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Effect of Non-Metallic Inclusion from the Continuous Casting Process on the Multi-Stage Forging Process and the Tensile Strength of the Bolt: A Case Study

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Abstract**—**The paper presents the influence of non-metallic inclusions on the multi-stage forging process and the mechanical properties of the dodecagon socket bolt used in the automotive industry. The detected metallurgical defect was so large that it directly influenced the mechanical properties of the bolt and resulted in failure to meet the requirements of the mechanical property class. In order to assess the defect, an X-ray examination and metallographic examination of the defective bolt were performed, showing exogenous non-metallic inclusion. The size of the defect on the cross section was 0.531 mm in width and 1.523 mm in length; the defect was continuous along the entire axis of the bolt. In analysis, a finite element method (FEM) simulation of the multi-stage forging process was designed, taking into account a non-metallic inclusion parallel to the sample axis, reflecting the studied case. The process of defect propagation due to material upset in the head area was analyzed. The final forging stage in shaping the dodecagonal socket and filling the flange area was particularly studied. The effect of the defect was observed to significantly reduce the effective cross-section as a result of the expansion of the defect perpendicular to the axis of the bolt. The mechanical properties of products with and without the defect were analyzed. In the first step, the hardness test confirmed that the required value for the mechanical class 8.8 of both bolt types was obtained. In the second step, the bolts were subjected to a static tensile test. The bolts without the defect gave a positive result, while all 10 bolts with the defect gave a negative result, achieving a tensile strength below the requirements. Tensile strength tests were confirmed by metallographic tests and FEM simulation with perpendicular inclusion spread in the area of the head. The bolts were damaged directly under the bolt head, which is inconsistent with the requirements of ISO 898-1. It has been shown that non-metallic inclusions with orientation in accordance with the axis of the bolt can directly cause loss of functionality and these defects should be detected even before assembling in the machine element.

Keywords**—**Continuous casting, multi-stage forging, non-metallic inclusion, upset bolt head.

I. INTRODUCTION

THE cold forging process is one of the most efficient manufacturing processes for fasteners. The advantages of the process include high volumes of finished products per minute, surface continuity and grain flow pattern. Undoubtedly, non-metallic inclusions constitute a threat to cold-forged and heat-treated products. The development of industry in recent decades has forced steelmakers to change their processes, which results in obtaining ever cleaner steels with advanced chemical compositions and mechanical properties in the shortest possible time [1]. The development of the steel industry also focused on the phenomenon of defects in the form of non-metallic inclusions, a number of studies on the formation were carried out and many solutions were implemented to reduce this defect [2]-[4].

An aspect widely studied is the effect of non-metallic inclusions on fatigue failure. Zerbst et al. showed an overview of this issue, starting from the origin of inclusions, through their location or orientation in the product, and ending with the negative effects [5]. There are many concrete examples of equipment failure where one of the main causes was a metallurgical defect. The failure of the crankshafts of diesel engines was analyzed by Pandey [6]. The main cause of premature shaft failure was the fatigue mechanism. Surface defects from machining and grinding could be a likely location for cracks. Additionally, the crankshaft has been found to be sensitive to any non-metallic inclusions. Stevenson et al. examined the failure of the high-speed pinion shaft of a marine diesel engine [7]. The examined shaft failed after 30 years of use as a result of the high-cycle fatigue mechanism. The metallographic evaluation showed the distribution of inclusions near the crack initiation. The size of inclusions was not sufficient to initiate cracks and the main reason was the misalignment of the shaft operation caused by the last service. Baldizzone et al. compared two production batches of the crank pin connecting the crankshaft with the piston rod in a motorcycle engine [8]. Both production batches had non-metallic inclusions: batch one - B1 thin and elongated, batch two - B2 52 μm in size. B2 was a failing batch; the probable cause of the failure was the flaking process during crankpin work. The damage sites were located near the clusters of non-metallic inclusions that could cause nucleation of the cracks. The failure analysis of a bolt used in the railway industry was performed by Farahat et al. [9]. They investigated the failure aspect on the threaded part. Metallographic tests confirmed the presence of non-metallic inclusions, and their high content accelerated the initiation and propagation of cracks. The failure of the wire rope was analyzed by Balan by performing such tests as metallographic, fractographic, visual, strength, chemical composition analysis and microanalysis of the electron probe [10]. The obtained results showed the incompatibility of the material used for the production of the wire rope with the requirements and a large population of non-metallic inclusions being the place of fatigue initiation.

