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CAUSES OF STRESS-RELIEF CRACKS IN FORGED DIFFERENTIAL GEAR

Summary. The article investigates the formation of stress-relief cracking and lamellar cracking in steel forgings used for differential gears for transport components. The forging and heat treatment processes, conducted under consistent technological conditions, revealed the occurrence of carburizing annealing cracks caused by plasticity depletion during stress relaxation. Additionally, stress-relief cracks were microstructurally analyzed, and the primary cause of the disturbance of the equilibrium state, which resulted in the formation of these cracks, was sought. Die-tool wear and damage during forging were identified as key contributors to the formation of non-metallic oxide inclusion, transferring surface defects and creating lamellar propagation during subsequent heat treatment. The findings underscore the influence of tooling conditions and process parameters on the quality and reliability of steel forgings.

Keywords: stress-relief cracking, lamellar crack, forging, differential gear

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1. INTRODUCTION

The increasing demands for transmitting greater torque forces through differential gears bring many challenges to the designers of individual components. Even proven processes for producing precision drop forgings can ultimately introduce errors into subsequent progressive methods of increasing the mechanical properties of steel, which can ultimately be counterproductive due to material failure.

The production of a gear wheel made of alloyed stainless steel for an axel - differential, represents a technologically demanding process, wherein strict adherence to defined manufacturing procedures is essential for ensuring the required quality of the final product. The resulting properties of the components are significantly affected not only by the applied technological operations but also by the precise chemical composition and microstructural characteristics of the input material.

In conventional industrial practice, the identification of latent defects during processing remains a considerable challenge. In many cases, such defects become apparent only during special processes, or final inspection and quality control procedures. This necessitates detailed post-process analysis aimed at identifying the root causes of the observed nonconformities.

Effective detection and classification of defects in forged components require a systematic and comprehensive approach to their typology. Among various defect types, crack-like discontinuities are particularly problematic due to the complex and multifactorial nature of their origin, which may involve thermal, mechanical, or metallurgical influences throughout the entire manufacturing cycle.

A fundamental classification of surface crack types is described in the EN 1011-2 standard [5]. While this standard primarily addresses cracks arising during welding, it is not limited to those occurring in welds but also includes cracks in the heat-affected zones of parent metal. According to this standard, base materials include not only sheets but also pipes and forgings. Categorized cracks based on their temperature of origin during forging and their type—taking into account orientation relative to the forging axis, location on the forged part, and the forging method used [6,7].

Researchers Viňáš, Brezinová, Maňková, and Brezina [3] as well as researcher Brziak [4] adopted the basic classification of cracks from the EN 1011-2 standard and further refined it into four primary groups, each with subcategories. These groups include hot cracks, such as solidification, liquation, and polygonization cracks. Cold cracks are a broad category without subdivisions. Lamellar cracks are divided into exogenous and endogenous types and annealing cracks, and have been a subject of study for many researchers. Researchers Ito and Nawrocki investigated the mechanism of crack formation due to stress relief [8, 13, 14].

Although the basic mechanisms of stress-relieving annealing cracking are generally known and extensively documented in the literature, the details of crack initiation and the factors influencing them remain a matter of debate [10]. In general, stress-relief cracking occurs when the stresses during annealing exceed the local deformation capacity of the material [15].

The following mechanisms are generally necessary for crack initiation:

- almost complete dissolution of carbides and carbonitrides in the coarse-grained heat-affected zone;
- partial supersaturation of carbide-forming elements due to rapid cooling;
- precipitation of dissolved elements and formation of carbides in the matrix during subsequent heat treatment.

The formation of these cracks is associated with high-stress states in the carburizing zone during phase transformations when cooling the materials above the heating temperature Ms - 180°C. The temperature of heat treatment and holding time depend on the chemical composition and especially on the material thickness. In cases where the mechanical stresses are already too high, it can be necessary to perform a so-called intermediate stress relief heat treatment [2, 10, 12].

