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THE FIBROUS STRUCTURE OF THE BOLT AND ITS EFFECT ON THE JOINT RELIABILITY

The use of cold forging is a widely used solution in many industries. One application is the manufacture of bolts and fasteners. The largest amounts of bolts are used in the automotive and machine industry. Those customers demand high standards of quality and reliability from producers based on ISO 9001 and IATF 16949. Also, the construction, agriculture and furniture industries are raising their expectations for deliveries from year to year.

Automotive companies issue their standards specifying specific requirements for products. One of these standards is the aviation standard SAE USCAR 8-4; 2019, which speaks of a compatible arrangement of fibers in the bolt head and in the area of transition into the mandrel.

The article presents the cold forging process of flange bolts. Obtaining a compatible, acceptable and incompatible grain flow pattern based of the above mantioned standard was presented. Then the results of FEM simulation were correlated with the performed experiment.

The effect of incompatible grain flow system was discussed and presented as the crack initiating factor due to delta ferrite, hydrogen embrittlement, tempering embrittlement. The reliability of the connections was confirmed in the assembly test for yield stress on a Schatz machine. The advantages of this method and the difference compared to the tensile test were presented.

Keywords: cold forging, bolts, fasteners, grain flow pattern

1. Introduction

Requirements for automotive manufacturers and suppliers in terms of quality systems are contained in IATF 16949: 2016 [1] based on the ISO 9001: 2015 standard [2]. The IATF standard emphasizes an interdisciplinary approach and teamwork as an organization's success in project implementation. In addition, the process approach, continuous improvement, leadership and the systemic approach to management required by ISO 9001 create conditions for efficient implementation of production and financial goals. Risk analysis should result from the company's experience, emerging complaints or necessary repairs. Understanding the context of the organization and including top management as involved in quality management systems is required. Komarnicki at al. [3] lists the most important changes when introducing the IATF 16949: 2016 requirements such as guaranteeing safety resulting from compliance with product and process requirements.

Currently used technology allows obtaining small and precise shapes in the cold forming process [4,5]. These processes require simulation support to accurately predict the direction and potential movement of the material. As Żmudzki at al. [5] showed that FEM programs can not only optimize technology understood by changing tool geometry, but also reorganize technology from waste forging to waste-free forging. The development of technology based on FEM programs has been used in the production of bolts with complex shapes as a tool to reduce time and minimize the costs of starting the production of a new element [6,7].

The plasticity of the material, as noted by Ziółkiewicz at al. [4], affects the way the material fills the working area of the tools between the slider and the anvil. Therefore, in the production of bolts, spheroidizing annealing processes are used for the wire, which soften the material and reduce the likelihood of plastic cracks. In addition to the annealing process, it should be remembered that the wire and its quality are affected by processes such as bonder application and wire drawing [8-9].

The application of the bonder coating on the wire rod is only beneficial for the forging process, at a later stage of production zinc phosphate belongs to the threats to high-strength steels [10,11]. The phosphate that has not been removed from the bolt surface during the heat treatment process creates delta

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ferrite, which corresponds to, among others for a decrease in bolt strength and the possibility of microcracks. To the list of hazards for high-strength bolts, the tempering embrittlement of the first type, most strongly occurring at 300°C, should be added [12]. Another negative aspect is the hydrogen embrittlement resulting mainly from the processes in which the product is hydrogenated, especially the electroplating process [13].

The listed hazards for high-strength classes are dangerous for the durability of the bolt in long-term use. However, already at the forging stage, there is a major threat to the reliability of the connector, which is an incompatible grain flow pattern. The Ford USCAR 8-4;2019 „Grain Flow Pattern for Bolts, Screws and Studs" standard clearly shows the requirement for the forging process [14]. Directly from the Ford standard there is a transition to surface continuity requirements according to ISO 6157-3 [15]. Forging lap, i.e. lack of surface continuity, is a stress concentrating notch. Incompatible fiber arrangement together with the mentioned threats increases the risk of bolt breakage. The article presents requirements for the grain flow pattern, reference is made to FEM simulation, susceptibility to cracking was verified and bolts were tested in tests of mechanical properties according to ISO 898-1 and ISO 16047 [16,17].

2. Material used for bolt manufacturing

30MnB4 steel grade in accordance with ISO 10263-4 was used for forging bolts. The use of manganese-boron steel makes it possible to obtain classes of mechanical properties from 8.8 upwards while maintaining the throughput of the wire in cold forging. The wire rod used for production was supplied in coils, in this case the wire diameter was Ø8.5 [mm]. The smelter uses iron in the form of scrap metal to make steel. The charge comes from an electric furnace. Rolled metal underwent the entire surface preparation process, which consists of 5 subprocesses. All steps in the process are important and dependent on each other. The wire rod was subjected to an etching operation to remove mill scale. The next stage was a spheroidizing, consisting in achieving a charge temperature close to AC1 and then cooling down. This treatment allowed to increase the plasticity of the material, resulting from changes in the shape of cementite separation into spheroidal. Before drawing, the wire rod was subjected to an etching operation that cleaned the wire of iron oxides and a phosphating operation, i.e. the formation of phosphate crystals on the surface of the wire rod. Single drawing was performed for a diameter of Ø7.76 (–0.03) [mm], the drawing tool geometry was selected in accordance with the requirements of the delta parameter. Zinc phosphates together with drawing soap formed on the surface of the wire a lubricating layer reducing friction during forging.

3. Forging process

The test samples were forged on a forging harvester, performing operations of cutting, operating forging, chamfering and thread rolling within one machine. More than 60 tools are needed to make DIN 6921 M8 x60 bolts. The complexity of sets allows production flexibility and the use of individual tools in the production of bolts of other assortments. One forging operation requires two housings used in the anvil and slider. The housing mounted in the anvil usually includes the following elements: ejector sleeve and ejector responsible for the height of the bolt support, primer located at the bottom of the housing, crimping ring increasing the service life of the tool, die insert shaping the retaining surface, steel die with individual inserts, sinter insert responsible for part of the bolt pin.

The product produced on the forging harvester requires the setter responsible for retooling several years of experience. Each of the processes carried out on the forging harvester depends strongly on the previous one, in addition, each forging operation is highly sensitive to any changes in the previous operation. An important point in the forging stability is taking care of accurate tool reception and measurement of the most important parameters by the controller. Any change in the tool geometry brought along with the replacement of the worn tool causes variation in subsequent operations. This automatically involves a correction of the forging settings, which leads to a decrease in process efficiency.

