DOI: 10.24425/amm.2019.130115

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AN IMPACT OF ASSEMBLY INTERFERENCE ON STRESSES IN THE DIE TOOL SYSTEM DURING BOLT FORGING

The article presents an analysis of stresses in the current tool system of the die during the implementation of the third forging operation of the screw M12 class 10.9 with cylinder head and hexagonal socket. It was assumed that the level of negative cracking due to stress can be reduced by using a mounting interference between the die and the tube blank. Due to the design of the tool system value of the die, the interference value cannot be too large. Therefore, an analysis of the influence of the interference between the die and the tube blank in a die tool system on the value and distribution of stresses in the individual components. An analysis of the assembly stresses and the stresses occurring during the process of deformation of the shaped head of the screw was done. The calculations were performed using a commercial software package MARC / Mentat.

Keywords: forging, modelling and simulation, bolts, stress analysis

1. Introduction

The basic method of screws forming is a multi-operation forging process. The screw head is upset by the sequential steps of a rod, freely first, and then in the die [1,2]. The technological process of forming a typical screw usually consists of seven technological operations. Four of them relate to plastic forming of the cold treatment of screw head and are carried on special machines for the production of screws. Technological process of forming conventional screws is a cold treatment, which makes a considerable burden of forming tools. In industrial practice, the adverse phenomena that may occur during the forging of screws are: cracking tools or other tooling, their intense wear or permanent deformation. A properly designed, constructed and operated tool enables to provide high quality products at a sufficiently high volume of production, low cost, and the required level of security.

Tool durability and its usefulness for production depend on a number of factors which often cause opposite effects. There is no clear criterion for the selection of tooling materials and one has to largely based upon the experiences of manufacturers and users of tools, including the possibilities offered by modern information technology tools in the form of computational programs supporting engineering works in the analysis of processes and the design of tooling. Still there are few publications on simulations of fasteners in spite of the use of MES software by manufacturing companies. The reason may be the disclosure of new developments and technological solutions.

Few studies include information confirming the possibility of modeling by MES of the selected technological operations occurring in the production of fasteners. For example, the work [3] relate to simulation of various steps in the production of selected kinds of screws using the Qform 3D software. There were described the simulation results of operations of upsetting the head and the diameter of the mandrel forming the rolling thread. The deformations distribution with the characteristic silent zones was obtained. An attempt was done to simulate the technological operation of manufacturing of hexagonal-head screw in the technology of the head manufacturing by upsetting hexagonal in the die using non-waste technology. During upsetting the hexagon some unfilled sections occurred and the flash which disqualifies the product as incompatible with the relevant standards. In paper [4] focuses on the modeling, simulation and analyses of the hot forging die for Pan head bolt and insert component die. The final results are in the form of different stresses distribution occurs in die cavity.

The comparison of the material flow during a multistage forging of the fasteners made of DP and BS steel was shown in [5]. When analyzing the obtained results for the three component operations of forming hexagonal screws, it was noted the local concentration of stresses and deformations in the lower area of the head, nearby the adherent surface and the radius of the transition of the adherent surface in the mandrel. These areas are important in terms of ensuring the mechanical properties for screws which cannot be treated with heat as well as for the heat-improved screws because they are exposed to the possibility of cracking during the quenching operation.

The subject of the study were also the issues of screw movement while trimming [6,7] and an analysis of nearly full

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technological process of forging fasteners incorporating the technology of production hexagonal screws for additional drawing operation [8,9].

The share of the cost of the tools during the production of fasteners is the second component of costs after the feed material in the total cost of production. Therefore, the process of tools manufacturing in the aspect relating to the fulfillment of construction requirements of their stability and precision of performance and durability is particularly important. The largest number of studies and articles on the study of the die consumption applies to adhesive and abrasive wear. The wear of the forging die in most cases is of the abrasive wear [10]. There is no universal mechanism of wear or a simple relationship between the size of the abrasive wear and the degree of degradation of the surface. However, it is widely recognized that in the conditions of abrasive or adhesive wear the volume of separated material is directly proportional to the pressure on the adherent surface and friction road and inversely proportional to the hardness of the material subject to wear. It is included in the Archard model [11]. So far, there is a big number of various modifications of the Archard model which also take into account the effects of temperature. The analysis and optimization of the technological process of hexagonal screw with a flange to reduce the wear of tools are presented in [8]. To evaluate the results of the abrasive wear the Archard model was applied. An analysis of abrasive wear of forming tools and an analysis of the impact of charge parameters selection to the process of manufacturing of hex screws on their way of wear was carried out in [5,12]. One analyzed the impact of a change in the diameter of wire rod in the drawing process on the dies wear, and then how this choice affects the wear of dies forming the coupling element in the cold forging.

