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THE INFLUENCE OF THERMAL GOUGING PROCESSES ON THE STRUCTURE AND HARDNESS OF S420MC AND THE POSSIBILITY OF REPAIR WELDING

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Abstract: In the article, the influence of thermal gouging process (oxygen jet, plasma arc, covered electrode, arc-air electrode) on the structure and properties of thermomechanically treated fine-grained structural steel S420MC. The influence of these changes on the quality of welds deposited by the GMA (Gas Metal Arc- referred to by its subtypes metal inert gas (MIG) and metal active gas (MAG)) method in grooves with and without oxide removal was also shown. Visual, magnetic particle inspection, macroscopic, microscopic tests, and hardness measurements were performed. It has been shown that the highest quality grooves are obtained by gouging with an oxygen jet, while the lowest quality is obtained by gouging with coated electrodes. As a result of the thermal cycle of the gouging processes, a ferritic-bainitic structure is formed at the groove surface, while in the HAZ area, the grain is refined. The tests carried out have shown that repeated exposure to the thermal cycle of the gouging and surfacing process causes deterioration of the properties of S420 MC steel, especially in the HAZ area. In the case of welding or surfacing of materials prepared by thermal gouging, it is recommended to mechanically remove the oxide layer and residues from the gouging area in order to eliminate defects such as incomplete fusion and porosity.
Key words: thermal gouging, thermomechanically rolled steel, MAG surfacing, repair welding

1. INTRODUCTION

The main material used to build various types of structures, machines, and devices operating in different conditions is constructional steel. This group includes thermomechanically treated steels, which are characterized by high strength and resistance to cracking. Thermomechanical treatment is a process of controlled hot rolling followed by accelerated cooling, which increases the yield strength of steel. In 1962, accelerated cooling in the continuous rolling of steel strip was successfully applied in Great Britain [1-3]. The fastest development of constructional steels, and especially the increase in their yield strength, took place in the 1970s [2]. In unalloyed steels, the yield strength was about 200 MPa; in low-alloyed higher-strength steels in the normalized condition, it increased to about 350 MPa. The use of thermomechanical treatment made it possible to obtain steel with a yield strength of 400 – 700 MPa [1-6]. Most of the scientific works on the weldability of thermomechanically treated steels concern materials with a yield strength up to 460 MPa. Works [1-5] in this area shows that due to the lower content of alloying elements (especially carbon), thermomechanically treated steels show a lower tendency to harden in the HAZ, compared to normalized steels. In the HAZ of thermomechanically treated steels, a narrow softened area can be observed with a hardness lower than the hardness of the base material with slightly lower strength properties. This area may be sensitive to brittle and fatigue cracking and reduction of plastic properties. [1-5] Due to their lower carbon equivalent and high metallurgical purity, these steels are more easily weldable than steels supplied in the normalized condition. Thermomechanically treated steel is used for main pipelines, offshore drilling platform structures, pressure vessels, welded structures in steel construction, and the machine industry [1-3]. Although thermomechanically treated steels are well weldable (low carbon equivalent), there are difficulties during repair welding of these steels related to a significant decrease in impact strength, especially in the HAZ area, due to the introduction of a significant amount of heat [1-9].

When welding high-strength steels, attention should be paid to [1-5]:

• using appropriate welding consumables containing alloying elements that will ensure the appropriate level of strength properties of the weld compared to the base material;

• the amount of heat input to the joint and the structure of the welds.

2. EXPERIMENTS PREPARATION

This work aimed to determine the effect of thermal gouging processes on the structure and properties of thermomechanically treated fine-grained steel S420MC, fig. 1, table 1 and 2. The influence of these changes on the quality of the padding welds made by the GMA method in grooves with and without the removal of oxides was investigated.

