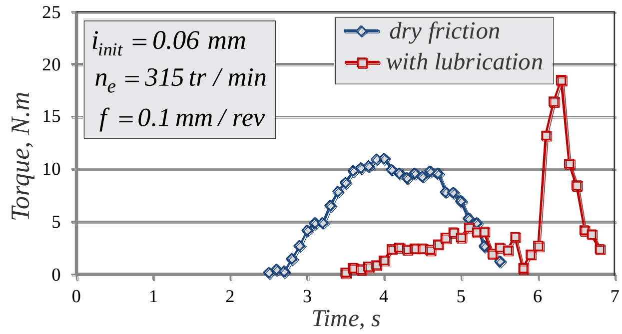

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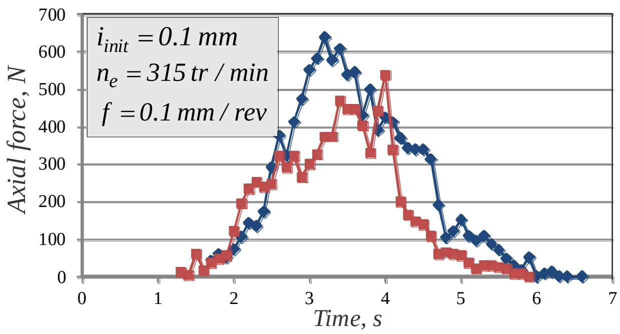
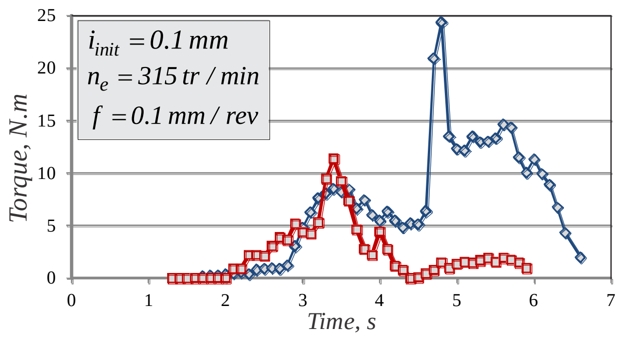
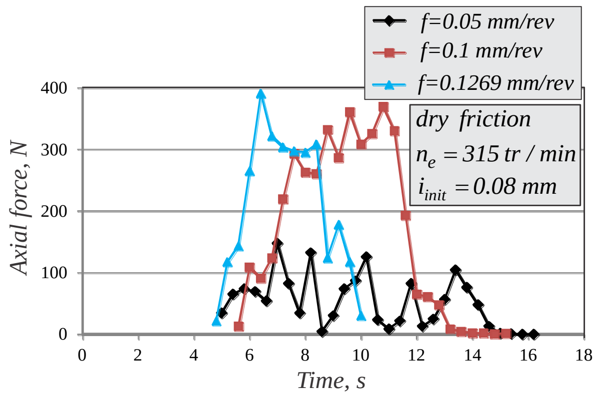


c)



d)

Figure 7 – Comparison between axial force and torque in conditions of dry friction and with lubrication for different tightness



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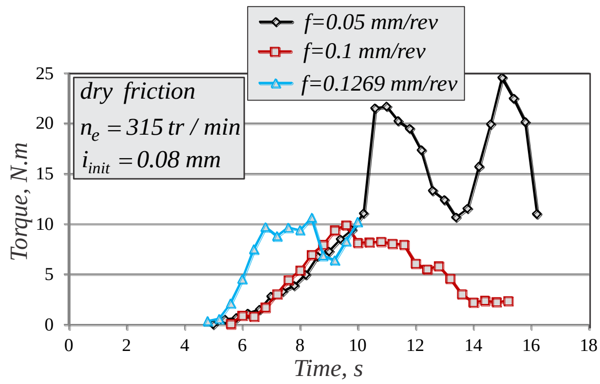

b)

Figure 8 – Alternation of axial force and torque depending on feed

4. Study of the temperature during the FSHE process.

For assessment of the temperature effect during the FSHE process, two measurements of the maximum registered temperature are made for a part from the samples – when the working part of the mandrel is in middle position with respect to the height of the hole being treated; when the working part of the mandrel is in end position. A thermal-visual camera FLIRE6 has been used. The measurement is directed to regions which are close to the hole periphery. The experimental outcomes are depicted in Table 2.