Due to the strongly developing large-scale modeling methods and mathematical models of describing the structure of [13-17] in the literature one can find a combination of finite element method with cellular automata method [18,19] applied to analyze the production process of fasteners. Simulation by CAFE method enables simultaneous calculation of the phenomena occurring in the macro and micro scale. In [20] CAFÉ was used in the simulation of technological process of the head upset in the manufacturing of fasteners while production of a hexagonal screw. It was shown that the large-scale simulation method gives great opportunities to predict the development of micro-cracks as well as the accurate determination of actual local deformations.

Thanks to the use of modern computation methods the simulations of process data can be performed without the need for long-term experimental research. Already at the stage of simulation research it is possible to take into account certain factors and phenomena that have an unfavorable impact on tools, and then design the process and tooling in such a way to eliminate them or at least to limit to a certain extent.

The paper presents an analysis of the process of forming the screw head M12 with the Allen head seat. For the forming operation, in which in industrial practice there are the largest burdens of tools often leading to the formation and development of cracks in the die, there was analyzed the influence of the interference between the die and the tube blank on the value of the stress distribution in a tool die.

2. Experimental researches

Tool sets for the production of screws comprise many components that have to withstand high mechanical loads, and thus have a high durability. As previously noted, in current technology, a screw is achieved in several steps, which further increases the risk of negative effects within the tooling. The industrial practice shows that the lowest durability have the tools intended for the fourth forming operation of the screw head. In this operation, there is the highest tool burden, which not only results in the most intense wear, but often in industrial implementation of the process leads to the formation of dangerous cracks elements of the tool, i.e. dies and the tube blanks. The need to reduce or eliminate this very unfavorable phenomenon with no technical possibilities to change the overall dimensions of the tool was the basis to undertake research in this area.

The experimental studies included the process of producing M12 screws class 10.9 with cylindrical heads and hexagonal seat. Implementation process of cold forging of screws was executed on the machine type SACMA SP38 EL (Fig. 1). The screw was made of 30MnB4 steel type with the chemical composition given in Table 1.

Fig. 1. Experimental stand for the screw forging process

TABLE 1

The chemical composition of the screw material

Material	C	Mn	Si	Ni	B
30MnB4	0.32	1.8	0.3	0.3	0.002

The technological process of forming the analyzed screw consisted of several technological operations (Fig. 2). The first concerns the cutting of the rod, four consecutive ones included forming the screw head first by the free upsetting (II and III steps), then the die upsetting (IV and V steps). Then, in the VI operation the chamfering was performed and at the end in the VII operation the thread rolling was done.

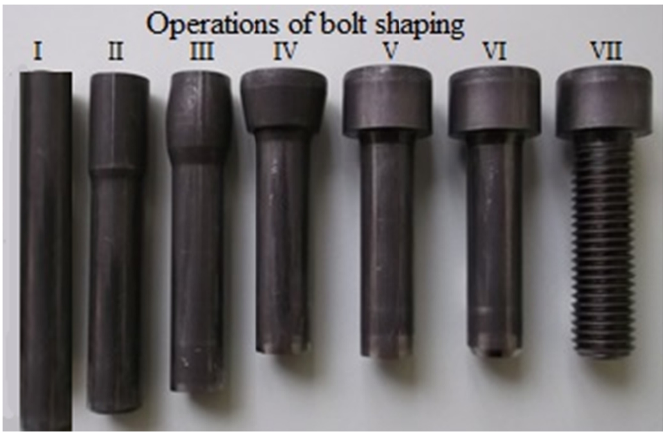

Fig. 2. Subsequent operations of plastic forming of screw with hexagonal internal head (Allen)

A set of die tools to achieve the fourth forming screw operation with the highest stresses of tools are shown in Figure 3. The die was made of steel 1.3343 (EN HS6-5-2) with the chemical composition given in Table 2.