Numerous research results on precipitation behavior and carbide development in low-alloy steels have been published in the last 60 years. While there is agreement in the literature that crack initiation takes place during the heating phase of the heat treatment, there are widely differing statements on the critical temperature range of crack formation, from which a very broad range between 315 and 705°C can be derived [11]. While the time-temperature behavior of carbide formation is documented in detail, the influence of the forging process has so far received little attention.

All defects introduced into the forgings during the forging process present a significant challenge in the production of steel forgings, as defects can drastically affect the quality and mechanical properties of the forged components. Such defects may lead to product failure in applications subjected to high mechanical or thermal loads.

The paper presents the results of research aimed at determining the causes of lamellar stress-relief cracks in carburizing forgings.

2. MATERIALS AND METHODS

Experimental observations of defect occurrences were conducted on the product "gear wheell," designed for axle-differential applications for LKW and heavy-duty machinery. The product features a simple geometric shape - a rotational disk with a central hole and a non-uniform cross-section.

The product dimensions are as follows: outer diameter - Ø 315 mm, inner diameter of the central hole - Ø 658 mm, height - 60 mm, thickness - 30 mm, weight of the forging is approximately 16 kg.

The forging is manufactured from 18CrNiMo7-6 steel, classified according to EN 10084:2008. Highly stressed machine parts with a cemented surface. After heat treatment, the cemented layer reaches a surface hardness of 62 up to 64 HRC, while the core of the cemented part is quite tough even with relatively high strength.

This products from 18CrNiMo7-6 steel after forging are recrystallization heat treatment to achieve a ferritic-pearlitic microstructure. Subsequently, they are subjected to machining, hardening with cementation, and grinding to achieve the desired roughness.

The technological and production operations for the forging of the bearing ring are summarized in Figure 1. The heating of the billet is performed in a gas furnace at a temperature range of 1150 to 1280°C.

The forging of the "gear wheel" is carried out on a mechanical forging air hammer with a maximum working force of 17 500 kN. The forging tools for this operation are designed to combine two phases:

- pre-forging (open die): this phase involves reducing the billet to the desired height of the preform and shaping it to prepare for the next phase;
- final forging (closed die): this phase involves filling the forging cavity to achieve the desired shape of the forging. The result includes a slug for the central hole and flash along the edges of the forging.

Fig. 1. Final product – gear wheel

Subsequently, on a separate machine – a mechanical press with a maximum working force of 15000 kN - the forging undergoes flash and slug removal.

Tab. 1.

Technology operations overview

Working operation	Material	Working temperature [°C]
Heating	18CrNiMo6-7 + U	1150-1280
Forging	18CrNiMo6-7	900-1150
Annealing	18CrNiMo6-7	710-750
Tempering	18CrNiMo6-7+FP	550-690
Machining	18CrNiMo6-7+FP	20-30
Carburizing	18CrNiMo6-7 + gas	930 – 940
Cooling	18CrNiMo6-7 + oil	25-35
Quenching	18CrNiMo6-7	830-840
Cooling	18CrNiMo6-7 + oil	25-35
Tempering	18CrNiMo6-7	180
Griding	18CrNiMo6-7	20-30

After the forging process, the product undergoes heat treatment, beginning with recrystallization annealing in continuous gas furnaces equipped with electronically controlled temperature regulation systems, in accordance with the DIN 17052-1 standard (Requirements for temperature uniformity). The treatment is carried out at a temperature of 750 °C with a holding time of 200 minutes.

Following controlled cooling, the forgings are subjected to shot blasting to remove surface contaminants and prepare them for final quality inspection. Non-destructive testing is then performed, specifically visual inspection in accordance with the EN 13018 standard. Subsequently, the forgings undergo machining operations, including turning and milling.

The next stage of heat treatment involves gas carburizing. The components are placed in a furnace and exposed to a controlled carbon monoxide atmosphere. The furnace is heated to a temperature range of 930–940 °C, corresponding to the austenitic phase region of the steel. The carbon potential of the atmosphere is precisely regulated to achieve a target surface carbon concentration of approximately 0.5%. The required effective case depth of carburizing is in the range of 1,1-1.5 mm.