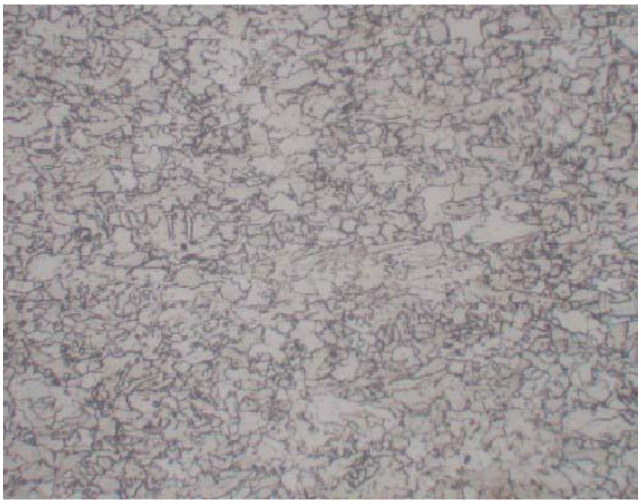


Fig. 1. Ferritic-pearlitic structure of S420 MC steel

Table 1. Chemical composition of S420MC steel

Chemical composition [%]									
C	**Si**	**Mn**	**P**	**S**	**Al**	**Nb**	**V**	**Ti**	**Ce***
0.10	0.03	1.50	0.025	0.01	0.015	0.09	0.20	0.15	0.39

*Ce – carbon equivalent

Table 2. Mechanical properties of S420MC steel

Mechanical properties			
Tensile strength, Rm [MPa]	Yield point, Re [MPa]	Elongation A_5 [%] t<3	Elongation A_{80} [%] t>3
480-620	min. 420	20	20

2.1. Thermal gouging process

The thermal gouging process of 10 mm thick S420 MC steel was carried out using the following methods:

-oxygen jet gouging with parameters: acetylene pressure: 0.05 [MPa]; oxygen pressure: 0.5 [MPa]; acetylene consumption: 0.92 [m^3/h]; oxygen consumption 5.3 [m^3/h].

-plasma arc gouging with parameters: plasma gas pressure: 0.45 [MPa]; plasma nozzle diameter: 2.6 [mm]; inclination torch angle: 30^0; gouging current: 60 [A].

-coated electrode gouging with parameters: type and gouging current: = (+), 250 [A]; electrode diameter 3.2 [mm]; inclination electrode angle: 20^0.

-arc air gouging: type and gouging current: = (+), 250 [A]; electrode diameter 3.2 [mm]; inclination electrode angle: 30^0; oxygen pressure: 0.6 [MPa].

The visual tests of the grooved showed that the highest quality of the grooved surface was characteristic of the groove obtained by the oxygen jet gouging method. The grooves with plasma and arc-air gouging have greater roughness, while the greatest groove irregularities were obtained when gouging with coated electrodes, Fig. 2. The magnetic tests carried out showed that the grooves were free from cracks, only in the case of gouging with coated electrodes, cracks appeared at the gouging start point, Fig. 3.

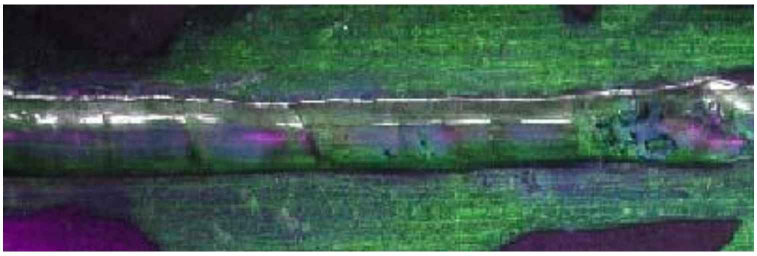
oxygen jet gouging

plasma arc gouging

coated electrode gouging

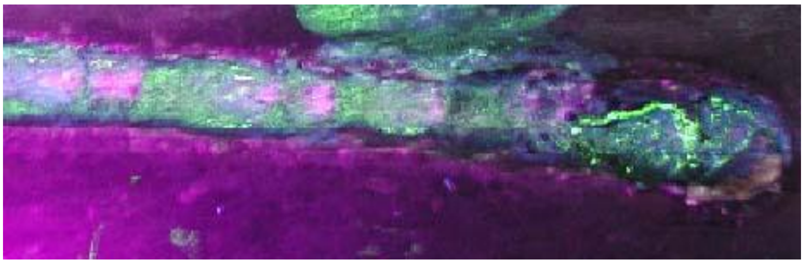
arc air gouging

Fig. 2. View of the groove of 10 mm thick S420 MC steel after a) oxygen jet gouging, b) plasma arc gouging, c) coated electrode gouging, d) arc-air gouging