Fig. 3. The components of the tool die shaping operation for the fourth bolt: 1 – die, 2, 3, 4 – spacer sleeve, 5 – the centering tube blank, 6 – casing

The tooling system of the die consists of the die 1, the spacer sleeve 2,3 and 4, the centering tube blank 5 and the housing 6. The die 1 is mounted directly in the housing 6 without or with very low interference assembly. Its butting face lies on the tube blank 2, which together with the tubes 3 and 4 carries axial load. 2-4 tubes are positioned in the housing 6 with the centering tube 5. Elements of the die tooling system after the assembly are shown in Figure 4.

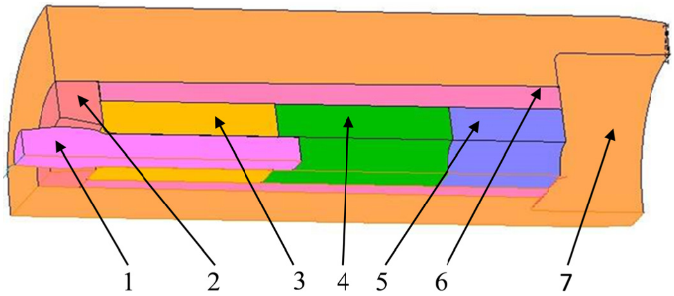

Fig. 4. Geometric model of the a tool systems with individual deformable bodies: 1 – screw, 2 – die, 3, 4, 5 – spacer sleeve, 6 – the centering tube blank, 7 – casing

Many years of research in industrial conditions allowed to distinguish places in the tooling system which are the most vulnerable to wear and loss of cohesion. In the present case one could observe the die cracking (Fig. 5), which in turn could also cause damage to other elements of the tooling. Hence, an attempt to eliminate or substantially mitigate this effect was done by applying the proper interference between the die 1 and the housing 6, which will reduce operating stresses in the die 1. Accordingly applied assembly interference can contribute to a more uniform loading of the die material throughout its area. In addition, it introduces an initial installation tension, which affects the lowering of the working stress, which is very advantageous from the viewpoint of service life of tools. It should also be borne in mind limited use of the interference since the use of too large interference increases the risk of cracks appearing in other system components, for the analyzed case in the housing.

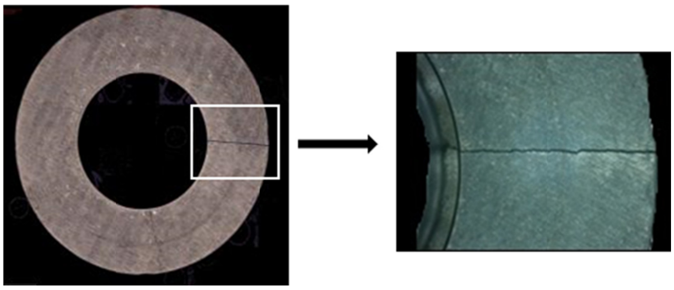

Fig. 5. Die with visible crack

The mechanical properties of the screw material, i.e. the yield stress and the course of the consolidation curve was determined based on a sample of uniaxial stretching conducted on

TABLE 2

The chemical composition of the die material, (%)

Material	C	Mn	Si	P	S	Cr	Ni	Mo	W	V	Co	Cu
HS6-5-2	0.82-0.92	max 0.4	max 0.5	max 0.03	max 0.03	3,5-4.5	max 0.4	4.5-5.5	6-7	1.7-2.1	max 0.5	max 0.3

the testing machine Zwick / Roell Z100 (Fig. 6a). The application of the compression test gives the possibility to determine the strain-strengthening curve in a wider range of deformation than in the tensile test. However, the basic limitation in the test of compression of ductile materials that hinders the interpretation of the results of this test is the friction between the sample and the tools. It causes an increase in the compression force by about (10-15)% and is the cause of non-homogeneous state of stress and deformation in the material under test. The influence of friction, and thus the deformation heterogeneity, increases significantly with the degree of deformation of the test sample. This problem does not occur in the case of uniaxial stretching in the range of uniform deformations (i.e. until the neck formation). For this reason, the uniaxial stretching test is by far the most widely used to describe constitutive compounds during the modeling of cold forming processes.

In a further step numerical studies were conducted to determine the impact of the level of interference between the die and the sleeve and the value of the stress distribution in a tool die.

