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How to replace the original material for the welded structure manufacturing

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Abstract
Due to difficult pandemic situation with COVID-19 decease, as well as due to current geopolitical circumstances in the world, we are facing the shortage of steel and therefore the impossibility of delivering the contracted products within the agreed deadlines. It is thus necessary to find suitable steel for replacement. The procedure for selecting one such steel for substituting the deficit steel 25CrMo4, for the purposes of producing a responsible welded assembly, is described in this paper. After the careful analysis, the steel 42CrMo4 was taken into consideration as a possible substitute material. Prior to applying the new selected steel, it was necessary to perform the following tests: analyze its chemical composition, determine its most important mechanical properties and evaluate its weldability. Then, the optimal welding and heat treatment technologies were determined, so that the quality of the responsible welded structure would meet all the requirements, as the structure made of originally used steel. For the new steel, all the mentioned and some additional tests were conducted and the appropriate welding technology was prescribed. To verify the selected technology, appropriate tests were conducted on the model welded samples, the results of which are presented in this paper. Based on the analysis of the obtained results, it was concluded that the 25CrMo4 steel can be replaced by the 42CrMo4 steel, however, with the mandatory application of appropriate supplementary measures.

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1. Introduction

Steel is one of the basic raw materials for production in various branches of industry. If, for some reasons, this very important raw material becomes scarce, either on the domestic or the world market, that can cause a significant negative impact on the business of various companies, since that would inevitably lead to delays and even the impossibility of delivering the products within the agreed deadlines. To avoid the consequences of such delays (among others payment of penalties), it is necessary to find an adequate substitute material.

When choosing such a replacement material, there are certain criteria that must be met. For the less important/responsible parts and constructions, the necessary condition is to choose the material that has similar or better mechanical properties than the original one. However, when we speak of responsible parts and structures, especially in the case of responsible welded structures, the more detailed analysis of various properties of the substitute material, besides the basic criteria related to the mechanical properties, must be conducted. Such an analysis should include examination of other important factors influencing the output properties of a structure (Tasković et al., 2021b). The adequate mechanical properties are, of course assumed, however, the weldability of the substitute material must be examined to find out what kind of heat treatment, if any, is necessary to execute; what would be the output properties of the welds, like hardness and microstructure, as well as what type of additional materials – filler metals should be used etc.

It is well known that the heat, released during the welding, leads to deterioration of the mechanical properties of welded structures. This is actually, the most important factor, which should be examined, i.e. the influence of the heat released during the welding on the output properties of the welded joint. For those properties of a structure to be as good as possible, its necessary to prescribe the appropriate welding technology, as well as the heat treatment. One must always keep in mind the quality of the end product – in this case the welded structure. The product quality verification can be executed by various methods (Siwiec and Pacana, 2021).

A detailed procedure for selecting the adequate substitute material for the 25CrMo4 steel is presented in this paper. The heat treatment impact during the manufacturing of an exceptionally responsible structure, which operates under the conditions of extremely high impact-dynamic loads, is presented.

2. Literature review

In modern day industry, which is developing rapidly, quenched and tempered (QT) steels, due to their good price to quality ratio and ability to get their properties improved using the heat treatment, are often considered as the first-choice material for producing various parts and welded structures.

(Craig-Smith, 2001) was investigating the possibility/necessity for replacing the underground steel water pipelines, performing the series of different types of tests. The problem that also appeared is the techo-economic assessment, which would incur less costs – to refurbish or replace that steel structure.

Similar query – whether to replace or not to replace the damaged structure, was posed to (May et al., 2016), when they were investigating the parts of the climbing equipment – the carabiners, which sustained the impact damage. In this case, as in the previous one, the real question is not only whether to replace or repair the steel structure/part, but which material should be used if it was decided that the replacing of the corroded or damaged structure is necessary.

(Laxmi et al., 2021) have investigated the influence of quenching oil viscosity and tempering temperature on impact toughness and hardness of the 42CrMo4 steel. Tests were conducted by quenching the 42CrMo4 steel samples from temperature of 920°C, in different viscosity oils. After the quenching, samples were heated and held at temperatures between 340 and 490°C for 4 hours. After the heating and holding, samples were air cooled to room temperatures. Prior to quenching all the samples were normalized for 2 hours at 920°C. After the heat treatment, tests for measuring the impact toughness and hardness were conducted. Obtained results have shown that increasing the tempering temperature results in increasing values of impact toughness, but lowering the hardness values and vice versa. Results also show that combination of quenching the 42CrMo4 steel in oil with 41 mm^2/s viscosity, followed by tempering at 362°C, represents the optimal heat treatment procedure for obtaining the good combination of impact toughness and hardness properties.