oxygen jet gouging

plasma arc gouging



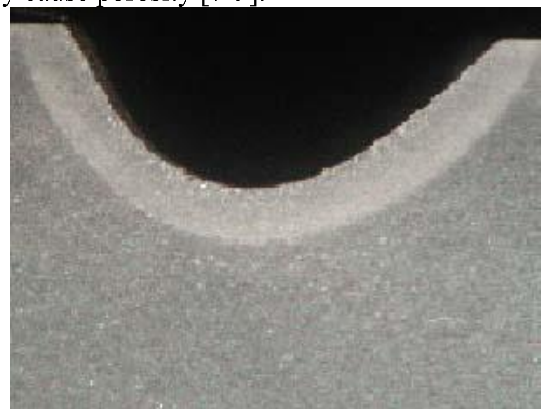
coated electrode gouging

arc air gouging

Fig. 3. Results of magnetic testing of grooves of 10 mm thick S420 MC steel after: a) oxygen jet gouging, b) plasma arc gouging, c) coated electrode gouging (visible cracks where the gouging starts), d) arc-air gouging

Macroscopic examination of the grooves did not reveal any internal defects in the groove area, and the HAZ was uniform and of similar width in each case, Fig. 4. Microscopic examinations have shown that as a result of the thermal cycle of the gouging processes, a ferritic-bainitic structure is formed at the groove surface, fig. 5. In the HAZ area, grain fragmentation occurs, fig 6. The results of microscopic examinations confirmed the hardness measurements, which showed an increase in hardness at the gouge surface to a value of approximately 260 HV1 compared to the hardness of the parent material of 200 HV1. The hardness of the HAZ was about 220 HV1, fig. 7, table 3. If the gouging process is not carried out correctly, it may result in the formation of infiltrations at the bottom of the groove, the material melted and recrystallized, fig.8. As a result of unfavorable conditions, this layer may become heavily nitrided, which may cause porosity [7-9].