3. Numerical modelling

A more detailed numerical analysis was conducted for the die tooling system in the fourth operation of the process of forging Allen screws. The numerical calculations were performed using commercial software MARC / Mentat. The process of forming the screw head in the fourth operation was modeled for the die deposited without interference and with three different values of the assembly interference. This enabled to determine the distribution and stress values in the busiest parts of the tool. Material properties of the die were described considering the model of elastic-plastic body of nonlinear strengthening. The scope of elastic deformations were described by the Hooke's law (E = 210000 MPa, ν = 0.3) while the plastic ones with the strain hardening curve (Fig. 6b). A two-dimensional geometric model of the process was built, which was analyzed on the assumption of axial symmetry (model axisymmetric). The tested model of the tooling system to simulate the fourth operation of forming the screw head was shown in Figure 4.

The friction model has been described by Coulomb's law. In the modeled process between two bodies in contact there are two types of friction, i.e.: static and kinetic. For this reason, a coefficient for kinetic friction equal to 0.1 was assumed between the screw and the die as well as the screw and the punch. However, a static friction coefficient of 0.15 was assumed between the die, the individual tube blanks and the housing.

The die and other elements of the tool system shown in Figure 3 can be loaded during forging only in the area of elastic deformation. To calculate the distribution and values of stresses occurring in individual elements of the tool system, these elements were modeled as deformable bodies. Their description is based on the model of the perfectly elastic body described by the Hooke's law. The values of constants in the constitutive equation were the same for all steel elements of the modeled tool system (E = 210000 MPa, ν = 0.3). For the construction of the finite element mesh of the deformed materials elements of class 4 type 10 – axisymmetric quadrilateral ring [21] were applied. Numerical simulation was performed using the global remeshing option. The size of finite elements of individual deformable bodies varied depending on the size of their deformation and the type of contact between them. The size of four-node finite elements for the die and screw was about 0.20 mm, which caused the die to be divided into about 2,000 elements, while the screw was about 32,500. For the remaining deformable bodies of the matrix tool system, the size of the elements was about 0.4 mm. Assuming such a quantity, the number of finite elements was about: 1500 for 3, 4, 5 spacer sleeve, 2800 for blank tube and about 11500 for casing. The punch speed is 250 mm/s.

The study took into account four cases. The first one without assembly interference and three with different values of the assembly interference, i.e. δ_1 = 0.003 mm; δ_2 = 0.006 mm;

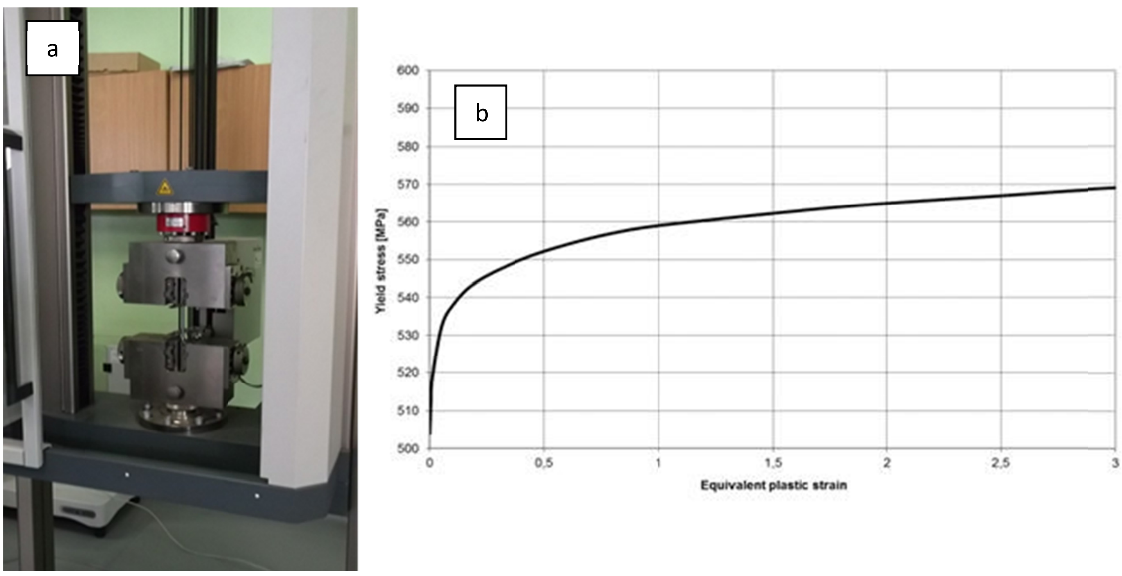

Fig. 6. The testing machine – a) and strain hardening curve for the screw material – b)

δ_3 = 0.009 mm and determine the hoop stresses affecting the radial die cracking observed in the experiment and the substitute stresses by Huber-Mises which occur in the die material and under the load during the process of shaping the screw head.