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Open Science Index, Mechanical and Materials Engineering Vol:15, No:9, 2021 publications.waset.org/10012250.pdf

The current forging processes are multi-stage processes that require prediction of defects during the process and negative effects of defects in its use. All kinds of cracks and surface discontinuities that may affect the usability of the forged element are unacceptable. The multi-stage process of forging a high-strength, one-piece input shaft without defects was proposed by Jo et al. [11]. In the work, using the finite element analysis (FEA), it was checked that the shaft is free from internal defects (cracks). The mechanical properties were approximately 45-50% better than that of the conventional manufacturing process. The more widely studied range of defects is the occurrence of chevron cracks in drawing or cold extrusion processes. Im et al. verified simulation of chevron cracks using the Cock Croft-Latham crack criterion [12]. They found that the fracture parameters depended on the size of the element and the boundary conditions at the tool contact. The study of non-metallic inclusions in forged elements is included in the work of Singh et al. [13]. It was determined that aluminum oxides strongly influenced the crack initiation mechanism and were close to the core of the defective sample. The ML25Mn steel cracking during plastic working was tested by Li et al. [14]. Chemical composition tests were performed and non-metallic inclusions were identified. The crack was excluded due to the hardness of the material and the main cause of non-metallic inclusions was selected as the main cause. Hosseini et al. investigated the formation of the central flaw during the forward extrusion process by means of a FEM simulation experiment [15]. Taguchi analysis was used for the analysis, obtaining the smallest possible waste from the process based on the parameters of friction coefficient, die angle, area reduction and critical thickness. It was observed that a more important factor for the defect was the increase in height than the radius of the central cavity in the final stages of extrusion.

In the multi-stage forging process, it is important to understand how the non-metallic inclusion affects the final mechanical properties of the product; how the defect propagates in the process of shaping the bolt head, where the wire segment was upset. The presented research demonstrates with an example a direct impact of the defect on the functionality of the product after production, before use.

II. MATERIALS AND METHODOLOGY

The tested objects are M8 x65 bolts with the entire thread and dodecagon socket. The bolts meet the requirements of mechanical property class 8.8 according to ISO 898-1 and are made of the material 20MnB4 [16]. The products are made of wire rod produced in the continuous casting process. The supply of wire rod was verified according to the requirements of EN 10263-1 [17]. Before the forging process, the wire rod was subjected to the processes of pickling, annealing, zinc phosphate coating and wire drawing. The forging process takes place in a multi-stage forging machine, in this case, it is a four-stage forging machine presented in Fig. 1. After forging, the product was heat treated in order to obtain the required mechanical properties, and from there to a coating ensuring appropriate corrosion resistance and friction coefficient required for assembly.

Fig. 1 Successive steps of multi-stage forging a bolt, (a) side view in the Z axis, (b) upper view in the Y axis

During routine tensile strength tests, the bolt failed to comply with the requirements of the standard. Analysis of the defective piece by means of an X-ray image (Fig. 2) showed the presence of non-metallic inclusions. Defective bolts were subjected to metallographic tests in order to analyze the size and determine the direction of the inclusions. At a further stage, the FEM analysis was performed for the case with an internal material defect (wire and wire rod) to determine the manner of the defect propagation as a result of the upsetting and socket forming process. The last stage was the examination of the mechanical properties. The hardness of the bolts with and without the defect was tested to confirm the correctness of the heat treatment process. Then, the static tensile test was performed on the bolts with and without the defect. The collected results made it possible to analyze the risks of the occurrence of defects in the form of macro inclusions.

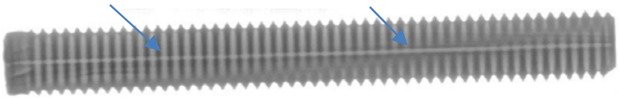

Fig. 2 X-ray image of the defective threaded bolt pin with visible non-metallic inclusion

III. NON-METALLIC INCLUSION

Non-metallic inclusions get into steel in metallurgical processes. A distinction is made between endogenous and exogenous inclusions; the classification is based on the origin of the contamination. Endogenous inclusions result from the reaction of the liquid alloy with oxidants. As oxidants, there are particles of manganese, silicon or aluminum. Endogenous inclusions can be divided into four groups: primary and secondary from 1 µm to 20 µm, triple and quaternary from less than 1 µm. Endogenous inclusions become more difficult to remove as the size of the inclusions decreases. Exogenous inclusions, the so-called macro-inclusions larger than 20 µm come from external sources such as slag, refractory materials [5], [18]. Exogenous inclusions have their origin in the following cases shown in Fig. 3:

- Oxidizing ladle slag,
- Reoxidation by air,
- Tundish slag,
- SEN (submerged entry nozzle),
- Mold slag,
- Indigenous, exogenous inclusions,
- All sources [2].