(Lazic et al., 2016) were investigating which material should be used for manufacturing for the boiler pipes in a steam plant. That construction consisted of components exposed to different influences – components subjected to water and steam pressure and to high temperatures, parts subjected to various external loadings and parts subjected to chemical influences. Those components sustain various types of loading like tension, compression, bending, shear, but the most frequently they are subjected to combined loads. Thus, selecting the adequate material means a complex process, where all those different aspects have to be taken into account.

(Feng et al., 2017) have investigated the influence of applied heat treatment procedure on mechanical properties of the 42CrMo4 steel. In that paper, influence of the two heat treatment procedures on steel's mechanical properties were investigated, austempering on temperatures above 350°C and low temperature isothermal transformation, conducted bellow the M_s temperature (approximately at $T = 310$°C). After this preparation, the samples were quenched, tensile strength samples were machined and ultimate tensile strength tests were conducted. Obtained results show that isothermal transformation at $T \approx 310$°C (bellow the M_s temperature) can increase the proof strength values without degrading the ductility. In addition, the ultimate tensile strength of 1684 MPa at 14.5% elongation has been reached in that test.

(Vicen et al., 2022) have considered influence of the surface treatment – the shot peening, on wear properties of the C55 (medium carbon steel). This material is used for various components in the transportation equipment, where they are exposed to various kinds of cyclic loading. Thus, it is extremely important to monitor the wear behavior of such a material, as well as the possibilities for its improvement. In this case, it was investigated how an improvement of wear characteristics of the C55 steel could be achieved by the surface treatment by the shot peening. Authors reported increase in the compressive residual stresses at the material's surface, as well as increase in surface roughness and coefficient of frictions.

(Kešner et al., 2017) have investigated the influence of microstructure on abrasive wear of the 25CrMo4 and 51CrV4 steel. Samples for both steels were heated to 800°C and held for 20 minutes, followed by the 3-stage cooling. The first stage consisted of cooling the samples in the salt baths (temperatures 300-400°C) for a certain time period, followed by the second stage, which was the air or water colling and the third stage, which was cooling down to 20°C in air. Following the heat treatment, several types of samples were produced, differing according to their microstructure properties. The prepared samples were then subjected to investigation of tribological properties and obtained results show that the 51CrV4 steel, specifically heat treated so that it contains 60-80% of bainite and 20-40% of martensite, shows the greater wear resistance than the steel 25CrMo4.

(Tanasković et al., 2021a) were considering selection of the adequate substitute material for welding of a burner pipe, namely, which electrodes are more suitable for that structure repairing. Damages that have occurred in a burner pipe welded joint (either during its manufacture or previous repair welding), have resulted in the need to replace the previously used electrodes with more suitable ones for the exploitation conditions to which the burner is subjected. Authors tested two different types of electrodes, Castolin and 6825 and PIVA 25/20 Band and then performed both micro- and macro-analysis of the tested specimen welds, as well as the hardness test. They concluded that the Castolin 6825 electrode was better suited for the burner pipe repair welding. After the test welds, the repair welding of the burner pipe was executed, followed by the penetrant tests of the welded pipe.

(Kralj et al., 2006) have investigated the influence of welding processes and their parameters on hardness of the welded joint of the 25CrMo4 and 42CrMo4 steels. The laser and TIG welding procedures, with different parameters, had been executed on previously prepared samples of mentioned steels, followed by machining and hardness measuring on samples. Obtained results generally show that the higher hardness values were measured on the TIG welded samples and steel 42CrMo4, due to its higher carbon content. The influence of shielding gas and welding parameters (energy input) for both the laser and TIG procedures on steels 25CrMo4 and 42CrMo4 hardness could not have been determined.

3. Experimental procedure

The experimental setup is presented in (Ivkovic et al., 2023).

The 25CrMo4 steel, which was originally used as a raw material for production of this extremely responsible part, possesses the mechanical properties shown in Table 1. As already explained, this steel has become scarce on the market. Thus, to continue the parts' production, one had to look for the adequate substitute material. Based on the analysis of availability of steels on the market, as well as experience of authors of this paper, the 42CrMo4 steel was proposed as an adequate replacement material. Its mechanical properties are also shown in Table 1. Both steels (original - 25CrMo4 and a substitute - 42CrMo4) belong to the group of the low-alloy chromium-molybdenum steels and, according to the purpose, they also belong to the group of steels for tempering.

Table 1. Mechanical properties of 25CrMo4 and 42CrMo4 steels

Property	25CrMo4	42CrMo4
Yield stress [MPa]	min 400	900
Tensile strength [MPa]	560-650	1100-1300
Elongation [%]	21.5	10
Contraction [%]	59.6	40
Impact toughness [J]	min 45	35

From Table 1, from comparison of these two steels' mechanical properties, one can clearly conclude that the proposed substitute steel – 42CrMo4 has significantly better mechanical properties than the original material. Thus, the basic criterion, related to mechanical properties, was fulfilled. However, that would not be not sufficient for production of the highly responsible part, thus the additional tests, related to other relevant material properties, had to be conducted.