The forging harvester has the ability to greatly adjust the settings of the tools, and thus receive different geometrical bundles. This possibility was used to prepare the samples, affecting part of the stick height intended for shaping the head of bolt.

4. Grain flow pattern testing required

During standard bolt production, surface and mechanical properties requirements are defined by ISO 6157-3 and ISO 898-1. However, for automotive products, parts manufacturers receive more stringent requirements. They are included in special standards directly developed by car manufacturers. One of these standards is SAE USCAR 8-4, developed by FORD. The SAE USCAR 8-4 standard draws attention to the arrangement of fibers formed during cold forging, it focuses on the area of transition of the bolt head into a pin, the main requirement is the lack of cutting of the fibers. The outline of the fiber system visible in Figure 1 is the orientation of grains, separated carbides and steel impurities resulting from the plastic deformation. For the best assessment of this parameter, metallographic specimens are prepared. FEM simulation of the tensioned bolt (Fig. 2) shows two places heavily loaded during stretching – the first thread pitch and the mentioned radius of transition from the mandrel to the head of the bolt.

5. Forging process - description of individual operations

The wire is introduced into the forging machine through the material feeding unit. It is equipped with a straightening apparatus, consisting of rollers, the grooves of which are adapted

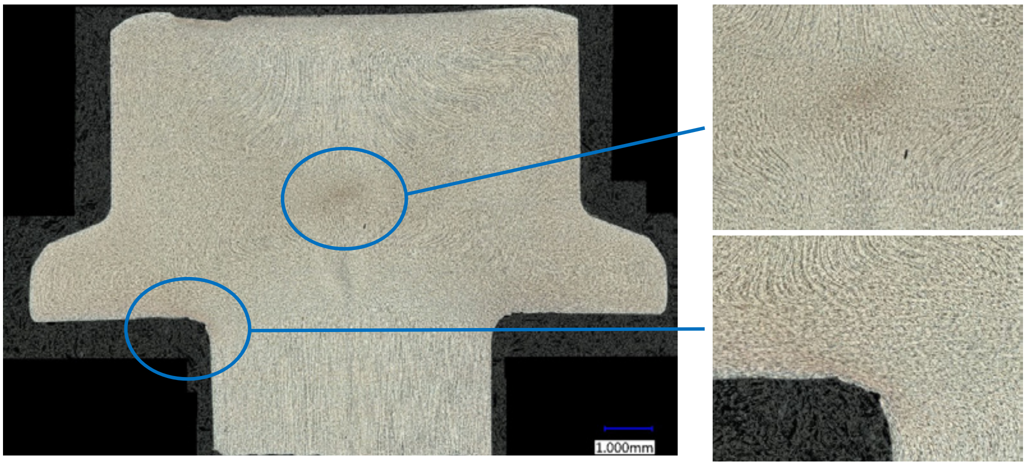

Fig. 1. Macrostructutre of cross section of the bolt after cold forging

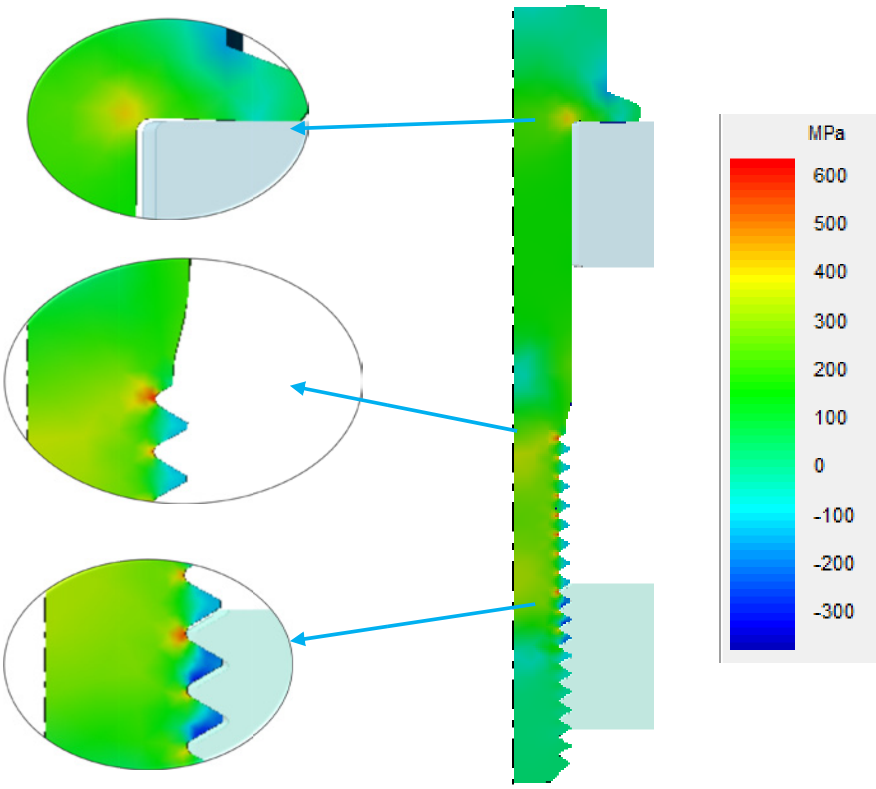

Fig. 2. FEM simulation of equivalent stress distribution in the tensioned bolt

to the diameter of the wire. Their arrangement allows the wire to be straightened horizontally and vertically. The straightened wire goes to the cutting apparatus. The material is cut into equal sections (sticks) by plastic cutting. The correct cut stick has no burrs and the front surface is perpendicular to the axis of the cut. The semi-products (Fig. 3) are fed between operations with the help of paws.

The forging process on the operating forge in the case of flange head bolts can be represented as follows:

A. Cutting begins with determining the height of the stick and accepting the volume of material needed to forge the bolt. Next, the stick height to form the bolt head must be determined. The principle of constant volume and reduction of radius die in subsequent operations should be taken into account here.

B. The first operation is upsetting the intended height of the stick to the head by semi-free forging. The material is limited from below by the die and from above by the upset. From the beginning of forging there is an increase in the diameter of the pin (approximately 0.02 mm per operation) resulting from the pressure of the upset and blockage of the stick from the bottom by the ejector.