oxygen jet gouging

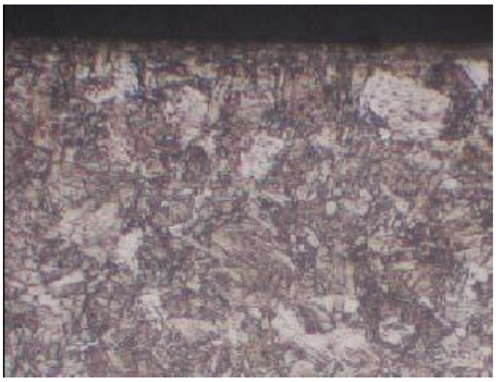


plasma arc gouging

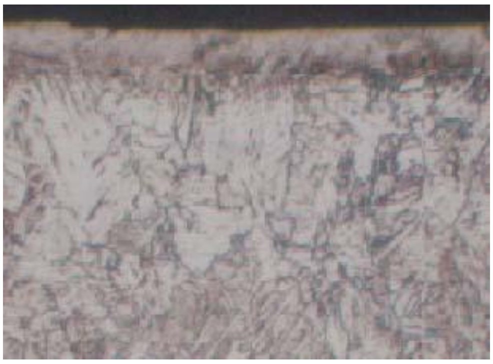
coated electrode gouging

arc air gouging

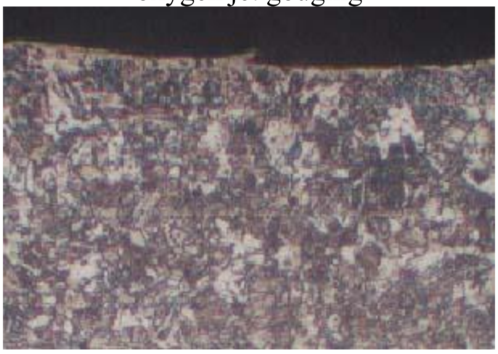
Fig. 4. Macrostructure of grooves of 10 mm thick S420 MC steel after: a) oxygen jet gouging, b) plasma arc gouging, c) coated electrode gouging, d) arc-air gouging



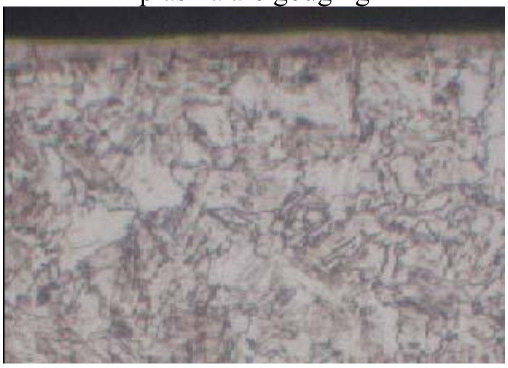
oxygen jet gouging



plasma arc gouging

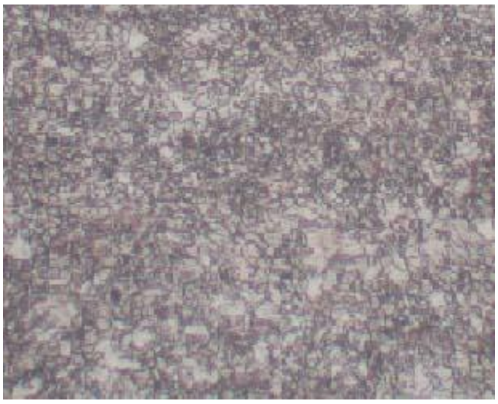


coated electrode gouging

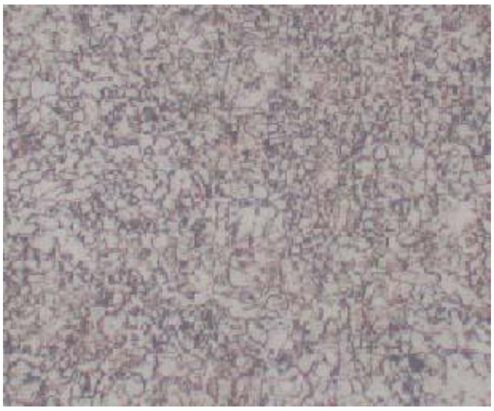


arc air gouging

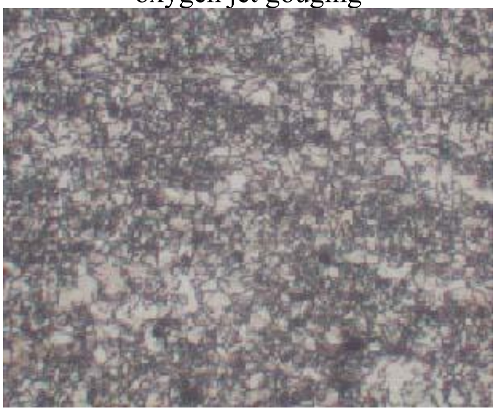
Fig. 5. Microstructure at the groove surface of 10 mm thick S420 MC steel after: a) oxygen jet gouging, b) plasma arc gouging, c) coated electrode gouging, d) arc-air gouging