Following carburization, the parts are rapidly cooled by oil quenching, transforming austenite into martensite and thereby increasing surface hardness. The quenched components are then quenched and tempered at a lower temperature (e.g., 180 °C) to relieve internal stresses and improve toughness.

The subsequent processing step is grinding, which ensures the desired surface finish and dimensional accuracy. The final process is non-destructive testing (NDT) - a visual inspection of the pieces to detect any defects.

To evaluate the mechanical properties, chemical composition, and microstructural characteristics, a cross-sectional specimen was prepared for analysis. The chemical composition was determined using optical emission spectroscopy. The results, presented in Table 2, confirm that the elemental composition of the material falls within the specified limits for 18CrNiMo7-6 steel and for the carburization layer of this steel.

The obtained measurement results fall within the specified tolerance limits, confirming compliance with the prescribed quality criteria. The applied technological procedures led to the achievement of the required mechanical and structural properties in both the base material and the cemented surface layer. Detailed results are presented in Table 2 and 3. The base material, prior to mechanical processing, exhibited the prescribed microstructure, hardness, and chemical composition. Subsequent heat treatment processes resulted in the formation of a martensitic cementation layer on the material surface, with a depth of approximately 1.5 mm, as required.

Tab. 2.

Chemical analysis of two different zone (wt.%, Fe balance)

Chemical element	Core material [wt.%]	Carburized layer [wt%]
C	0.17	0.46
Si	0.27	0.27
Mn	0.56	0.55
P	0.010	0.009
S	0.009	0.009
Cr	1.63	1.61
Mo	0.276	0.275
Ni	1.58	1.55

The aim of the research is to verify the primary cause of cracks in cemented forgings, based on empirical observation using laboratory microstructural and other analyses. The Brinell hardness test was conducted in accordance with EN ISO 6506-1 method HBW 2,5/1850/10. The microstructure materials were observed under an optical microscope at 500x zoom, on an etched sample with 5% Nital taken directly from the crack location. The microstructure of the crack was observed under optical microscope at 200x zoom. Final quality control was performed using Non-Destructive Testing (NDT) - Visual Testing (VT) was according to EN 13018.

Tab. 3

Test results

	Core material	Border zone	Carburized layer
HBW	361	428	570
Type of microstructure	Ferit-perlite	Upper bainite	Tempered martensite
Thickness of layer [mm]	0-30	0.1-0.2	1.1-1.5

3. RESULT

An VT analysis was conducted of 293 pieces. The number of defective forgings after each inspection phase were 21 pc, that is 7,17% scrap forgings.

(a) (b)

Fig. 2. Inspected forging in visual testing (VT): a) Location of cracks on forging; b) Location of cracks on forging in section

The cracks are localized on the bottom and upper sides of the forging (Figure 3, zones A and B). The length of the cracks ranged from 40 to 120 mm (Figure 2a,b). The depth of this crack ranges from 0 to15 mm. These cracks were observed only in special zone with radius R6 mm in part of its perimeter. The start of the crack (Figure 2a) is on surface R6, and progression is lamellar toward the outer side (Figure 2b) of the forging.

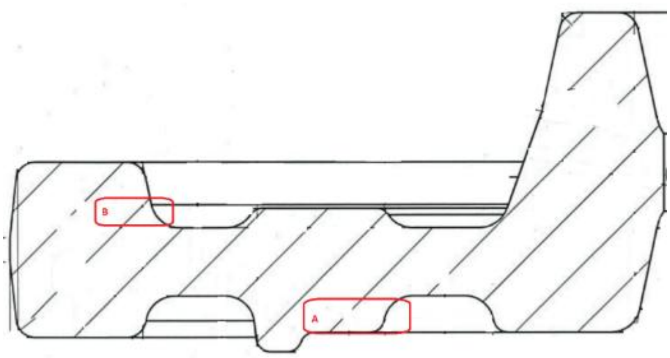


Fig. 3. Localized crack after VT only in two zones, A and B (red color on section scheme)