C. The second operation is semi-free forging, however, the tools more restrict the flow of material. A cylindrical shape of the bundle is formed in the part of the bolt head. Already in this operation you can see quite strongly the flow of

Fig. 3. Wire cut, semi-products and finished bolt with thread

material in the lower part of the head, which will form the collar.

D. In the next, third operation, the outline of the hex head is pre-shaped, which is responsible for the possibility of mounting the bolt. In this operation, die forging occurs. The header tool works with a dowel to completely fill the material. The pin is reduced on the section intended for thread rolling. The reduction die is responsible for the reduction with the set reduction height so that the thread length complies with the requirements of the standard.

E. The fourth operation is proper shaping of the turnkey dimension and obtaining a bolt flange. In this operation, the hallmark pin marks the manufacturer's and the mechanical property class on bolt head.

6. Research methodology

For testing of the grain flow pattern, DIN 6921 M8 x60 10.9 bolts were chosen, i.e. the bolt geometry was made in accordance with DIN 6921 (hexagon flange bolt), the bolt thread is M8, its length is 60 mm and the requirements of the mechanical property class are met 10.9 according to ISO 898-1. Four variants of settings on the forging machine were prepared for the tests. All major changes were based on changing the length of the cold-head part in the first operation. The change in proportions in the first operation translated directly into subsequent operations, where the necessary manipulations of the machine settings were performed to ensure geometric compatibility. From the forging process, 4 variants of the same bolt were obtained, differing essentially in fiber systems. The following tests were performed on bolts and semi-products from individual operations:

- grain flow pattern assessment according to SAE USCAR-8;
- assessment of surface discontinuities according to ISO 6157-3;
- testing the hardness distribution after forging;
- testing for susceptibility to brittle cracking;
- hardness test after heat treatment;

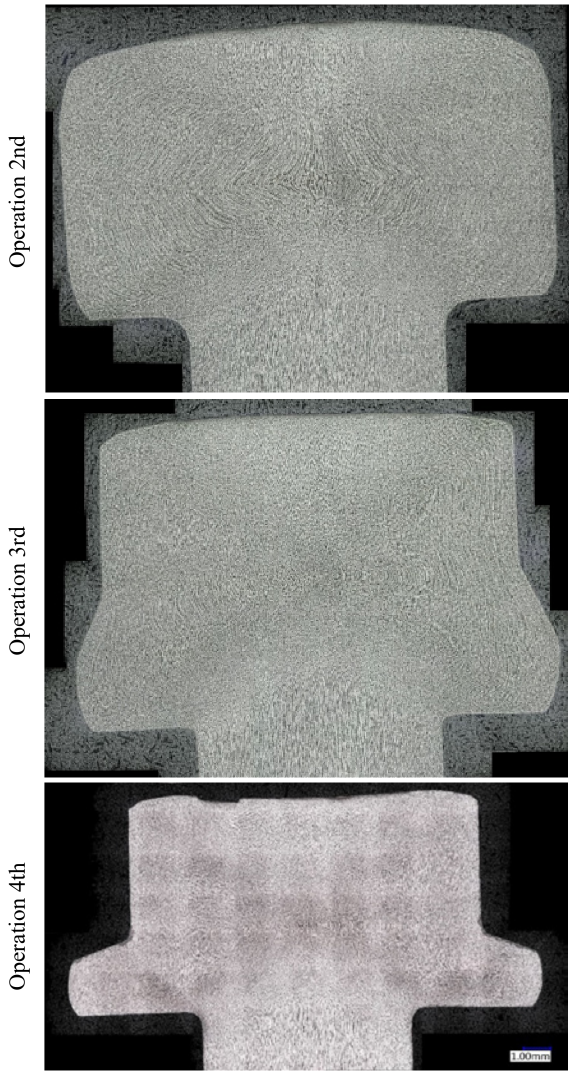

Fig. 4. The metallographic analysis of three forging operations

- tensile strength test;
- tightening test at the yield point.

The metallographic section obtained in the forging operation were made longitudinally.

Using the KEYENCE optical microscope, photos of the microstructure with the disclosed fiber system were taken. Pictures were taken at ×100 magnification. The microscope allows them to be automatically assembled, which gave the image of the material's shape over the entire bolt head cross-section. The radius under the bolt head was measured and the height of the largest compression zone from the base of the flange was determined.

Tests were carried out on the LECO hardness tester using 10HV load. Half of the specimen was tested because of the symmetry of the sample. The results allowed the development of hardness maps.

The metallographic analysis included three forging operations (2, 3 and 4) is shown in the Figure 4.

7. Grain flow pattern

The metallographic analysis of two forging operations for four variants is shown in Figure 5. In each variant, the input