The impact of non-metallic inclusions on the use of the product depends on:

- Shape,
- Distances from the surface of heavily loaded areas,
- Chemical composition and microstructure,
- Orientation of its main axis in relation to the load direction [19].

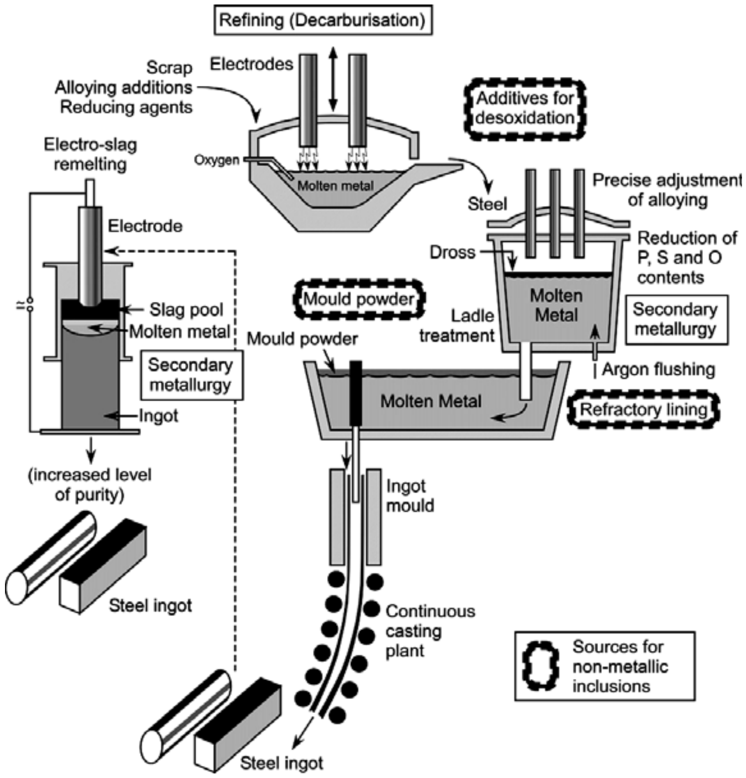

Fig. 3 Scheme of steel production with places of potential sources of non-metallic inclusions [19]

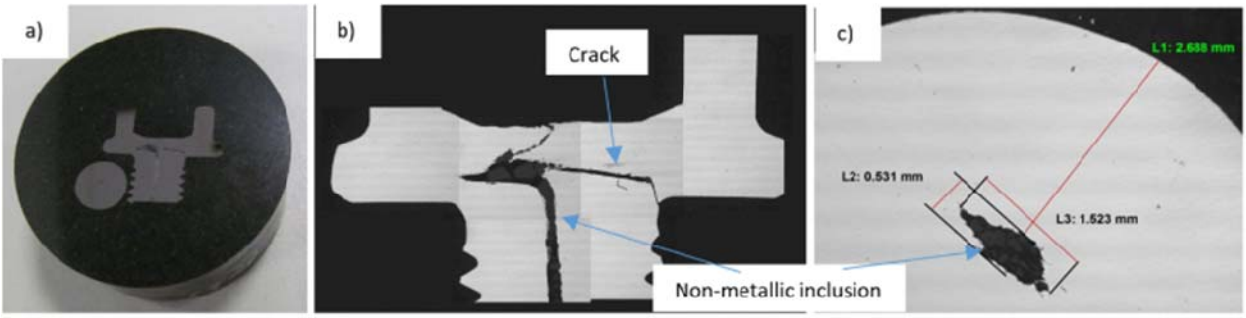

Fig. 4 (a) Metallographic sample with a visible defect, (b) longitudinal section through the bolt head, (c) cross section through the threaded portion of the bolt

Endogenous inclusions due to their size may not be revealed immediately after mounting the element in the device. The negative effect of this type of defect may only be revealed after prolonged use. In turn, exogenous inclusions ranging in size from 20 to several hundred µm have a direct negative effect on the element made of steel. They pose direct threats to the installer and end use, negatively affecting the mechanical properties. In the currently used methods of continuous casting of steel, the occurrence of exogenous inclusions is negligible, but when such a product is released

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for production in an uncontrolled manner, the produced element becomes dangerous [2], [5].