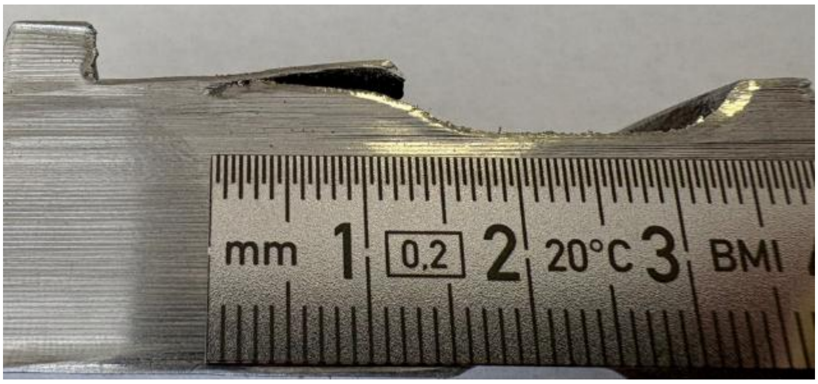


Fig. 4. Length crack in zones A

The direction of the cracks is parallel to the surface of the hardened layer. On macroscopic observation of the crack – Fig. no. 4 and 5, an oxide layer is clearly visible along its entire length. The crack starts in the martensitic structure and runs and ends in the bainite microstructure - boundary zone. The start of the cracks is on the surface at a radius of R6, on the forgings.

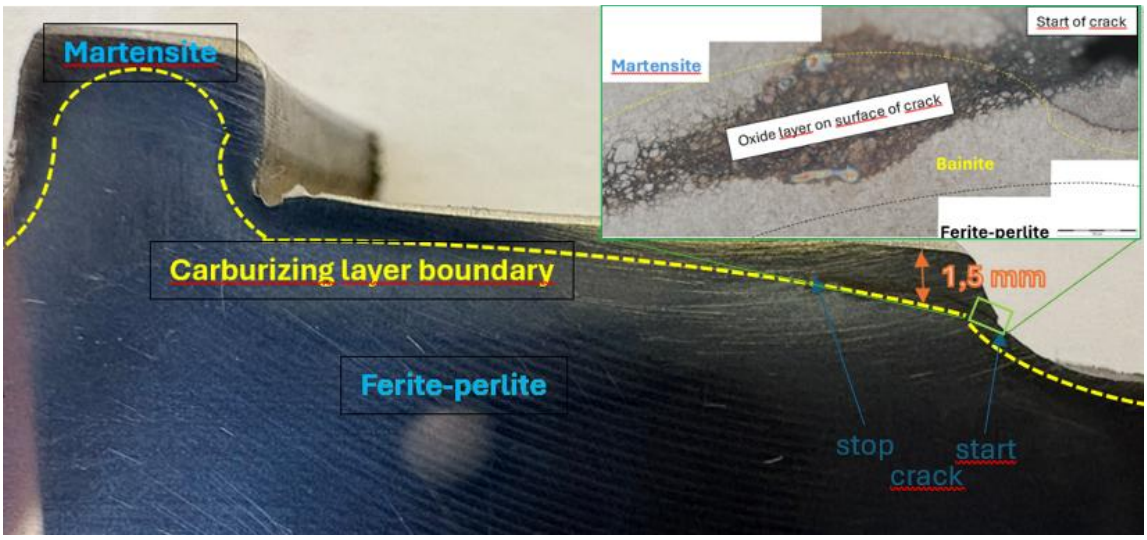


Fig. 5. Macroscopic observation of the steel structure

The crack is bounded along its entire length by an oxide layer (Figure 5 up), beneath which a gradual intergranular breakdown of the bainitic structure is observed.

The observed microstructure differs depending on which part of the forging layer it is located.