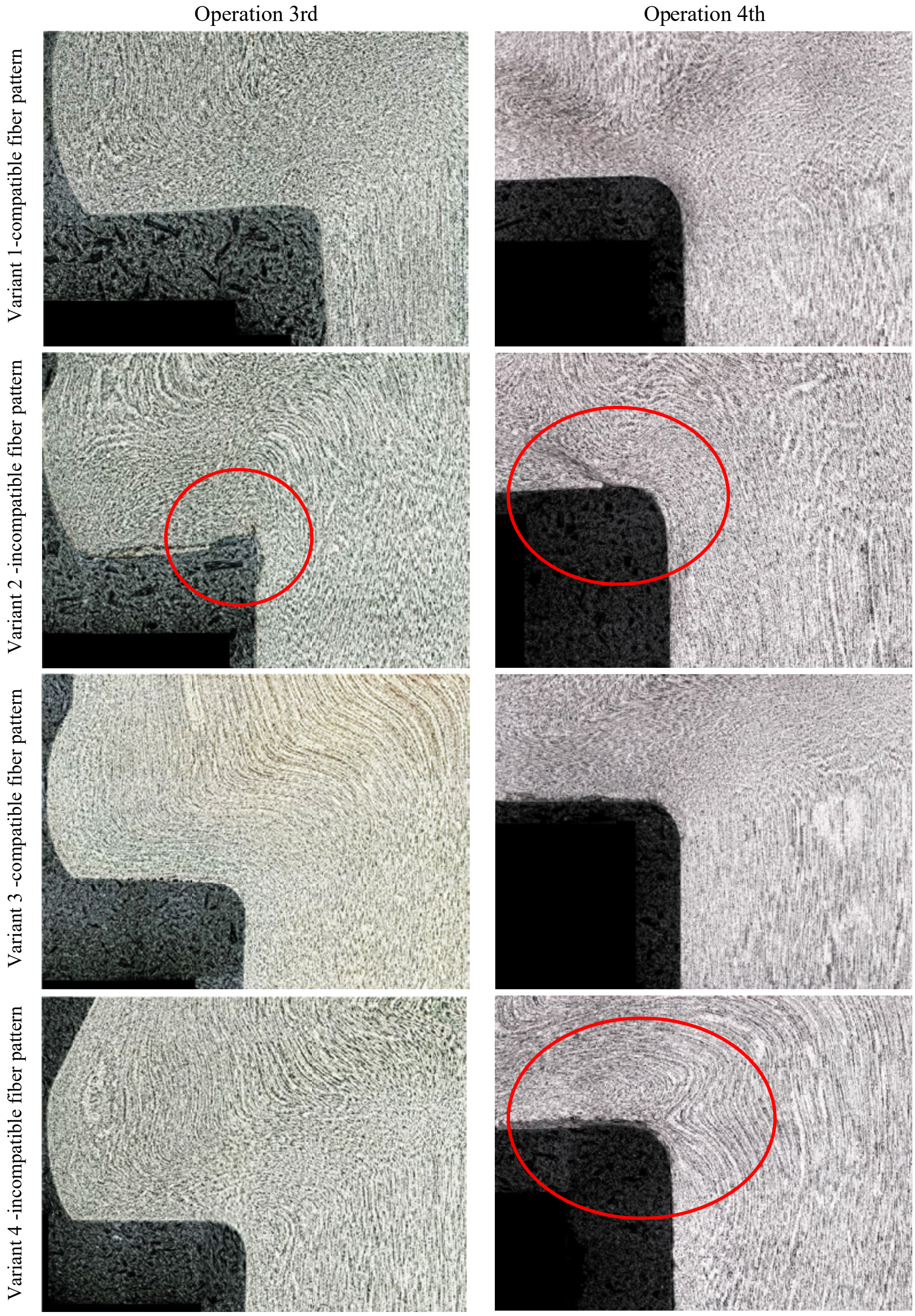

Fig. 5. The metallographic analysis of two forging operations for four variants

material was wire with a diameter of 7.73 mm and length of 84.71 mm. The bolts in the last forging operation were in accordance with the requirements of DIN 6921.

Variant 1 has a compatible fiber arrangement. The length of the pin in the first operation is 53,80 mm, while the total length is 70,96 mm. The fibers continuously pass from the mandrel into the bolt head, forming on the transition radius. The microstructure compliance is transferred from operation 3 to operation 4, i.e. the main assumptions of bolt head shaping such as the principle of constant volume of material and the principle of gradation of radius are met.

Variant 2 has an incompatible fiber pattern. The length of the pin in the first operation is 52,86 mm, while the total length is 69,94 mm. It results from excessive bolt support in 3 operations, where the fibers shifted from the height of the abutment surface to the height of the flange profile. The fibers were cut at the transition radius to form a forging lap. In operation 4, the material shifted to the bearing surface, and the fibers cut across the transition radius.

Variant 3 has an acceptable fiber arrangement, however, discontinuities will disqualify the product. The length of the pin in the first operation is 54,96 mm, while the total length is 72,1 mm. In operation 3, the flow of material and the shape of the blank is similar to operation 3 in option 1. In operation 4, the material was pushed from the head into the bolt bolt. This was due to the ejector support lower by 1 mm compared to variant 1, so when shaping the bolt head some of the material went into the bolt.

Variant 4 has an incompatible fiber pattern. The support was set 2 mm lower than in option 1. The length of the pin in the first operation is 55,84, mm, while the total length is 73,03 mm. In the first forging operation, material allowance was placed on the bolt head so as to obtain head filling in operation 4. In operation 3, the fibers are rounded over the transition radius. In the forging operation 4, the pressed material led to fiber break in the transition radius. In addition, a forging lap occurred on the bearing surface under the head.

8. Material flow lines in FEM simulation

Material flow lines (Fig. 4) determined in FEM simulation using the QFORM program (Fig. 6) do not fully reflect the results of the experiment. The most discrepancy is in variant 4, where in the FEM simulation there was no forging lap and the flange was not completely filled. The discrepancies may result from the use of 19MnB4 material strengthening curves in the simulation and 30MnB4 in the experiment. The discrepancy between the materials used in the study and the experiment was due to the fact that at the beginning FEM simulation was performed, then the experiment was carried out. Due to production planning and the distant deadline for the production of flange bolts made of 19MnB4 material, it was decided to conduct an experiment on current production from 30MnB4 material. Variant 4 shows a high concentration of material flow lines in the transition radius. In variant 2, the simulation correctly mapped the experiment, the program showed a forging lap on the bearing surface. Variant 1 obtained a consistent result in the simulation and experiment.

9. Grain flow pattern and tool wear

Along with the processing of the material in the head part, it strengthens, which results in an increase in stress concentration. A properly made set of semi-products with a compatible fiber arrangement, in addition to product reliability, allows for cost reduction resulting from excessive tool wear.

Incompatible fiber arrangement leads to the strengthening of the material in the areas of the bolt head, where there are strong impacts on the tools. The increase in stress concentration is accompanied by an increase in hardness. The examination of the hardness distribution of individual bolt variants showed differences in the stress concentration (Fig. 7). The analysis carried out in this way allows determining the difference between variants in individual zones. Knowing the technology of the tools