Table 2 – Measured temperature during the FSHE process

№	Parameters of the FSHE process	Initial temperature t_0, °C	Temperatute in the middle position t_1, °C	Temperatute in the final position t_2, °C	Temperature difference $t_2 – t_0$, °C
1.	dry friction; *i=0,08 mm; n_e=315 tr/min; f=0,1 mm/rev*	27	60	86	59
2.	dry friction; *i=0,08 mm; n_e=400 tr/min; f=0,1 mm/rev*	27	55	99	72
3.	dry friction; *i=0,08 mm; n_e=500 tr/min; f=0,1 mm/rev*	27	94	128	101
4.	with lubrication; *i=0,08 mm; n_e=315 tr/min; f=0,1 mm/rev*	37	88	121	84
5.	with lubrication; *i=0,08 mm; n_e=400 tr/min; f=0,1 mm/rev*	35	88	96	61
6.	with lubrication; *i=0,08 mm; n_e=500 tr/min; f=0,1 mm/rev*	35,3	112	169	133.7
7.	dry friction; *i=0,04 mm; n_e=315 tr/min; f=0,1 mm/rev*	35,6	45	47.6	12
8.	dry friction; *i=0,12 mm; n_e=315 tr/min; f=0,1 mm/rev*	35,5	59	126	90,5

The results from Table 2 do not giveany information for the temperature in points from the hole surface. For that reason it cannot accurately assess whether the temperature of re-crystallization in the material immediately to the hole surface is reached. In Table 2, with one and the same color, the measured temperatures are shown for specimens, which are treated with one and the same values of the interference fit and process manufacturing parameters, as the difference is in the friction conditions – with and without utilization of lubricant. The juxtaposition of the results for the temperature difference of the couples specimens with numbers 1–4, 2–5, 3–6 does not show a clear tendency for the generated heat during the process depending on the conditions of the friction and the rotational speed. The reason is in the thermo-mechanical nature of the FSHE process and as a consequence – in the dynamics of the tangential contact between the tool and the hole surface. The localized heat around the hole decreases the manufacturing resistance and this practically leads to a variable interference fit during the process. The comparisonbetween the temperature difference of the specimens 7 and 8 shows that a deviation from the initial interference fit than 0,08 *mm* is reflected in a significant difference in the generated heat.

On the other hand, when the process is implemented in conditions of dry friction, deposition of particulate material on the working part of the mandrel is observed for some of the processed holes. This effect can be explained by sticking friction [3], which effect is absent when the process is carried out with lubrication.

CONCLUSIONS.The outcomes obtained can be generalized with the following conclusions:

1. The experimental results for the measured in a real time axial force and rotating moment prove the possibility for implementation of FSHE method for finishing of holes in aluminum alloy D16AT on conventional machine tools;

2. The FSHE process is essentially a thermo-mechanical, as the maximum values of the axial force and the rotating moment depend on the particular combination of technological parameters, the initial interference fit and conditions of tangential contact - with or without the presence of lubricant.

3. On the basis of the measured temperatures in the treated specimens close to the holes (even when using a lubricant, temperature of 169 °C is reached), it can be assumed that the material immediately around the hole reaches the temperature of re-crystallization. Therefore, an appropriate modification of the micro-structure can be expected. This modification can increase the fatigue strength of the aluminum alloy D16AT.

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ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ОСЕВЫХ СИЛ И КРУТЯЩЕГО МОМЕНТА ВО ВРЕМЯ ПРОЦЕССА РАСШИРЕНИЯ ОТВЕРСТИЯ ТРЕНИЕМ С ПЕРЕМЕШИВАНИЕМ В АЛЮМИНИЕВОМ СПЛАВЕ Д16АТ

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Представлены результаты экспериментального исследования процесса расширения отверстия трением с перемешиванием FSHE. FSHE-процесс направлен на улучшение сопротивления усталостному разрушению конструктивных элементов с отверстиями в алюминиевых сплавах. Объектом исследования является высокопрочный алюминиевый сплав Д16АТ. Изменение осевой силы и крутящего момента в режиме реального времени в зависимости от частоты вращения, скорости подачи и натяжения изучались в условиях сухого трения и смазки. Полученные результаты были доказаны термомеханической природой процесса FSHE.

Ключевые слова: расширение отверстия трением с перемешиванием, экспериментальное исследование, алюминиевый сплав Д16АТ, осевое усилие, крутящий момент.

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