- The Core – Ferrite and Pearlite (Figure 6a) is the core microstructure of the steel, which remains unaffected by the carburizing and hardening treatments. It consists of a fine-grained ferrite-pearlite structure with evenly distributed phases. The light-colored ferrite matrix is interspersed with dark, lamellar pearlite colonies. This microstructure offers good toughness and machinability, although it has relatively low hardness compared to the surface.
- Surface Layer – Tempered Martensite (Figure 6b), which is a fine, needle-like structure typical of tempered martensite, which dominates the carburized and quenched surface layer. The structure appears uniform and relatively dense, with possible traces of retained austenite

in certain regions. The martensitic needles are tempered, indicating that the sample underwent a post-quenching tempering process. This microstructure is associated with high surface hardness and wear resistance, which is essential for the functional performance of case-hardened components.

(a)

(b)

Fig. 6. Microscopic structure (200x zoom):
(a) ferrite-perlite structure; (b) tempered martensite structure

- Border zone – Upper Bainite (Figure 7) is the transition region between the hard case and the softer core. The microstructure consists primarily of columnar and equiaxed bainitic laths, which nucleate intragranular due to the presence of non-metallic inclusions. These grains are randomly oriented, providing isotropic mechanical properties. The lath-like morphology is characteristic of transition zones cooled at moderate rates, which prevents the formation of coarse pearlite or martensite. This gradient zone results from decreasing carbon content and a reduced cooling rate with depth. It exhibits a mixed microstructure comprising:
  - upper bainite, which appears darker and more compact;
  - acicular ferrite with minor polygonal ferrite;
  - in this zone oxide inclusion are observed.

Fig. 7. Microscopic observation of the borderline structure – bainite

The combination of different microstructures across the case depth – tempered martensite at the surface, a martensite-bainite transition zone, and a ferrite-pearlite core – demonstrates the effectiveness of the applied thermochemical treatment in tailoring the performance of 18CrNiMo6-7 steel.

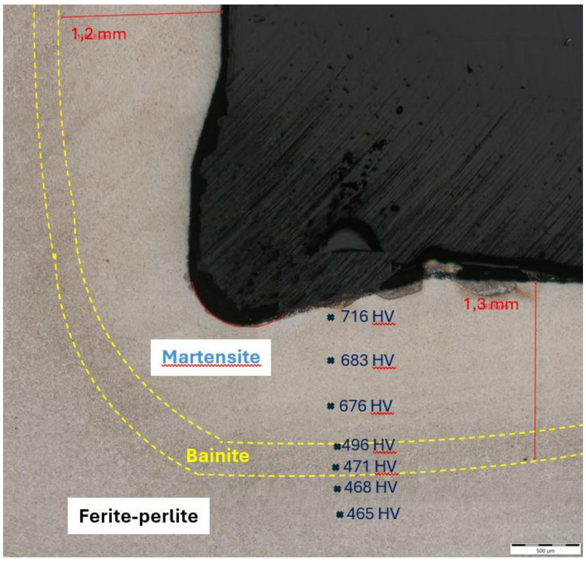


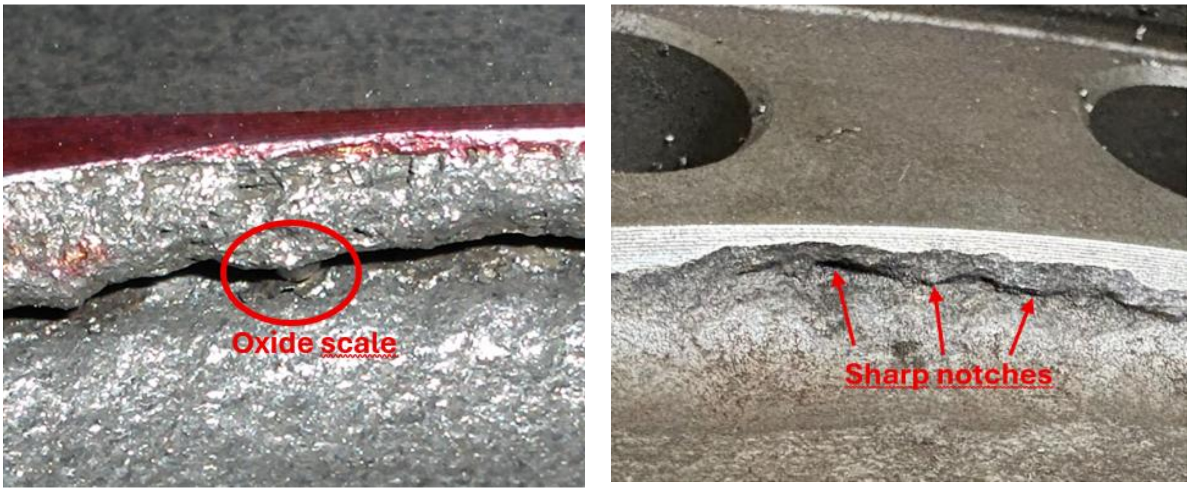
Fig. 8. Microscopic observation of the zone microstructure