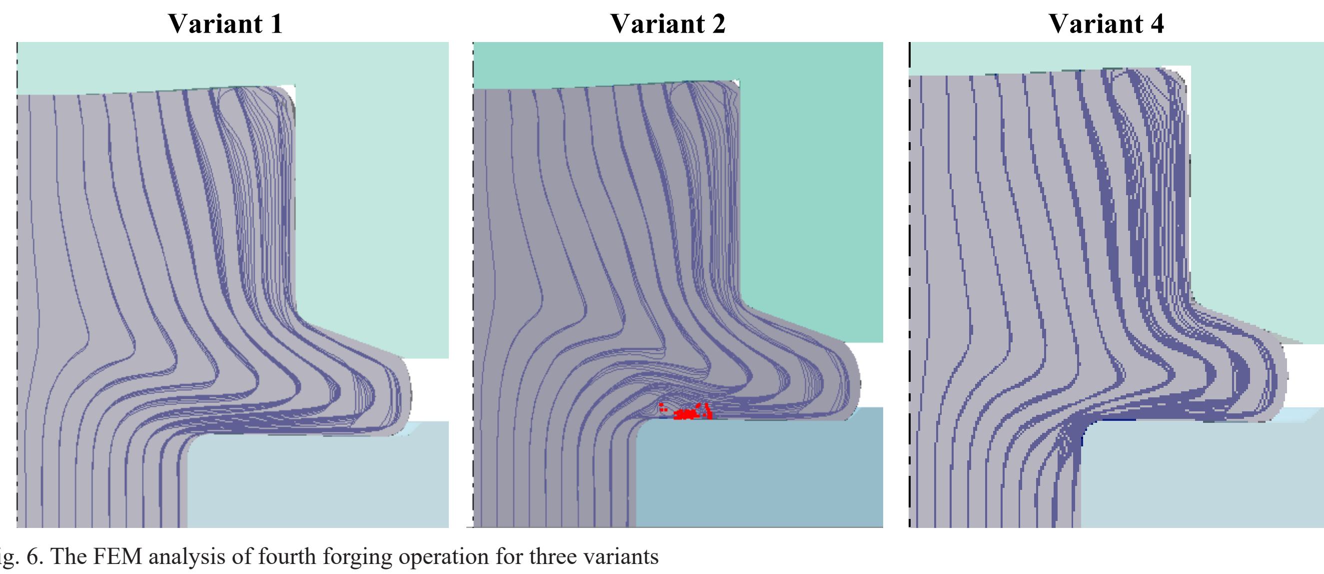

Fig. 6. The FEM analysis of fourth forging operation for three variants

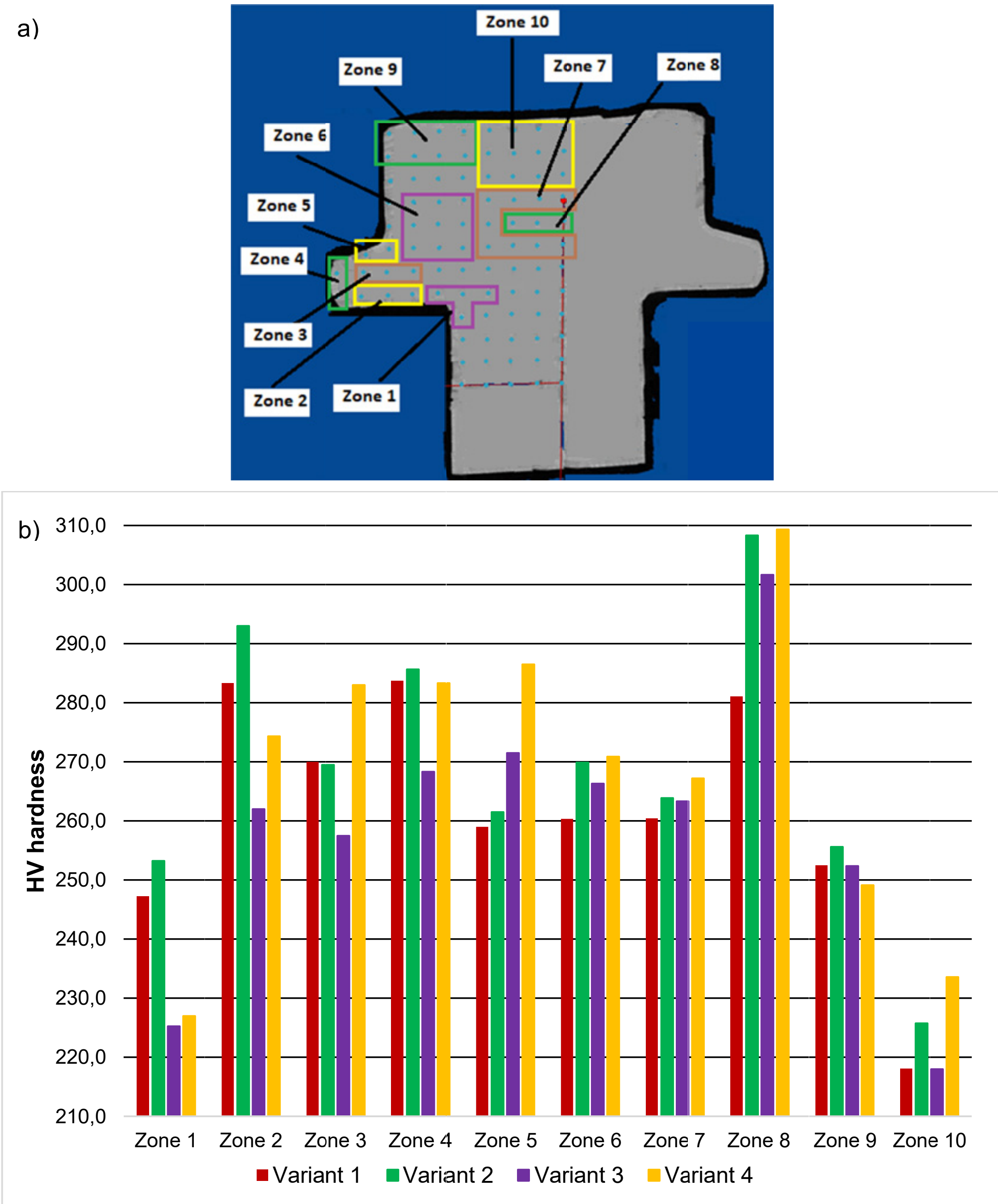

Fig. 7. a) The pattern of hardness measurements places in cross section of bolt head, b) Results of hardness measurements in particular bolt zones

and the wear of individual dies, the most optimal geometry of the semifinisheds is selected. The hardness distribution in the bolt zones is adapted to the tools, taking into account the service life of the tools.

The average hardness value of the mandrel, i.e. in a zone with low deformation, was 204 HV. The area of the bearing surface on the flange concentrates higher stresses in Option 2 equal to 293 HV, where as a result of high support material moves from the bolt pin into the flange. In turn, on the periphery of the flange, the highest hardness values of 283HV were tested in option 4, which results from the largest head volume allowance before operation 4. Inside the head, the lowest hardness values characterize the prepared variant 1, where in hardest zone 8 hardness 288 HV was obtained, and in zones 6 and 7 after 260 HV. In variants 2, 3 and 4, the hardness is 328 HV, 309 HV and 313 HV in zone 8 respectively. At the head surface, the most favorable hardness distribution is in options 1 and 3, and the tools will be most heavily loaded in options 2 and 4.