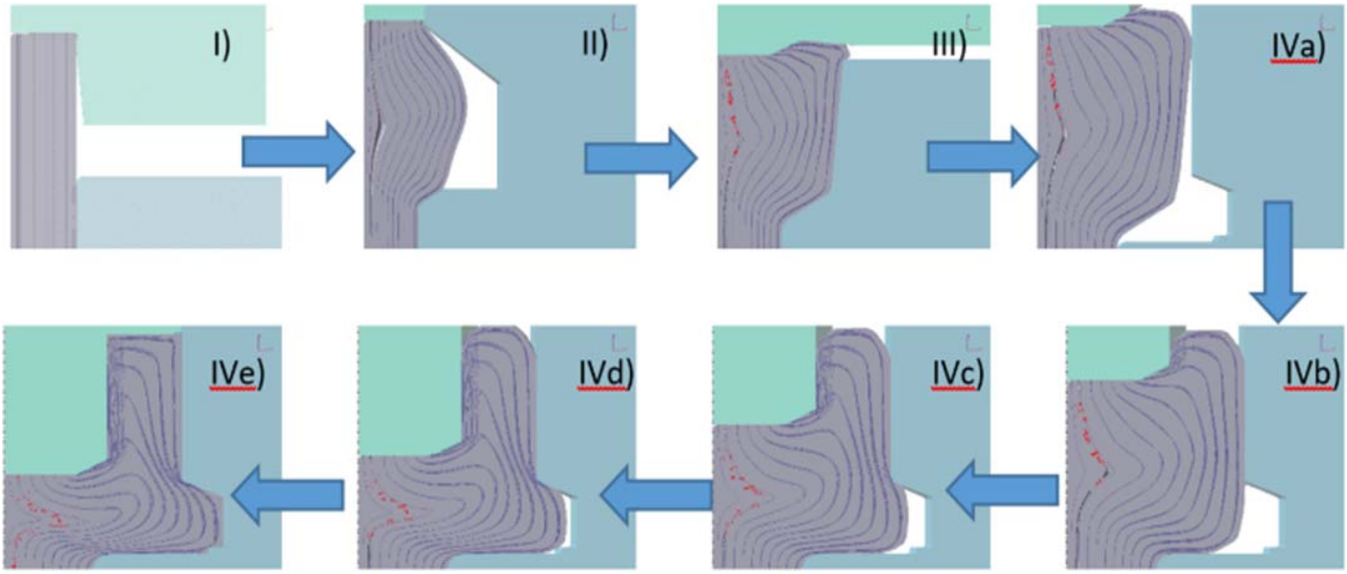


Fig. 5 FEM simulation results for multi-stage forging of a bolt with a wire internal defect

IV. Metallographic Research

The metallographic test was performed on one of the defective bolts and an inclusion was visible on the prepared polished surface (Fig. 4 (a)). Two samples of this bolt were prepared (Figs. 4 (b) and (c)); the first was a longitudinal cut through the bolt head, the second was a cross cut through the threaded part of the bolt. The longitudinal cut surface shows a non-metallic inclusion and a crack in the radial direction towards the outside of the bolt axis. The area of the non-metallic inclusion as a result of upsetting has widened in the radial direction of the bolt head. The non-metallic inclusion in the longitudinal cut area of the pin has an orientation that is parallel to the bolt axis. The crack may have been formed during forging or heat treatment. The size of the non-metallic inclusion is shown in the cross section. The inclusion is 0.531 mm wide and 1.523 mm long. The thread section of the bolt underwent the smallest deformation of the entire product, but it was subjected to the wire drawing process and in the forging operation, the diameter was reduced due to the adaptation of the pin to thread rolling. The actions performed changed the final size of the defect.