To evaluate the heat treatment process and separate microstructure zones a hardness test was performed on a cross-section of the forging. The individual measurement values are presented in Table 3. Based on this measurement, the depth of individual microstructural zones was determined, as well as the depth of the crack in the forging.

4. DISCUSSION

Based on the evaluation of the test results and laboratory analyses of the location, direction, and size of the cracks, it can be concluded that this type of crack propagated in the material during heating during steel carburization. Since oxide inclusions are present on both sides of the crack, it initiated in the heat-affected zone of the carburization zone of the steel. The main cause of the growth of these cracks is the loss of plasticity in the critical zone of the heat-affected zone during the carburization process, namely during the relaxation of residual stresses [2].

A detailed visual examination of the crack (Figure 9a, b) on the surface of the forging revealed that it was formed by sharp notches that penetrated the surface layer at radius R6 and thus disrupted its integrity. The inclusion material consisted of oxide scale residues that had entered the layer of the base material during forging. The shape of the oxide scale is flaky, and when mixed into the surface of the steel forging, a surface groove is created. The oxide scale was removed from the surface of the forging during the blasting operation, but traces remained in the form of notches and grooves.



(a) (b)

Fig. 9. Detail from a visual inspection of initial cracks on the surface:
(a) oxide scale in radius R6; (b) sharp notches on the surface

It is important to note that these stress-relieving cracks are only a consequence of the introduction of oxide inclusions into the surface of the forging and thus the creation of a notch concentrator of excess stress during the forging process in the austenitic phase [9]. The places of introduction of oxide inclusions are defined in two specific zones of the forging in local radii on the upper and lower parts of the forging. It should be noted that the material flow in the forging process causes abrasive wear of the dies, which, if not properly maintained, can cause a reduction in the radius of the radii and thus the formation of a place where oxide inclusions occur more frequently. Oxide inclusions are subsequently transferred from the die to the forging when the material in the austenitic phase does not flow properly. Mold failure in hot forging is complicated by various types of influencing variables, such as mold material, mold design, mold manufacturing, and forging operations [1]. Structural disharmony together with the notch effect on the surface of the forging leads to the formation of microcracks, which act as precursors to crack formation in the following heat treatment.

5. CONCLUSIONS

Stress-relief cracking is widely recognized as a phenomenon primarily induced by the synergistic effects of residual stresses, microstructural transformations along grain boundaries, and suboptimal thermal cycles during heat treatment. In the batch production of carburized forgings, even when technological parameters are correctly set, external and process-related variables can lead to significant quality issues and economic losses due to defect formation and product nonconformity.

The borderline bainitic microstructure is intentionally developed to withstand residual stress accumulation after the heat treatment of forgings between martensite and ferrite-perlite structures. Nevertheless, the integrity of this structure can be compromised by the presence of non-metallic oxide inclusions at the surface, which disrupt the structural continuity. These inclusions act as initiation sites for lamellar cracking, particularly at the interface between the carburized surface layer and the core material exactly in bainite structure.

The root cause of this degradation mechanism lies in the wear of the forging die, especially in regions with defined radii. During hot forging, steel is plastically deformed to its final geometry by filling the die cavities at elevated temperatures. The combined effects of thermal exposure, repeated mechanical impacts, and abrasive action result in the progressive deterioration of the die surface, leading to the formation of oxidized scale zones.