To determine the mounting interference δ the following formula was used:

$$\delta = \frac{D_{zw} - D_{wp}}{2} \quad (1)$$

where: D_{zw} – external die diameter, mm; D_{wp} – internal diameter of tool hollow, mm.

4. Results and discussion

In order to determine the effects of the interference value between the die and the sleeve housing on the value of hoop and substitute stresses in a tooling system of the die during the process of forging the screws, there were determined five measurement points in the most burden area of the die relevant to the strength of the tool. The places of readout of stress values are shown in Figure 7.

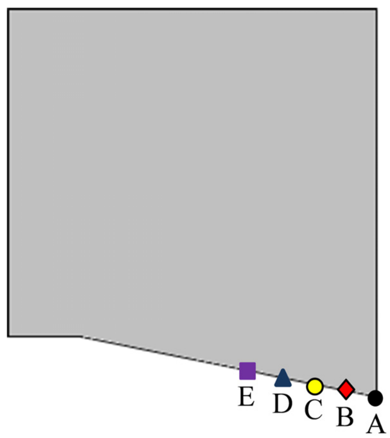

Fig. 7. Measurement points where the stresses were controlled

For all considered sizes of the interference, the biggest values of hoop assembly stresses were found at the measurement point A, or near the hole of the die (Fig. 8). Where the interference of δ_1 = 0.003 mm was applied, the hoop stress in the tested points of measurement were in a small range and were in the range (30-40) MPa. Doubling the value of such interference of δ_2 = 0.006 mm resulted in the emergence of the double value of the hoop stress in the analyzed measuring points, and the span value was higher and amounted to about 17 MPa. The largest range of stresses in the area appeared using interference δ_3 = 0.009 mm. Such an increase in the value of interference caused a threefold increase in stress as compared with interference equal δ_1 = 0.003 mm and one and a half growth in relation to interference d_2 = 0.006 mm. On the other hand, the range of results for the largest applied interference in the measurement points was 2.5 times greater than the interference δ_1 = 0.003 mm and 1.5 times larger than the application of interference δ_2 = 0.006 mm.

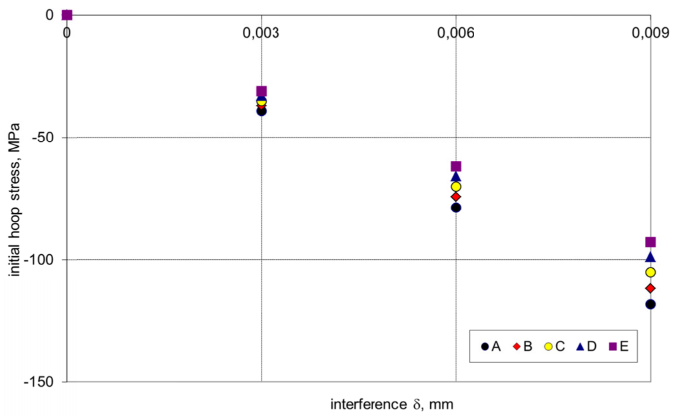

Fig. 8. The values of initial assembly hoop stresses in the measurement points of tools depending on the interference used

Figure 9a shows the distribution of initial hoop stresses in the die (after assembly), whereas in Figure 10b the distribution