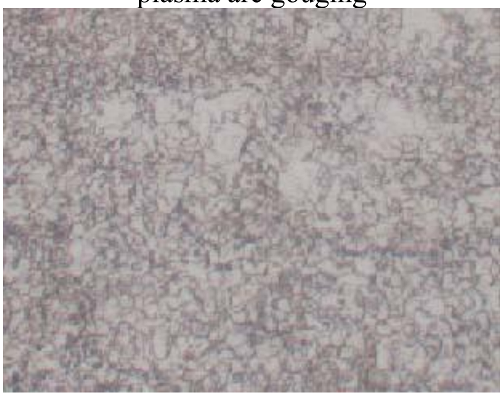
oxygen jet gouging



plasma arc gouging



coated electrode gouging



arc air gouging

Fig. 6. Microstructure of the HAZ of the grooves of 10 mm thick S420 MC steel after a) oxygen jet gouging, b) plasma arc gouging, c) coated electrode gouging, d) arc-air gouging

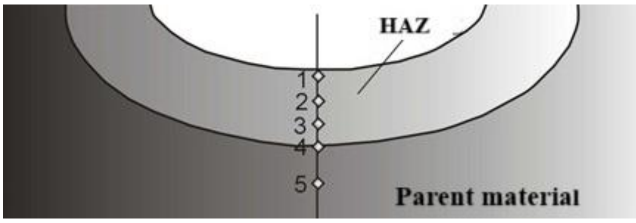


Fig. 7. HV1 hardness measurement points of thermally grooved S420 MC steel

Table 3. HV1 hardness measurement results of thermally grooved S420 MC steel with a thickness of 10 mm

Measurement points according to Fig. 7	Oxygen jet gouging	Plasma arc gouging	Coated electrode gouging	Arc air gouging
1	261	254	263	249
2	218	213	225	219
3	219	222	212	213
4	209	205	211	207
5	200	199	202	198

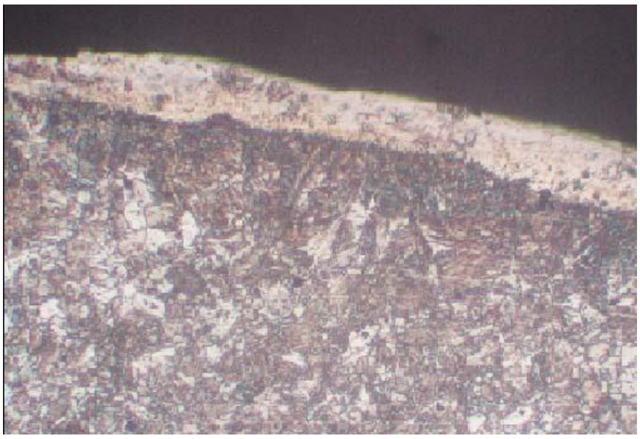


Fig 8. Microstructure of the solidified metal residue in a groove of 10 mm thick S420 MC steel, grooved with a coated electrode, etching: nital, magnification 50x

2.2. Surfacing process

The surfacing welds in the grooves were made using the MAG method with OK. Autrod 12.51 wire (table 4, 5) with a diameter of 1.2 mm in the M21 active mixture shield, with the following parameters: arc voltage: 20 V; surfacing current: 150 A; surfacing speed: 50 cm/min; linear surfacing energy: 3.65 kJ/cm.
The surfacing welds were placed in grooves with and without the removal of oxides after the thermal gouging process.

Table 4. Chemical composition of OK. Autrod 12.51 wire

Chemical composition [%]									
C	**Si**	**Mn**	**P**	**S**	**Al**	**Cr**	**Mo**	**Ni**	**Cu**
0.078	0.85	1.46	0.013	0.012	0.005	0.03	0.01	0.04	0.07

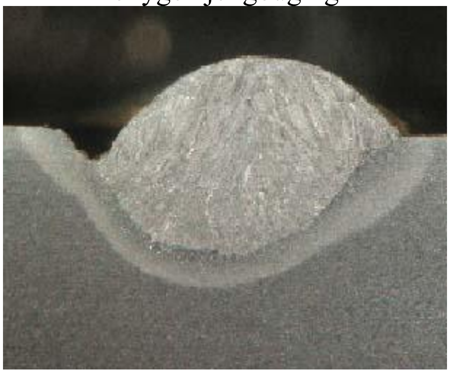
Table 5. Mechanical properties of OK. Autrod 12.51 wire