This degradation subsequently facilitates the entrapment of oxide scale within the surface layer of the forging and promotes the formation of stress concentrators such as notches. During subsequent heat treatment, these surface discontinuities serve as preferential sites for crack initiation and propagation. The presence of such defects significantly compromises the structural integrity of the forgings, adversely affecting their functional reliability in service conditions.

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References

1. Bílik, J. 2027. *Teoretické A Technologické Aspekty Mechanického Spevňovania Povrchových Vrstiev.* AlumniPress, STU, Trnava, Slovakia. ISBN: 978-80-8096-020-9. [In Slovak: *The Theoretical and Technological Aspects of Surface Layers Mechanical Strenghtening*].
2. Bentley K.P. 1964. *Precipitation during stress relief of welds in Cr - Mo - V steels*. Br Weld J. P. 507-515.
3. Brezinová J., J. Viňáš, D. Draganovská, A. Guzanová. 2020. *Základy materiálového inžinierstva*. Study literature edition. Košice, Slovakia. ISBN: 978-80-553-3745-6. P. 256-273. [In Slovak: *Fundamentals of Materials Engineering*].
4. Brziak P., et al. 2020. *Materiály a ich správanie sa pri zváraní*. Welding Research Institute - Industrial Institute of the Slovak Republic, Bratislava Slovakia. ISBN: 978-80-96933-09-9. [In Slovak: *Materials and their behavior during welding*].
5. ČSN EN 1011-2:2002/A1. *Svařování - Doporučení pro svařování kovových materiálů - Část 2: Obloukové svařování feritických ocelí.* Praha: Czech Norms Institute. [In Czech: *Welding - Recommendations for welding of metallic materials - Part 2: Arc welding of ferritic steels*].
6. George E. Dieter. 1993. “Material Factors Affecting Workability”. *ASM Handbook Forming and Forging* 14: 782-794.
7. George E. Dieter. 1993. “Forging Defects”. *ASM Handbook Forming and Forging* 14: 834-841.
8. Ito Y., K. Bessyo K. 1968. “Cracking parameter of high strength steels related to heat affected zone cracking”. *Journal of the Japan Welding Society* 37(9): 983-991. DOI: 10.2207/qjjws1943.37.983.

9. Kotecki D.J. 2016. “Fourth round robin report-trace elements in Cr-Mo-V steel weld metal”. *Weld World* 60(4): 639-643.
10. Kromm Arne, Thomas Lausch, Dirk Schroepfer, Michael Rhode, Thomas Kannengiesser. 2020. “Influence of welding stresses on relief cracking during heat treatment of a creep-resistant 13CrMoV steel Part II: mechanisms of stress relief cracking during post weld heat treatment”. *Welding in the World* 64: 819-829. DOI: 10.1007/s40194-020-00881-8.
11. Kroupa A., A. Výrostková, M. Svoboda, J. Janovec. 1998. “Carbide reactions and phase equilibria in low-alloy Cr–Mo–V steels tempered at 773–993 K. Part II: theoretical calculations”. *Acta Materialia* 46(1): 39-49. DOI: 10.1016/S1359-6454(97)00239-5.
12. Nakamura N., T. Wnjo, Y. Kikuchi. 1992. „Effects of heat-affected zone microstructure on reheat cracking susceptibility of Cr-Mo steels”. *Weld Int* 6(6): 436-442.
13. Nawrocki J.G., J.N. DuPont, C.V. Robino, J.D. Puskar, A. Marder. 2003. “The mechanism of stress-relief cracking in a ferritic alloy steel”. *Welding Journal* (Miami, Fla) 82. 25/S-35/S.
14. Nawrocki J.G. 2002. “Stress-relief cracking of a ferritic alloy steel”. *Welding Research Abroad* 48: 16-23.
15. Tamaki K., J. Suzuki. 1983. “Reheat cracking test on high strength steels by a modified implant test – (Study of reheat cracking of Cr-Mo steels, Report I)”. *Trans Jpn Weld Soc Bd* 14(2): 33-38.

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