The hardness distribution showed that the correct fiber arrangement generates much lower stress values in areas close to the sample axis. In turn, in the area of the bolt flange, Variant 1 is no longer as optimal for the tools used there. It should be borne in mind, however, that the basic criterion for developing the technology is to ensure the reliability of the bolt, i.e. to achieve a compatible grain flow patter and surface continuity. In the third place should you put the tool life resulting from the developed technology. The technologist's task is to find a compromise that meets these and other criteria for designing the forging process.

10. Quality and process approach in controlling the grain flow pattern

In the case of responsible fasteners in cars or machines, where human health and life depends on their reliability, fiber system testing is performed for each production batch. This solution is part of the methods of continuous improvement, the emergence of requirements for the correctness of grain flow pattern was the driving force for organizing the appropriate procedures. Orientation on organizational culture, i.e. the consolidation of the forge operator's habit that the key aspects of the bolt that affect quality and safety should be checked have facilitated the minimization of bad batches. It is the employee of the forging department who gives an impulse in the form of providing samples before approving production to laboratories. To optimize real forging times, these tests are performed first, so the operator doesn't have to wait long for the forging to start. In addition, USCAR – 8 testing is required by an IT system and production cannot be started without the approval of a laboratory employee. System confirmation of product quality gives 100% certainty that the bolts have been checked. The quality control process is maintained, i.e. the contact of the production employee with the laboratory team. The applied solution is also part of quality assurance through good production the first time and usefulness of use. An example is a product whose production is renewed every month (Fig. 8). Pictures shown in Figure 8 were taken from January to June 2019, where each picture corresponds to the production batch from the next month. As can be seen in the Fig, the accepted fiber arrangement was consistent in each month. The introduced system confirms the high quality of manufactured products and minimizes the risk of breaking the connectors during operation.

11. Susceptibility to brittle fracture testing

Cracking of products during use is the greatest threat to use. Sudden disconnection may lead to an accident or catastrophe. Loss of structure stability or a decrease in stiffness resulting from the destruction of one of several used bolts in a short time may result in the destruction of the other bolts and connected components.

The bolts produced were subjected to processes enhancing their susceptibility to brittle fracture due to prolonged stress.

1. The wire used for forging the bolts is covered with zinc phosphate (bonder) before the drawing process, where together with the drawing soap forms a sub-lubricating layer. The task of the produced coating is to minimize the friction produced in the process of forging bolts when the wire is in contact with the tool. The requirements for the heat treatment of bolts are necessary before the hardening process to remove phosphates. This operation is to prevent the formation of a hard, brittle, penetrating grain boundary and non-removable ferrite δ layer on the surface. Phosphorus dissolved in ferrite reduces its plasticity, which can cause microcracks on the surface of the product. Determining the phosphate content on the bolt surface after cleaning is one of the mandatory tests for controlling the heat treatment process. In the case of the tested bolts, washing was bypassed and the products went directly to the hardening tape. In the continuous furnace, they have undergone a full program compatible with the technology for high-strength bolts.
2. After hardening, the tempering process follows, aimed at reducing stress, reducing hardness, and increasing impact strength. In the FMEA of the heat treatment process, the tempering temperature and its duration have gained the

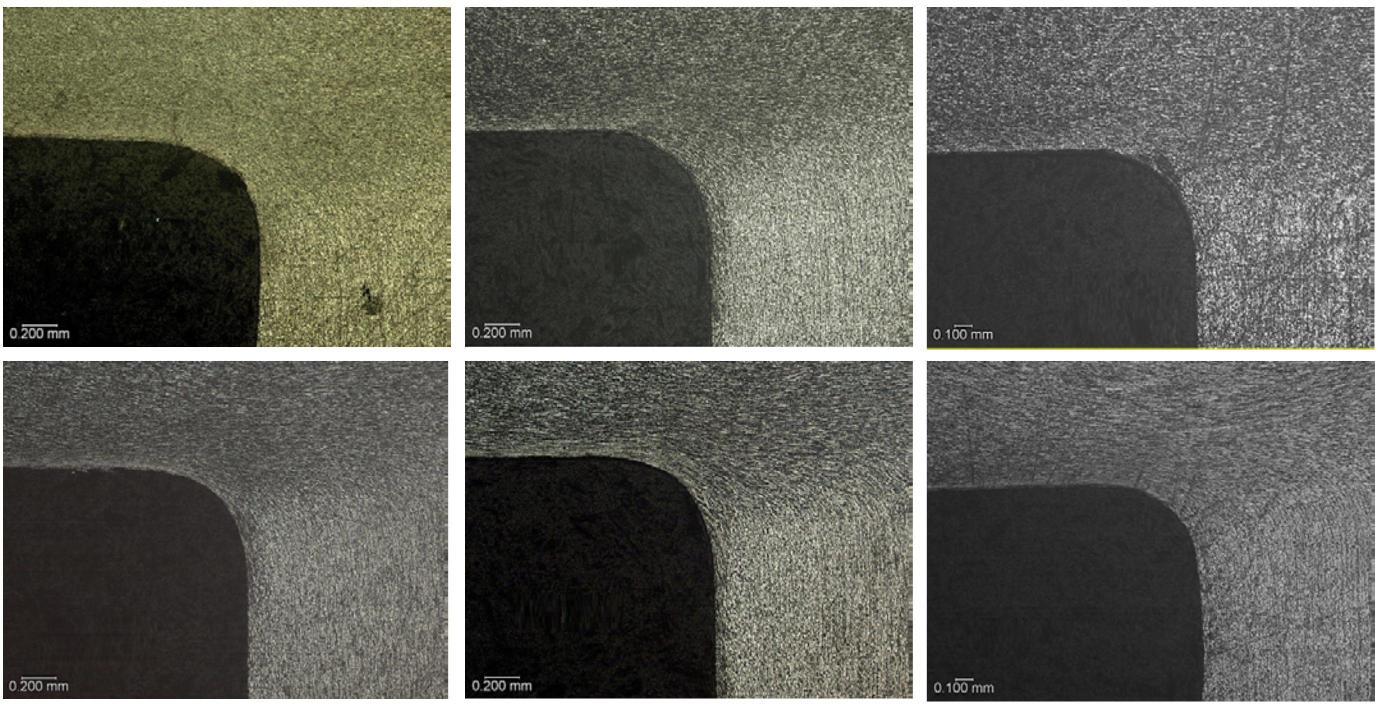

Fig. 8. Grain flow pattern tests on a new batch of bolts with each new resumption of production

greatest importance for the functionality of the product. This is due to the fact that these two parameters shape the physical properties of the bolt and are responsible for meeting the requirements of a given class of mechanical property. This translates directly into the use of the bolt starting from its assembly. In the case of tested bolts tempering was carried out at 300°C and lasted 2 hours. The tempering temperature of the M8 bolt made of 30MnB4 steel was too low and was within the range of brittleness tempering type 1 [12]. Thanks to this treatment, durable and hard bolt were obtained.