Mechanical properties		
Tensile strength, Rm [MPa]	Yield point, Re [MPa]	Elongation A5 [%]
560	470	26

The macroscopic examinations of the surfacing welds showed that the surfacing process resulted in a significant increase in the width of the HAZ area, Fig. 9,10. In the surfacing welds placed in the grooves with the oxides removed after the gouging process, no welding defects were observed. Failure to remove the oxide layer from the groove increases the risk of defects such as incomplete fusion and porosity, Fig. 11.


oxygen jet gouging


plasma arc gouging


coated electrode gouging


arc air gouging

Fig. 9. Macrostructure of surfacing welds made in grooves of 10 mm thick S420 MC steel without removed oxides after a) oxygen jet gouging, b) plasma arc gouging, c) coated electrode gouging, d) arc-air gouging

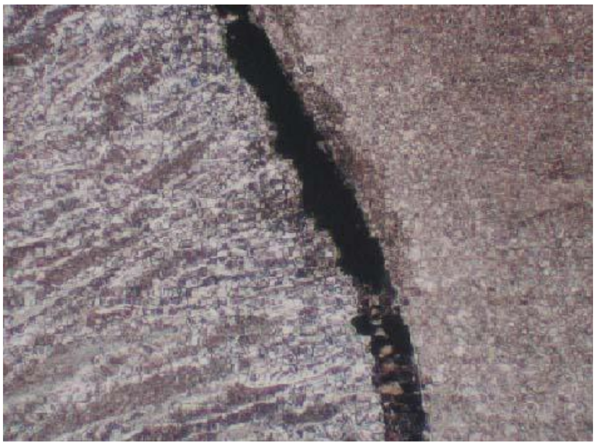

oxygen jet gouging


plasma arc gouging


coated electrode gouging


arc air gouging

Fig. 10. Macrostructure of surfacing welds made in grooves of 10 mm thick S420 MC steel with oxides removed, after a) oxygen jet gouging, b) plasma arc gouging, c) coated electrode gouging, d) arc-air gouging


oxygen jet gouging

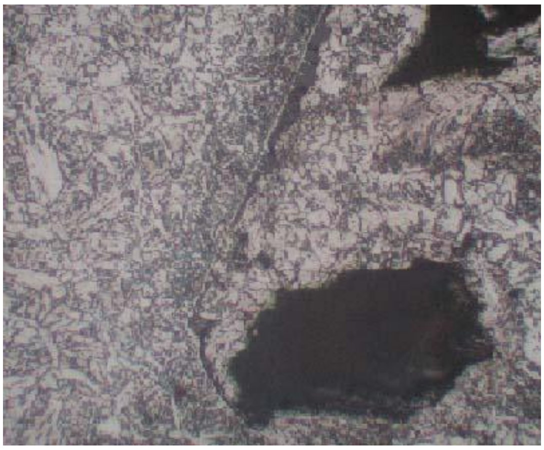
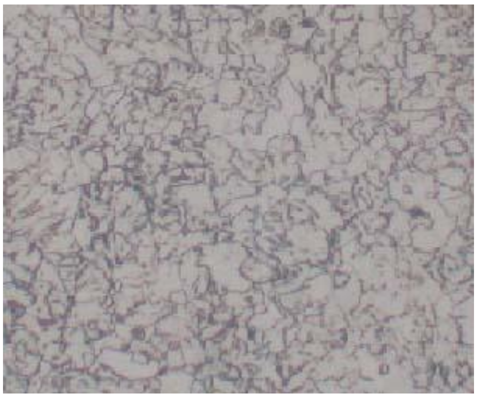
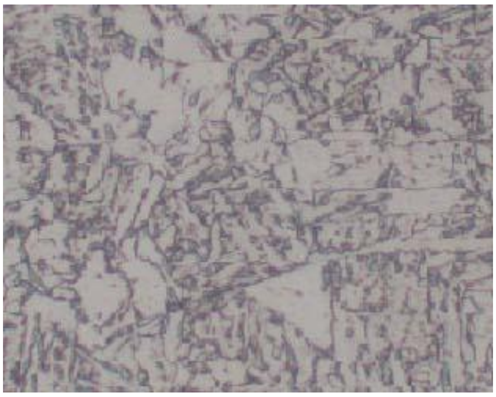
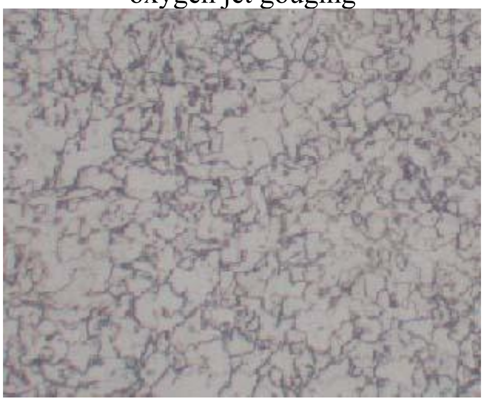