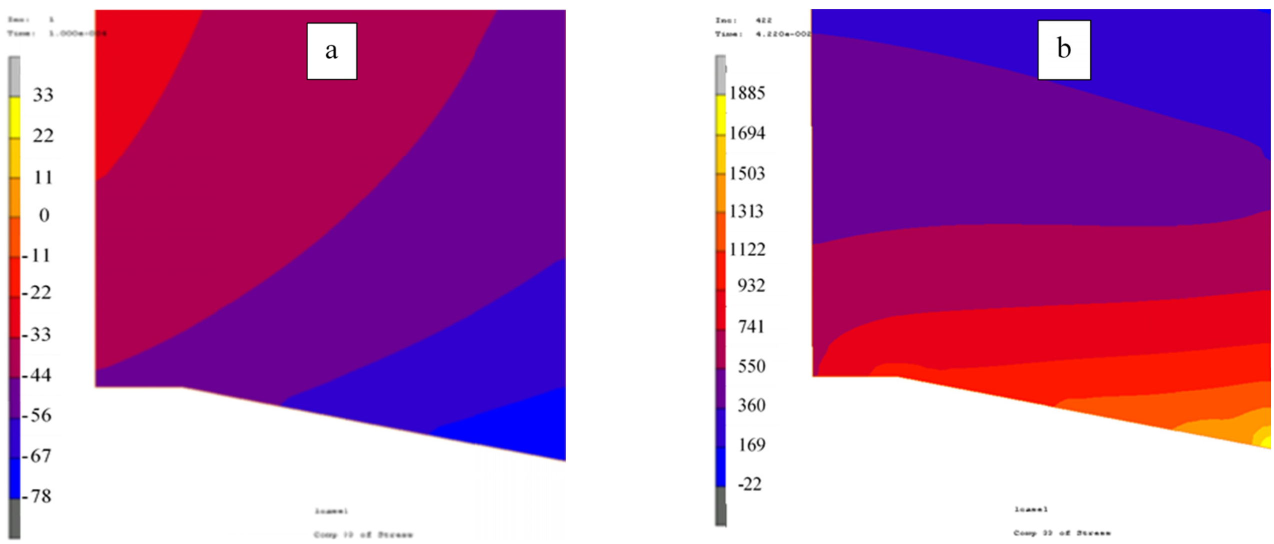

Fig. 9. Distribution of hoop stresses in the die: a) initial after assembly, b) maximum during forging (interference δ = 0.006)

of the same stresses occurring during forging ($\delta = 0.006$). When comparing the distributions in individual drawings, it is clearly visible that by far the biggest difference between fitting tension and stress during forging occurs at measuring point A. This tendency persists irrespective of the value of the used interference. This can be seen in the diagrams (Fig. 10 and Fig. 11) on which the stress values at point A have changed disproportionately compared to the stresses at the remaining measuring points, i.e.: B, C, D and E in the entire tested pressure range.

During the forging process the maximum hoop stresses present in the die in relation to the applied interference and the zero interference were determined (Fig. 10). In the absence of the interference, it was found that they achieve the highest value in all measurement points, the values range $\sigma_\theta = (1194\text{-}1950)$ MPa. Considering the measurement point A, which is located near the die, it was stated that the hoop stresses reached a maximum value of all values considered as in case of its absence. It is worth noting that the use of the interference caused quite a uniform reduction in the maximum values of hoop stresses with an increase of the interference. In the case of the zero interference they amount to approximately 1950 MPa and gradually decrease with the increase in the value of $\sigma_\theta = 1860$ MPa for interference $\delta_3 = 0.009$ mm. In other measuring points there were recorded similar dependencies. Wherein the maximum average value of the hoop stress decreased with respect to those without the use of interference by 2%, 3% and 5% respectively of the interference $\delta_1 = 0.003$ mm; $\delta_2 = 0.006$ mm; $\delta_3 = 0.009$ mm. It is characteristic that there is significant stress gradient between the measuring points.

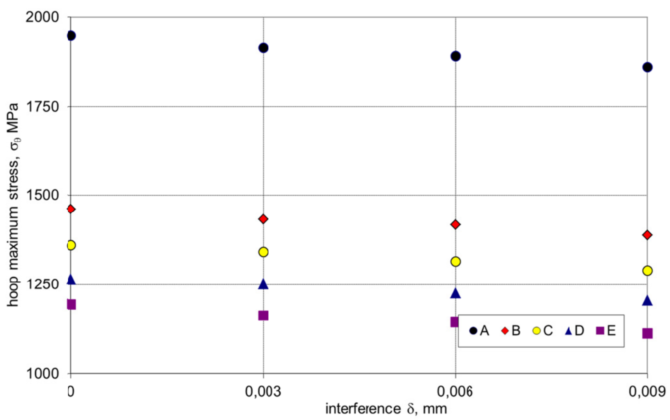

Fig. 10. The values of hoop maximum stress in the measurement points of tools during the forging of the screw head depending on the interference used

Occurring hoop stresses play a significant role in the strength of the tool die. Their large values can be the cause of radial cracks of the die material. As the results of calculations show the production of initial hoop stress by applying assembly interference has a positive effect of a significant reduction in the value of these stresses during forging compared to the process without interference.