3. Product galvanizing is another process to which bolts are subjected. The zinc coating on the surface of the product is to ensure corrosion resistance. The downside of this process is the absorption of hydrogen on the steel surface and penetration into it during etching and galvanization. The highest risk of hydrogen embrittlement occurs in high-strength bolts (classes 10.9 and 12.9).

The bolts (variants 2, 3 and 4) had 5 aspects that could cause brittle cracking, such as incompatible fiber arrangement, forging lap in the bearing surface, δ ferrite on the surface, brittleness due to tempering temperature and hydrogen embrittlement.

Test for susceptibility to brittle cracking was carried out as follows:

1. Lubricated the bearing surface under the head and the bolt thread.
2. Installation of randomly taken bolts from four prepared variants on a Schatz tester and determination of the torque, clamping force and the value of the coefficient of friction on the thread and under the bolt head during tightening to obtain stress causing plastic deformation in the bolt.
3. had a minimum hardness of 50 HRC) using a nut with a removed coating. During assembly, the torque determined in point 2 was used, which guaranteed the generation of voltage in the connector.
4. Repeat the steps for 10 bolts for each developed forging variant.
5. Putting aside the bolts for 48 hours.
6. Dismantling the bolts after 48 hours.
7. Bolts rating due to cracks on the macro scale.
8. Performing metallographic specimens on selected bolts to assess microstructure for cracks.

The tested bolts did not break brittle. However, a negative phenomenon can be observed, which was revealed in the assessment of microstructures. Based on literature sources the research carried out so far in the field of the impact of the zinc phosphate coating on the surface of bolts in heat treatment processes, the occurrence of the delta ferrite phase on the tested samples was defined [10,11]. The ferrite δ layer occurred not only on the surface of the product but was also trapped on the tip of the forging lap in bolt (Fig. 9). Zinc phosphate was localized in the forging lap already during the forging process. In this situation, after washing and removing phosphates, it will remain in this defect and lead to the formation of ferrite δ.

12. Comparison of bolt checking methods

After the zinc coating process, the bolts were tested for mechanical properties. Presented results of strength tests for bolts that have all the defects produced, i.e. variant 2 and variant 4. The first test was the assembly on a Schatz machine to determine the mechanical properties during tightening. The method of tightening to the yield point was chosen, i.e. to achieve stress causing plastic deformation in the bolt. Due to the complex system of forces (tensile I and torsional II forces shown in Fig. 10) in the tightened joint, the effect of friction on the results obtained was minimized, the bolts were covered with grease. The results of individual parameters from the assembly test at the yield point are given in Table 1. The number n indicates the number of the bolt being tested. From the second variant, 3 pieces from 1 to 3 were tested, while from the fourth variant 2 pieces from 4 to 5. The lubrication of the bolts allowed to reduce and stabilize the coefficient of friction μ_{tot} determined on the Schatz machine and obtain an average result of 0.11. The assembly test also determined the clamping force F, torque T, torque under the head T_b and on the thread T_{th} as well as the friction coefficient under the head μ_b and on the thread μ_{th}. The average clamping force F was 47.18 kN and the torque was 70.32 Nm.