The basic purpose of this research was, once the substitute steel was chosen, with requirements related to mechanical properties satisfied, to determine how it would behave during the welding. The task was to find out how the welding would influence materials/construction properties, namely what measures have to be undertaken so that those properties would remain within the limits required for the construction's behavior to be the same as if it was made of the original steel.

The chemical composition of the substitute steel was examined, results of which are shown in Table 2.

Table 2. Chemical composition of steel 42CrMo4, wt %

C	Si	Mn	Cr	Mo	P	S
0.38-0.45	max 0.40	0.60-0.90	0.90-1.20	0.15-0.30	0.025	0.035

Additional analysis included assessment of weldability, prescribing the appropriate welding technology and the eventually needed heat treatment.

Based on the steel's chemical composition, it is possible to estimate its weldability, using the chemical equivalent carbon (CE) value. In the considered case, using the formula (Arsić et al., 2022)

$$CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}, \tag{1}$$

the value of 0.815% was obtained. This value is higher than the limit value of 0.45%, so the steel 42CrMo4 can be considered as conditionally weldable. Accordingly, it is necessary to check the tendency of this steel to cold cracks. An analysis was carried out according to well-known formula for assessing the proneness of steel to cracks' appearance (Ito and Bessyo, 1972)

$$P_{CM} = C + \frac{V}{10} + \frac{Mo}{15} + \frac{Mn + Cu + Cr}{20} + \frac{Ni}{60} + 5 \cdot B, \tag{2}$$

the value of 0.525 was obtained. Since the obtained value is greater than the limit value of 0.3, one can state that this steel is prone to appearance of the cold cracks and that it is necessary to apply the preheating prior to welding.

The Séférian formula (Séférian, 1965) was used to calculate the preheating temperature

$$T_p = 350 \cdot \sqrt{C - 0.25} \tag{3}$$

where

$$C = CE \cdot (1 + 0.005 \cdot s) \tag{4}$$

and s is the part thickness. The obtained value for the preheating temperature was 297.5 °C. In this case, the adopted preheating temperature was T_p = 300°C.

For the purpose of defining the optimal welding technology, the laboratory tests were performed on specially prepared samples. The plates of 42CrMo4 steel, with dimensions 400 × 200 × 30 mm, were welded using the appropriate procedures, additional materials and regimes.

Since the parts to be produced from this steel, are of large dimensions, (including their cross-sections), which require the preparation and execution of welds of a large volume, it was decided to apply the MIG/MAG (Metal Inert Gas/Metal Active Gas) welding methods, so that the highest possible productivity would be achieved.

The part that is manufactured of this new steel is a part of the artillery tools, which is in operation subjected to intensive impact-dynamic loads. This is why it was necessary to take all the measures to obtain the greatest possible impact strength of the welded joint. The proposed technology consisted of application of the two different types of welding. The first (root) pass was applied with an electrode wire of high impact toughness. Then, the other passes (filling welds) were executed with an electrode wire of similar chemical composition and properties as the base metal. The electrode, with designation MIG 18/8/6 was selected for the root pass, while for the filler welds was used the MIG 75 electrode. Both filler metals are produced by Slovenian Steel Group, d.d., SIJ Elektrode, Jesenice, Slovenia. The chemical composition of used electrodes, their mechanical properties and the adopted welding parameters are shown in Tables 3, 4 and 5, respectively.

The driving energy and the time for cooling from 800°C to 500°C, i.e. time $t_{8/5}$, were calculated using the known formulas. Fig. 1 shows the CCT (continuous cooling transformation) diagram with entered cooling times $t_{8/5}$. The cooling curve obtained by applying the filler welds is marked in red, while the cooling curve obtained by applying the root welds is marked in blue.

From the state shown in the diagram, based on the time $t_{8/5}$, it can be clearly observed that the applied welding parameters generally produce a bainite-ferrite structure. This combination of structures gives good characteristics of strength and plasticity. Since the considered is an extremely responsible construction, the microstructure was recorded and the hardness was measured in the corresponding zones of the welded joints (Arsić et al. 2022).