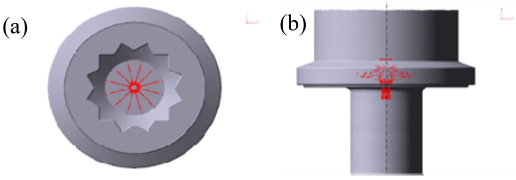


Fig. 6 Symmetrical view of the bolt after FEM simulation with shown propagation of the lap forging as an internal defect, (a) in the Y axis, (b) in the Z axis

V. FEM Simulation of the Defect

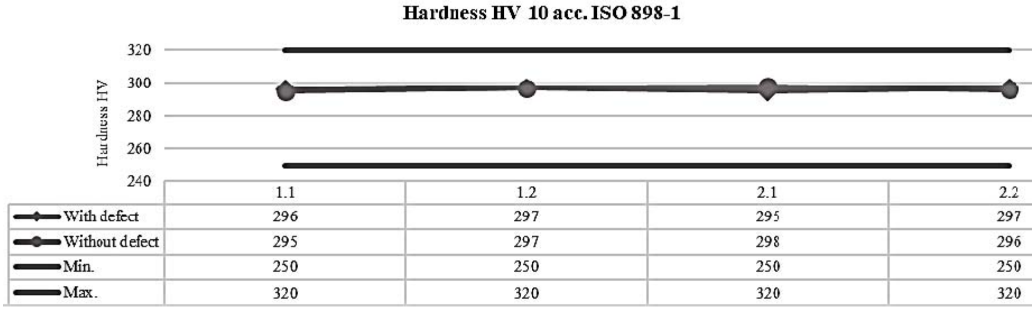
In order to analyze the impact of the defect on the strength of the bolts, the FEM analysis of the forging process was performed, presented in Fig. 5. The FEM simulation was based on the current technology of tool making and the dimensions of the input material cut. A hole was prepared in the cut of the charge material, which was to reproduce non-metallic inclusions parallel to the axis. The QForm3D program accepted the hole made in the subsequent stages of forging as the lap forging. The shaping process takes place in a multi-stage forging. In the presented example, four stages of forging are performed, forming the head of the bolts in each stage. Stage I is the initial upset of the material, and stage II is the further upset of the head area. In stage III, technical cavities for the punch are formed. For the first three stages, it can be seen how the defect widens in the radial direction. Stage IV was divided into five steps (a, b, c, d, e) to better visualize the growth of the defect, where stage IVa is the start stage, and stage IVe is the end stage and obtaining the final shape of the bolt head. This is due to the formation of the socket and the flange. The work of the die moves the material in the radial direction. The internal defect moves along with the movement of the material. The defect of a line to the axis of the bolt through plastic working has become a defect perpendicular to the axis of the bolt. Due to the round shape of the bolt, the defect has a circumferential character as shown in Fig. 6, depicting the view of the product in the Y and Z axes. The location of the defect perpendicular to the bolt axis is located at the height between the bolt socket and the radius of transition of the head to the pin bolt. Such a location of the defect led to a reduction in the cross-section of the bolt and a reduction in strength.

VI. MECHANICAL PROPERTIES OF THE BOLT

For mechanical tests, 12 bolts were chosen from the batch with and without defects. The samples were subjected to hardness and tensile strength tests, which are the basic tests for approving bolts for use.

A. Hardness Testing

The first test was the HV 10 hardness test on the Amh43 hardness tester using the Vickers method. The test was carried out on the threaded part of the pin at a distance of 1D (where D is Nominal diameter of the bolt) from the face of the bolt thread and at a distance of ½ r (where r is nominal diameter radius of the bolt) from the flank of the bolt thread. Two pieces were examined, making two readings on each tested piece. The test method complies with the requirements of ISO 898-1 for determining the mechanical properties of the bolt. The results are presented in Fig. 7, marking defective products as 'with a defect', while conforming products as 'without a defect'. HV hardness requirements for mechanical class 8.8 with a diameter less than 16 mm according to ISO 898-1 are from 250 to 320 HV. As can be seen in the graph, the results for all four samples are comparable with each other, the mean value of the bolts with the defect was 296.25 HV, while for the bolts without the defect it was 296.5. The spread for all eight readings was 3 HV. As it can be seen, the defect has no effect on the hardness. The obtained hardness values are in the upper half of the required hardness for the mechanical class and prove that the heat treatment process was correctly carried out.