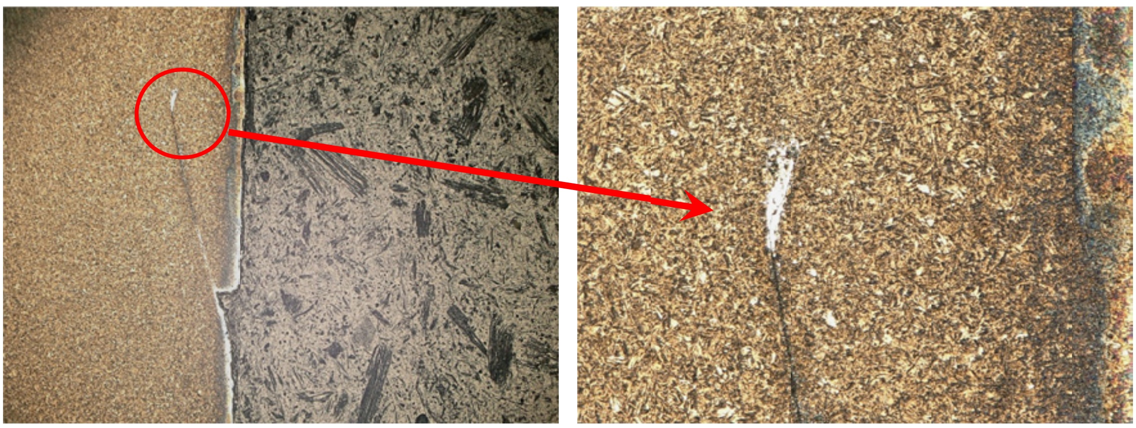

Fig. 9. Forging lap with ferrite δ layer on the bearing surface of the bolt

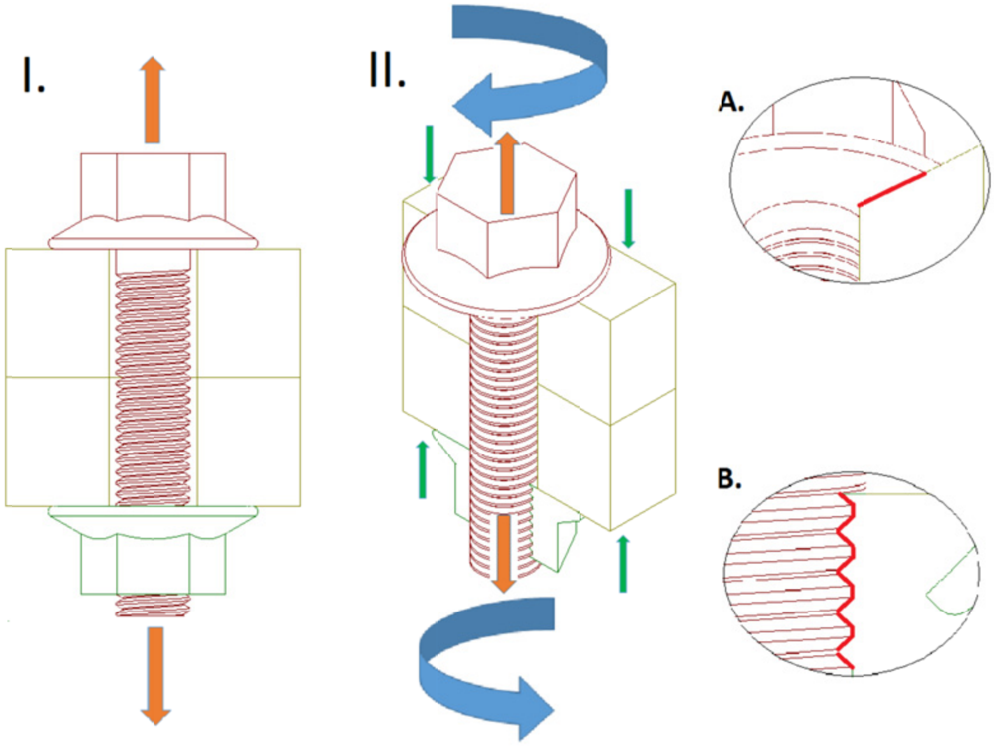

Fig. 10. I – static tensile test and simple system of forces. II – bolt assembly and complex system of forces

TABLE 1

The results of bolt assembly to reach the yield point on a Schatz machine according to ISO 16047: 2007

n	F	T	T_{th}	T_b	μ_{tot}	μ_{th}	μ_b
	kN	Nm	Nm	Nm			
1	46,39	70,42	42,29	28,13	0,11	0,10	0,12
2	47,28	69,18	41,00	28,18	0,11	0,10	0,11
3	47,64	75,55	48,45	27,10	0,12	0,09	0,13
4	46,82	70,60	42,64	27,96	0,11	0,10	0,12
5	47,76	65,86	37,59	28,27	0,10	0,09	0,10

TABLE 2

Tensile strength test

n	R_m	$R_{p0,2}$	F_m	$F_{p0,2}$
	MPa	MPa	kN	kN
1	1404	1397	51,39	51,13
2	1391	1381	50,91	50,54
3	1399	1391	51,22	50,91
4	1449	1436	53,02	52,56
5	1420	1414	51,98	51,75

TABLE 3

HV 10 hardness test

n	1	2	3
	HV	HV	HV
1	454	462	454
2	459	464	463

The second study was a statistic tensile test (Table 2). Samples were taken in the same way as for the assembly test, i.e. from 1 to 3 are bolts from the second variant and 4 and 5 are bolts from the fourth variant. Stresses and tensile forces were determined according to ISO 898-1. The third test examined the hardness of HV 10 (Table 3). One item from the second (n1) and fourth variants (n2) was tested. Three hardness test was carried out on one piece, where numbers 1, 2, 3 mean another measurement. The results obtained in Table 2 and Table 3 confirmed incompatible mechanical properties for 30MnB4 material obtained by too low tempering temperature.

The yield strength obtained in the assembly test is lower than that determined in the static tensile test. The difference results from the systems of forces occurring in the connection during the test. There is a complex system of forces in the tightening test. An important role for the results is played by the coefficient of friction on the thread and under the bolt head, creating the total friction coefficient. A change in its value will be responsible for a change in the clamping force obtained in relation to the torque. An increase in the coefficient of friction will cause a decrease in clamping force and an increase in torque, because more energy is used to overcome frictional resistance.

Testing the bolts by the assembly method determines the real parameters of bolt tightening at the stage of use. The difference between yield points determined in both tests is 8%, however, the size of the difference depends on the bolt coating and the friction coefficient obtained. The mounting method allows you to determine the maximum clamping force that a bolt will be able to produce on the joined elements. This is an advantage of the test because by modelling the assembly it is possible to determine the real values of mechanical properties obtained by the bolt.

13. Conclusions

The production of bolts is becoming more and more demanding for the manufacturer every year. Increasing expectations regarding the product must be confirmed in the quality of delivered parts. It is up to the bolt manufacturer to do more than is required of him and should close to 0 ppm defects. In addition to standard bolt tests, grain flow pattern requirements are becoming more common.

1. The grain flow pattern in the bolt corresponds to the reliability of the fastener in long-term use. Its compatibility is one of the most important attributes next to the mechanical parameters that must be preserved.
2. Tests carried out according to ISO standards after bolt production have shown that the bolts meet the strength and assembly requirements. The bolts did not break or crack during the static tensile test, installation on the Schatz machine and the test with preload. Standard bolt tests showed no difference between OK (compliant product) and NOK (non-compliant product) products.
3. A process approach is necessary to maintain high quality bolt production. Another factor required is having a team of laboratories at the factory, which will include a metallographic, measuring, chemical laboratory and independent quality control. The presented aspects would not be detected without the participation of a metallographic laboratory.
4. The radius of transition between the bolt head and the pin is one of the two places where the fastener breaks most often. It is important that this place is free from surface discontinuities and ferrite δ causing accelerated damage in operation.
5. Compliance of the fiber system is influenced by compliance with the principle of constant volume of material intended for shaping the head in subsequent forging operations, i.e. manipulation of the height of bolt stem support by the ejector. Another factor conditioning the compatibility of the fiber system is the correct shape of the previous blank.
6. Incompatible fiber arrangement, i.e. cut fibers in the transition radius increase the risk of cracks after prolonged use. Fibers form a natural path for propagation of microcracks, which under the influence of cyclic loads can lead to breakage of the connector.
7. Incompatible fiber arrangement intensifies the negative effects resulting from forging, hydrogenation, ferrite δ or bad tempering temperature. The starting point in obtaining a high-quality bolt is to achieve a compatible grain flow pattern.
8. The material movement shown by the bolt fibers is helpful in the design process of forging bolt technology. The material flow outline and microstructure view together with the simulation help to assess high stress zones affecting tool life.

Failure to demonstrate the effect of the grain flow pattern and other defects on assembly parameters is worrying. It should be borne in mind that the tests carried out will undoubtedly be reflected in the long-term use of screws. The authors see the need for further research in the presented aspects in terms of long-term use of bolts.

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