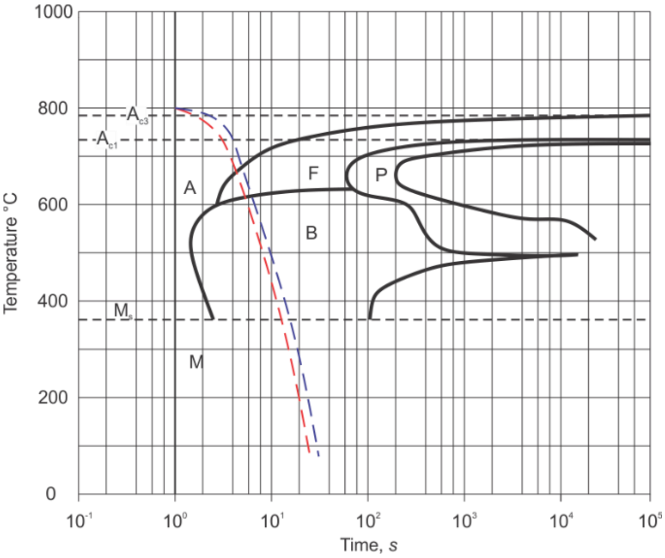


Fig. 1. The CCT diagram for the 42CrMo4 steel

As it was established that the 42CrMo4 steel is prone to formation of the cold cracks, to secure that the output properties of the welded construction would be within the prescribed limits, it was necessary to apply the appropriate heat treatment. It consisted of the steel tempering, with prior normalization. Quenching was executed at 850°C in oil and the high temperature annealing at 600°C. The diagram of the proposed heat treatment regime is shown in Fig. 2.

Table 3. Chemical composition of the used electrodes, %

Material mark		Elements					
Commercial	According to EN ISO	C	Si	Mn	Cr	Ni	Mo
MIG 18/8/6	G 18 8 Mn	0.080	0.800	7.000	18.500	9.000	-
MIG 75	Mn3Ni1CrMo	0.080	0.600	1.700	0.250	1.500	0.500

Table 4. Mechanical properties of used electrodes

Material mark		Property, units			
Commercial	According to EN ISO	Rp [MPa]	Rm [MPa]	A [%]	KCV [J]
MIG 18/8/6	G 18 8 Mn	> 380	560-660	35	at 20 °C 40
MIG 75	Mn3Ni1CrMo	> 690	770-940	>17	at 40 °C > 47

Table 5. Welding parameters

Material mark		Property, units				
Commercial	According to EN ISO	Power, I [A]	Voltage, U [V]	Welding speed [mm/s]	Driving energy, q_l [J/mm]	$t_{8/5}$ [s]
MIG 18/8/6	G 18 8 Mn	180	21	2.0	1606.5	18
MIG 75	Mn3Ni1CrMo	240	25	3.5	1457.1	15

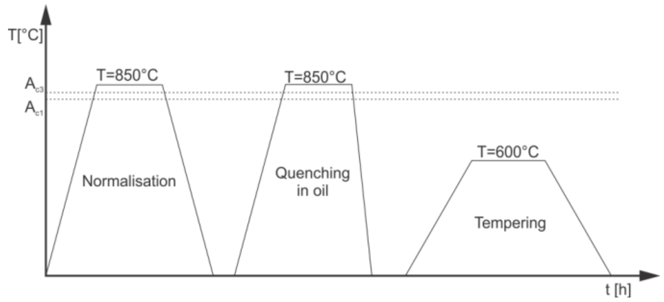
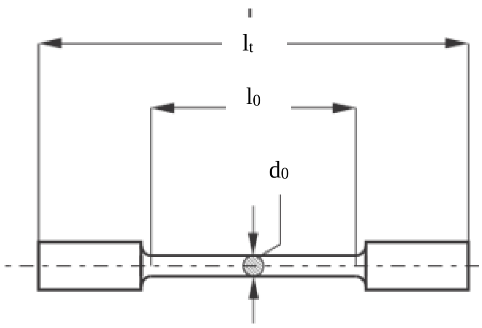


Fig. 2. The proposed heat treatment regime

Tests, related to the heat treatment effect, included comparative tests of material characteristics of both materials. The tensile tests were performed for obtaining the materials' yield stress and tensile strength, while the impact toughness tests were performed according to the Charpy method. Tests also included the appropriate metallographic investigations. Geometry and appearance of samples for the tensile test are shown in Fig. 3, while the schematic appearance of samples for the Charpy impact toughness test is presented in Fig. 4.



(a)

(b)

Fig. 3. Appearance of samples for the tensile tests: a) schematics; b) sample prepared for tests.

The heat treatment influence on the most important mechanical properties of the substitute material was to be assessed based on those test results. It was also necessary to find out whether the additional treatment, to which the substitute material was to be subjected, would introduce additional costs, i.e. whether would that be techno-economically justified.

For that purpose, the tests of the material's mechanical properties were conducted on the steel samples in the delivered state (annealed state), as well as in the heat-treated state.