	1.1	1.2	2.1	2.2
With defect	296	297	295	297
Without defect	295	297	298	296
Min.	250	250	250	250
Max.	320	320	320	320

Fig. 7 Results of the Vickers hardness acc. ISO 898-1 for bolts with defect and without defect

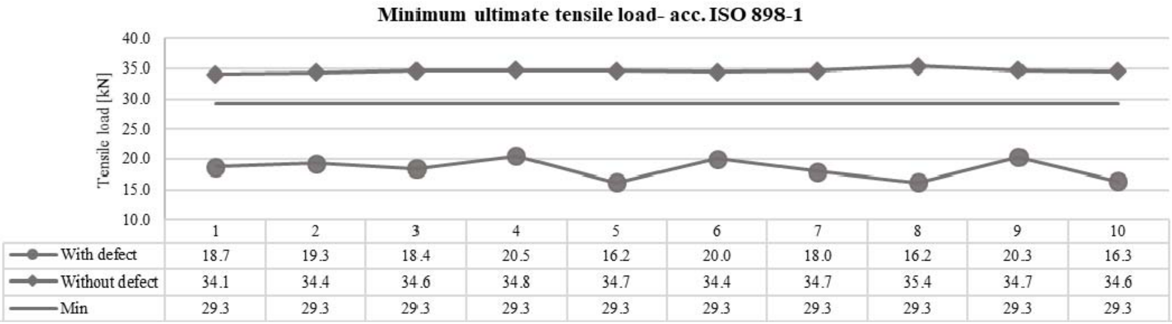
B. Tensile Strength Test

The tensile strength test was carried out on 20 samples using the static tensile machine. The samples were marked in the same way as in the hardness test. The test was performed in accordance with DIN EN ISO 6892-1, which is required by ISO 898-1 to determine the tensile strength of the bolt. The ISO 898-1 standard specifies the minimum tensile strength for bolts made in mechanical class 8.8 and with a diameter smaller than 16 mm, equal to 800 MPa or 29.3 kN. To calculate the tensile stresses, a cross-section of 36.6 mm^2 was adopted, the calculation of which is based on the core diameter of the bolt thread. Tensile tests according to the requirements of ISO 898-1 are as follows: the bolt is mounted in adapters with a minimum hardness of 45 Hardness Rockwell C (HRC), a washer with a properly selected hole diameter is mounted under the head of the bolt, a plug (nut) with an internal thread of the required tolerance class is mounted on the bolt thread. The free threaded length of the bolt under load must be at least 1d (where d is bolt pin diameter). The contact length of the threads should be at least 1d. The test speed should not exceed 25 mm/min. In the case of the tested head threaded bolts, a crack could occur:

- in the free threaded length of the bolt,
- start in the free threaded length of the bolt and spread to the section between the thread and the head or to the head.

Fig. 8 presents the results of the static tensile test. The bolts with the defect fell below the required value of the maximum tensile load, the average of the obtained results was 18.4 kN for 10 samples. The dispersion between the results was 4.25 kN, it resulted from the size of the defect for individual samples and the location of the bolt in the cross-section, affecting the strength. The products without a defect gave the results correct for the standard requirements, the average of the 10 tested samples was 34.6 kN. The dispersion was equal to 1.3 kN, it could have resulted from inaccuracy of the testing machine or minimal differences in the screw thread geometry. The strength of bolts with a defect is on average lower than that of bolts without a defect by 16.2 kN. In the tested case, a comparison of the tensile stress values based on the value of the nominal cross-section would be an error. The cross-section of the bolts with a defect is lower than that of bolts without a defect and depends on the size and geometry of the internal defect.

The method of bolt destruction is shown in Figs. 9 (a) and (c), the defective bolts broke directly under the head. The threaded part did not deform. The immediate cause of such a method of breaking was the internal defect, which expanded and decreased the cross-section due to the upsetting. The crack propagation went from the defect located in the head, Fig. 9 (b), to the area of the radius connecting the head with the bolt pin. Bolts without a defect were reduced in the diameter of the screw thread as required by the standard. The reduction took place in the area with the smallest cross-section, i.e., the core diameter of the bolt thread.