Of a great importance from the point of view of tools strength are also reduced stresses. They allow to compare the effects of stress conditions occurring in the tools with the uniaxial stress state which occurs in an attempt to uniaxial stretching.

Experimental studies [22,23] have shown that for the die material (HS6-5-2) reduced stresses corresponding to the maximum material effort depending on the parameters of heat treatment may be about 2300 MPa. Thus, the value of the working stresses in the die should be lower than this value. Thus, we analyzed the relationship between the working stress, and an interference used in the forging process of forging a screw head (Fig. 11). The lowest reduced stress values were recorded at the measurement point near the die hole (point A) used for interference $\delta_3 = 0.009$ mm and amounted $\sigma_\theta = 1887$ MPa. The value obtained was about 3% lower than the stress obtained during the forging without interference at the same measuring point. Meanwhile, the largest value of reduced stress was recorded at the measuring point B for the zero interference ($\sigma_\theta = 2340$ MPa) and was higher by about 4% from the value obtained when using the largest concerned interference $\delta_3 = 0.009$ mm. Significant differences appear in the values read out at the measurement point A, and the other measuring points and amount to the average of 150 MPa. From the obtained relationship between the reduced stress and the value of the interference one can conclude that the interference at small values (less than 0.006 mm) of stresses in the most loaded area of the die is slightly greater than the permissible stresses. However, the interference of 0.009 mm is lower than the permissible stresses, which shows the ability to eliminate adverse phenomena in this case.

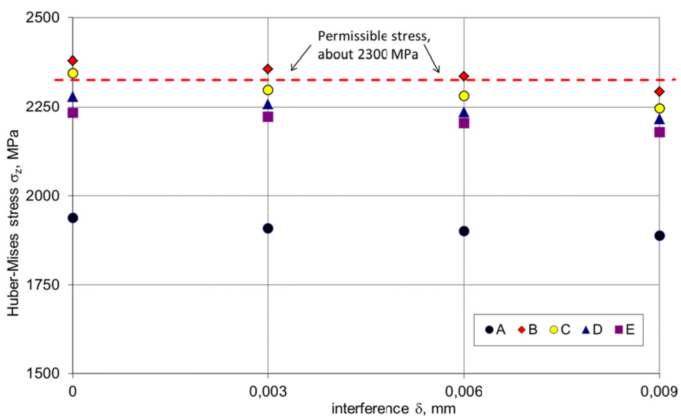

Fig. 11. The values of Huber-Mises stress in the measurement points of tools during the forging depending on the interference used

In order to determine the impact of the interference on the die tool system in addition to determining the stress values at selected points in the die, the distribution of circumferential stresses for all considered pressures was also analyzed. It is particularly important to compare the distribution of stresses in the initial phase of the process and at its end (Fig. 12).

In the example of the peripheral stress distribution shown in Figure 12 for the pressure value $\delta_1 = 0.003$ mm, it can be seen that the area of the die opening is the largest (Fig. 12a). This induced stresses propagating evenly in the radial direction into the tool. As a result of this, in the final stage of bolt forg-