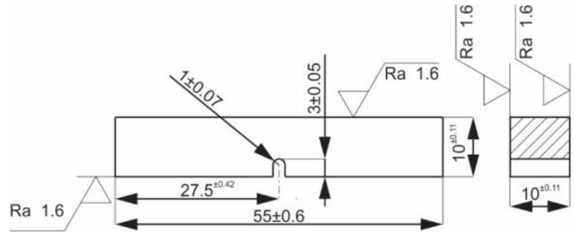


Fig. 4. Schematic representation of samples for the impact toughness testing

4. Results and discussion

4.1 Tensile tests

The cylindrical samples, were prepared for these tests, with the measuring part of a diameter d_0 = 8 mm and length l_c = 80 mm (10·d_0) and the total length l_t = 160 mm, Fig. 3(a).

The tensile test of the prepared samples was performed on a Shimadzu universal hydraulic tensile testing machine (tensile tester) according to the SRPS ISO 6892-1:2017 standard. The deformation rate was 1.5 mm/min. The test was performed both on the normalized and tempered samples, with three samples for each material condition. The test results are shown in Table 6 and the corresponding stress-strain curves for all the samples are presented in Figs. 5 to 10.

From comparison of the stress-strain diagrams obtained for the normalized state samples (Figs. 5, 6 and 7) and diagrams obtained for the tempered state samples (Figs. 8, 9 and 10), it is obvious that the latter samples have reached higher values of both the tensile strength and the yield stress. That means that by applying the previously proposed and described heat treatment procedure, which included quenching and high temperature annealing, (Fig. 2), the material properties were significantly improved, with respect to the initial normalized state. The tensile strength of the tempered samples was for 125 MPa (16.55%) higher than the value of the normalized samples and it reached 880 MPa. On the other hand, the yield stress of the tempered samples was higher for about 350 MPa (97.75%) with respect to the normalized samples' values. This increase in material's strength can be ascribed to the phase changes that occur in the material, resulting in appearance of an unbalanced bainite structure. The plasticity properties were somewhat reduced for the tempered samples (elongation was reduced for 23% and contraction increased for 22%, on average) at the expense of increased strength.

Table 6. The tensile tests results

Property, units / Direction		I-I	II-II	III-III		I-I
Rm [MPa]	Normalized state	760	746	755	Tempered state	880
Rp [MPa]		360	360	346		700
A [%]		18	15.33	16.67		12.5
Z [%]		42	44	51		58

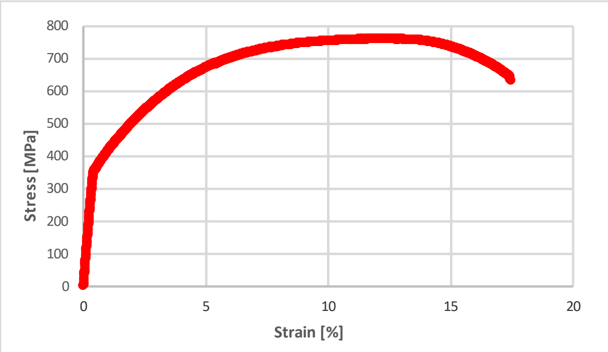


Fig. 5. The (σ-ε) diagram for the normalized state sample # 1.

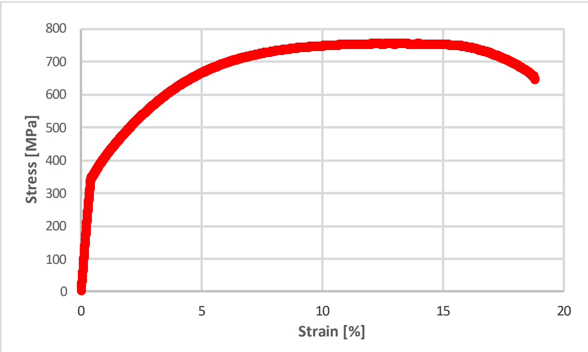


Fig. 6. The (σ-ε) diagram for the normalized state sample # 2.

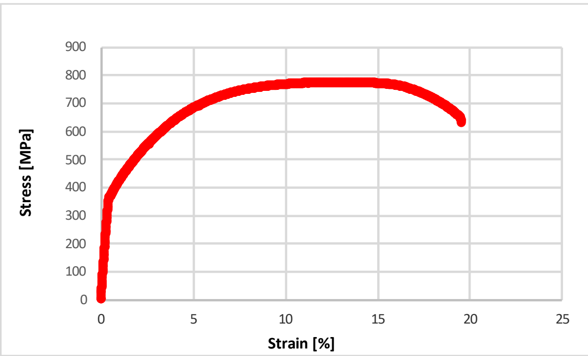


Fig. 7. The (σ-ε) diagram for the normalized state sample # 3

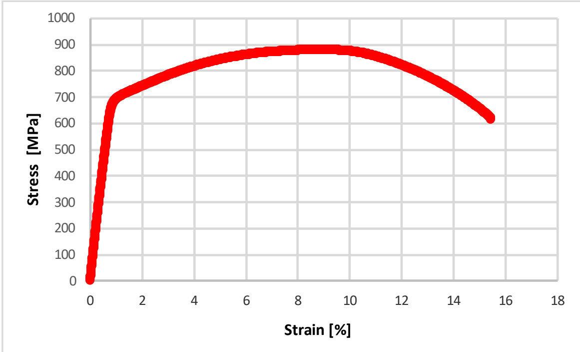


Fig. 8. The (σ-ε) diagram for the tempered state sample # 1.