	1	2	3	4	5	6	7	8	9	10
With defect	18.7	19.3	18.4	20.5	16.2	20.0	18.0	16.2	20.3	16.3
Without defect	34.1	34.4	34.6	34.8	34.7	34.4	34.7	35.4	34.7	34.6
Min	29.3	29.3	29.3	29.3	29.3	29.3	29.3	29.3	29.3	29.3

Fig. 8 Results of the minimum ultimate tensile load acc. ISO 898-1 for bolts with defect and without defect

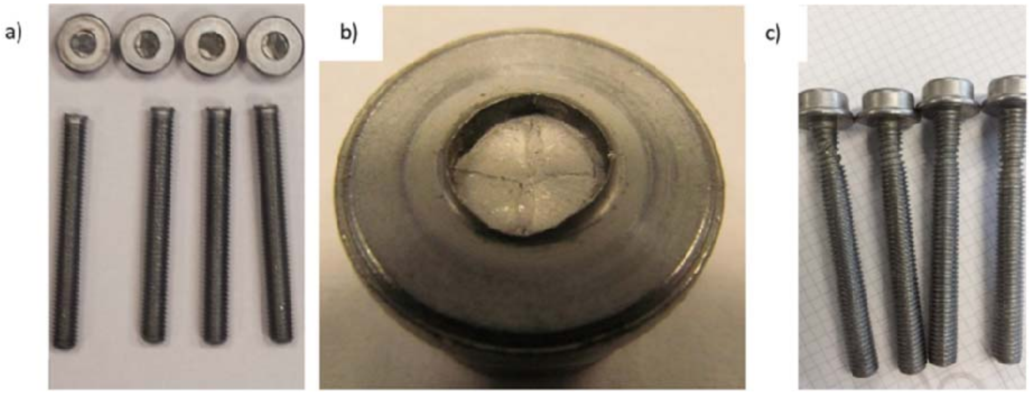


Fig. 9 Examples of static tensile test results, (a) bolts with the defect, (b) damage to the bolt due to a defect, (c) bolts without defect

VII. DISCUSSION

Bolt products with a certain strength given by heat treatment, as a rule, are special-purpose products used for machine parts in a way that allows easy disassembly during failure of the supporting element. The design of this bolt assumed the fulfillment of, among others, the following mechanical-physical properties: homogeneity of material parameters and mechanical properties, accuracy of workmanship. If at least one of the assumed requirements is not met, premature failure may occur, where additional non-metallic inclusions will reveal [6], [7], [9], [10]. The occurrence of non-metallic inclusions is often the driving mechanism for shortening the number of cycles performed by the element, and in the discussed case, loss of functionality is already at the production stage.

The spread of the defect in the form of non-metallic inclusions in the multi-stage cold forging by means of FEM simulation allowed us to predict the location of the largest defect concentration [11], [12], [15].

The wire rod delivery tests concern only a fraction of the delivered batch [17]. The samples are taken from the beginning or the end of the coil, the weight of which ranges from 1 t to 3 t. In the case of a wire rod with a diameter of ø8.5 mm and a weight of 2 t, the length of the coil is approximately 4400 m. This means that an internal defect in the coil of the wire rod will normally only be revealed after the product has been processed. In the absence of visible surface changes after processing and failure to find defective products during post-production inspection, the defect may only be revealed during assembly or by the end user.

Bolts are responsible for connecting important elements of machines and structures. In the case of the automotive industry, these will be wheel, seatbelt, engine, and others. Bolts are also used in the machinery industry, where they hold elements of the production line, such as actuators. In steel structures, they connect the individual load-bearing elements and define the resistance of the entire structure to loads such as snow or wind. It is important to detect a defect in the form of non-metallic inclusions at the stage of the metallurgical process or the manufacture of the bolt in order to prevent the product from being used.

VIII. CONCLUSION

Manufactured products with a defect should be separated before shipment to the customer. The size and arrangement of the defect led to the loss of the mechanical properties of the product and failure to meet the requirements of ISO 898-1.

In the presented case study, the following features should be noted:

1) Non-metallic inclusions of exogenous type may lead to direct loss of product functionality. These defects can directly affect the safety of the installer and user of the machine or structure.
2) Detection of non-metallic inclusions is not always possible at the stage of verification of wire deliveries from the steel mill. The chance of finding an internal local defect in the supply of wire rod is very small and requires specialized equipment.

3) Non-metallic inclusions arranged axially to the upset direction may expand as a result of the movement of the material and move radially outside the product. Such case may lead to a reduction of the strength in the direction of this axis.
4) It is unlikely that a non-metallic inclusion will be detected on a finished product, ready for use by the user.

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