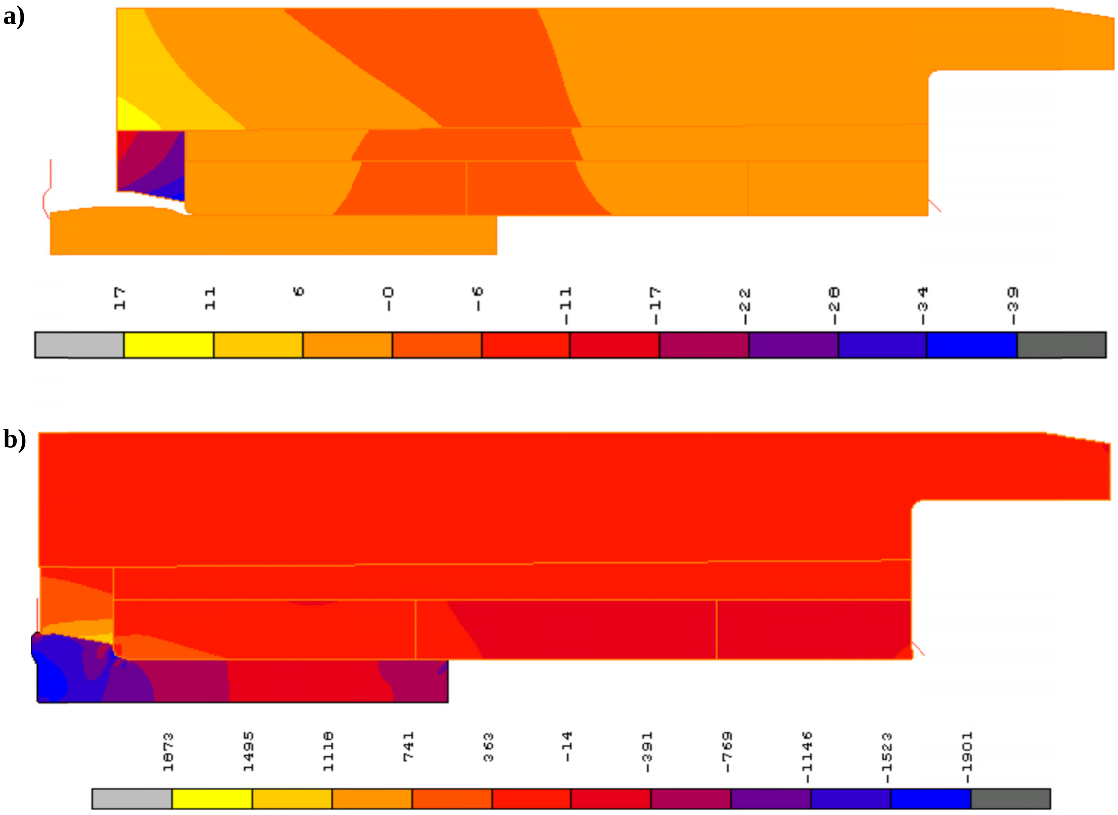

Fig. 12. The hoop stresses distributions for the screw and die material (in MPa) before forging – a) and at the final stage of forging – b), for value of interference $\delta_1 = 0.003$ mm

ing there is the occurrence of stresses with much lower values in the tool. Importantly, there are no large gradients of stress values in their distribution in the entire die area. As can be seen from the stress distribution disclosed in Figure 12b in the final forging step, the area of greatest stress is not concentrated in the calibrating part of the tool, but spreads over a larger area into the tool. This is advantageous as it consequently increases the durability of the die.

5. Conlusions

Due to the use of space in the tool die system, which during the implementation of the process are the most loaded, it can be partially relieved, thus reducing the probability of a negative phenomenon such as die cracking. In addition, the introduction of an appropriate interference between the die and the housing sleeve provides a more even load on the tools, which is very beneficial from the point of wear and service life.

The aim of the research conducted was to reduce the level of stress occurring in the die during forging to a level below the permissible value (of 2300 MPa) while maintaining the imposed dimensions of the tooling system. This goal was obtained by using the 0.009 mm push-button. The tests show that at low pressure values (below 0.006 mm) the stresses in the most loaded area of the die are slightly higher than the allowable stresses. On the other hand, when the pressure value is 0.009 mm, they are lower than allowable stresses, which indicates the possibility of eliminating unfavorable phenomena in this case. Further increase of the pressure value favorably reduces the level of maximum stresses occurring in the die during forging. This benefit increases in line with the trend achieved. In practice, however, there are a number of restrictions that prevent the use of pressures above a certain value. Among these limitations there can be mentioned the followings: lack of possibility of assembly of elements with too high pressure, too high hoop tensile stresses in the housing of the tool system, increase of outer diameter of the housing after assembly of the die which causes problems with assembly and disassembly of the tooling system in the forging press seat, difficulties in the case of frequent die replacement, etc. Due to the above limitations for the tool system under test, the smallest interference value, which provides the required level of stress in the die, is the optimal one, and at the same time can be successfully used practically. In engineering practice, further increase of the interference (above 0.009 mm) in the die system of the housing would be possible provided that the diameter of the housing was increased. In the case analyzed, however, this is impossible due to the standardized housing dimensions.

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