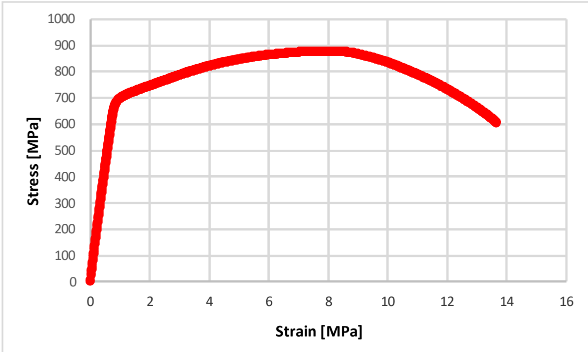


Fig. 9. The (σ-ε) diagram for the tempered state sample # 2.

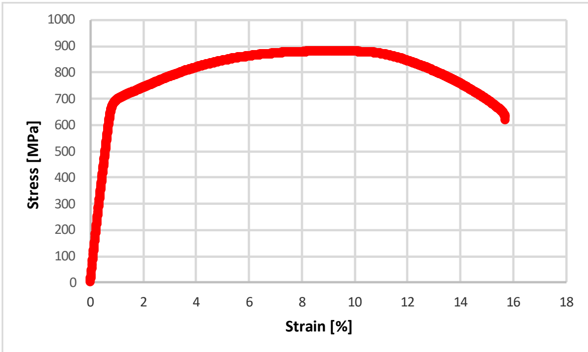


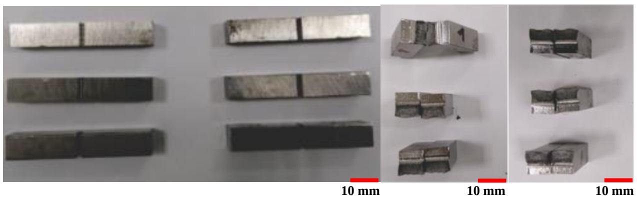
Fig. 10. The (σ-ε) diagram for the tempered state sample # 3.

4.2. Impact toughness tests

Samples for this test were prepared according to the SRPS EN ISO 148-1 standard; six samples for each state - normalized and tempered. Schematic appearance with samples dimensions is given in Fig. 4, while Fig. 11 shows the real impact toughness test samples before and after the test. The test results are presented in Table 7 and Fig. 12.

From analysis of those results, one can notice that the normalized samples had a relatively low toughness' values of 16 to 26 J, which were significantly increased by application of tempering, up to 38 to 44 J. This is explained by the newly composed material structure, obtained by tempering, which consisted of ferrite + bainite.

(a)



(b)

Fig. 11. Samples for impact toughness testing – prior to the tests (left) and after the tests (right): (a) in normalized state, (b) in tempered state

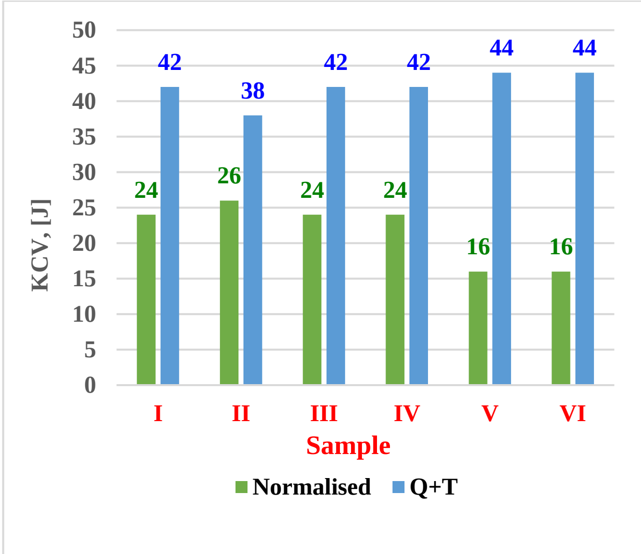
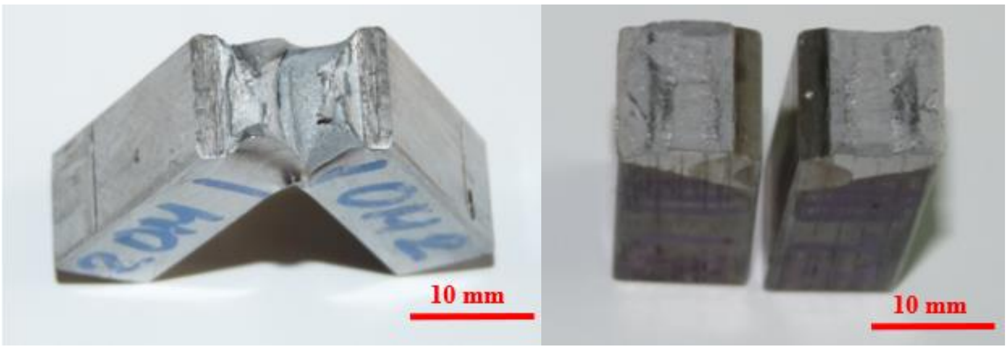


Fig. 12. Graphic presentation of the impact toughness test results

Fig. 13 presents the appearance of fracture surfaces of broken samples. From analysis of those fracture surfaces, it can be noticed that the normalized samples, Fig. 13(a), have significantly finer metal grains and a partly fibrous structure. On the other hand, in Fig. 13(b) can be seen the fracture surface of the tempered sample, which is a coarse-grained structure. The cross-section of one of the fractured tempered samples was not even completely broken, which is often an indication of a favorable material structure.



(a) (b)

Fig. 13. Appearance of fracture surfaces of the broken samples;
(a) in normalized state (ductile fracture), (b) in tempered state (brittle fracture).

Table 7. Impact toughness of steel samples, KCV [J]

	I	II	II	IV	V	VI		I	II	III	IV	V	VI
Normalized state	24	26	24	24	16	16	Tempered state	42	38	42	42	44	44

Finally, it is important to emphasize that the problem of replacing certain material needs to be carefully approached, especially if the responsible parts that work in demanding conditions are to be produced. Then, in addition to the mechanical properties, it is very important to consider the influence of appropriate production procedures on the final output properties of the realized structure. From this and past experiences, an algorithm was created (Fig. 14) to serve as a guideline when approaching the problem of selecting the most suitable replacement material.

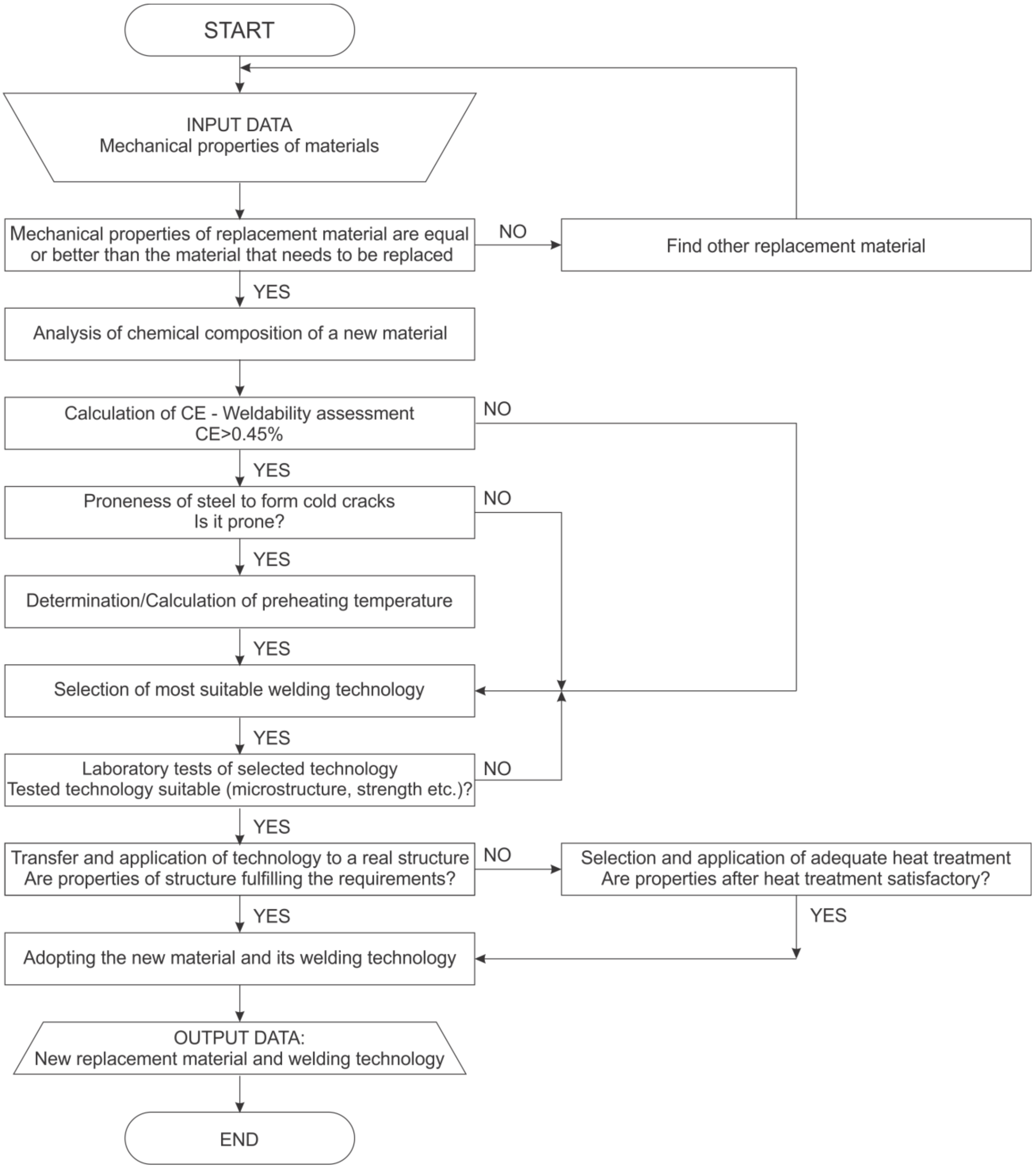


Fig. 14 Appearance of the procedure guideline algorithm

5. Summary and conclusions

The procedure for selecting the suitable replacement material for the scarce steel is presented in this paper. It is established that to find an adequate replacement for a certain material, it is necessary that the newly selected one meets the appropriate requirements. Those requirements are usually related to the important mechanical properties, i.e. the substitute material must have the same or better mechanical properties than the originally used material. However, in this case, the chemical composition of the new material was very important, as well, due to the requirements related to weldability, heat treatment etc. The steel that needed to be replaced was 25CrMo4, while, based on authors experience and recommendations from the manufacturer, the steel 42CrMo4 was chosen as the replacement material.

When the replacement steel was chosen, it was necessary to carry out the battery of tests to verify its suitability for manufacturing a responsible welded structure. As a part of the tests, an analytical assessment of the weldability of 42CrMo4 steel was performed. As the construction in question was a part of the artillery tool, it was necessary to improve the quality and output properties of the welded and heat-treated material to the greatest extent possible. That is why a decision was made to prepare appropriate samples/models of the 42CrMo4 steel and perform the test-welding on them and then to compare the properties of the heat-treated steel with the properties of the steel in the delivered (annealed) state. The samples were welded using the two different types of electrodes, for the root and the filler welds, MIG 18/8/6 - and MIG 75, respectively, manufactured by Slovenian Steel Group, d.d., SIJ Elektrode, Jesenice, Slovenia.

The tensile strength of the tempered samples was 880 MPa, which is 125 MPa (16.55%) higher than the value of the normalized samples. The yield stress of the tempered samples was higher than that of the normalized samples for about 350 MPa (97.75%). The increase in strength occurred as a result of the phase changes and appearance of an unbalanced bainite structure. The plasticity properties (elongation and contraction) were somewhat reduced for the tempered samples at the expense of increased strength.

Results of the impact toughness tests have shown that the normalized (as delivered) samples had a relatively low toughness (16 to 26 J), which was significantly increased by application of tempering (38 to 44 J). This is explained by the structure of the material obtained by tempering (ferrite + bainite).

Based on authors' previous experience, as well as analysis performed in this research, an algorithm was created to serve as a guideline for the whole procedure of selecting the most suitable replacement material for this particular case of selecting the substitute steel. However, such an algorithm can be used in other cases – for selecting some other substitute material, of course with necessary modifications related to that material specific properties.

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如何替代原有材料进行焊接结构制造

關鍵詞
钢
焊接
42CrMo4
25CrMo4

摘要
由于新冠肺炎（COVID-19）疫情的严峻形势，以及当前世界地缘政治形势，我们面临着钢材短缺的问题，因此无法在约定的期限内交付合同产品。 因此，有必要寻找合适的钢材来替代。本文描述了选择一种此类钢来替代缺陷钢 25CrMo4 的程序，以生产可靠的焊接组件。 经过仔细分析，42CrMo4 钢被考虑作为可能的替代材料。 在应用新选定的钢材之前，有必要进行以下测试：分析其化学成分，确定其最重要的机械性能并评估其可焊性。 然后，确定了最佳的焊接和热处理工艺，使得负责的焊接结构的质量满足所有要求，就像原来使用的钢材制成的结构一样。 对于新钢材，进行了所有提到的测试和一些附加测试，并规定了适当的焊接技术。 为了验证所选技术，对模型焊接样品进行了适当的测试，本文介绍了测试结果。 根据对所得结果的分析，得出的结论是，25CrMo4 钢可以被 42CrMo4 钢替代，但必须强制采取适当的补充措施。