plasma arc gouging

Fig. 11. View of defects in surfacing welds made in the grooves of 10 mm thick S420 MC steel without removed oxides after a) oxygen jet gouging (visible incomplete fusion), b) plasma arc gouging (visible porosity),

Microscopic examinations have shown that as a result of repeated thermal cycles in the HAZ of the welds, the phenomenon of recrystallization and even grain growth occurs, fig. 12. These phenomena may result in deterioration of the operational properties of components. The results of microscopic examination confirmed the hardness measurements. In the HAZ area of the surfacing weld, the hardness dropped to approximately 180 HV1, with the hardness of the parent material and the surfacing weld being 200 HV1, Fig. 13, Table 6.


oxygen jet gouging


plasma arc gouging


coated electrode gouging

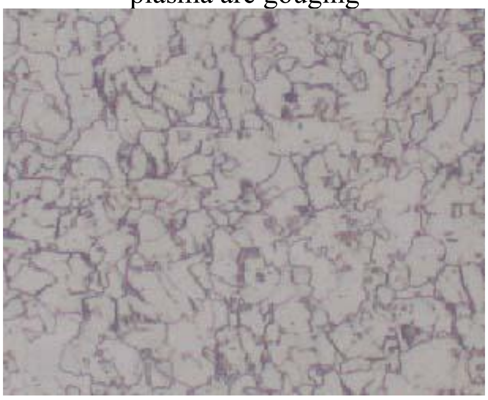

arc air gouging

Fig. 12. Microstructure of HAZ of surfacing welds made in grooves of 10 mm thick S420 MC steel with oxides removed after a) oxygen jet gouging, b) plasma arc gouging, c) coated electrode gouging, d) arc-air gouging

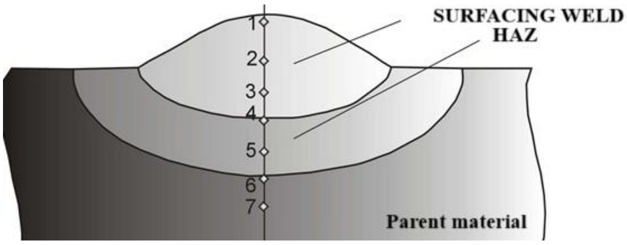


Fig. 13. HV1 hardness measurement points of surfacing welds made in S420 MC steel grooves

Table 3. HV1 hardness measurement results of surfacing welds made in thermally grooved grooves of 10 mm thick S420 MC steel

Measurement points according to Fig. 13	Oxygen jet gouging	Plasma arc gouging	Coated electrode gouging	Arc air gouging
No oxides removed				
1	201	210	207	201
2	198	205	200	203
3	196	202	193	205
4	207	207	197	199
5	188	190	176	182
6	187	187	180	175
7	208	203	196	202
With oxides removed				
1	204	205	213	207
2	214	204	207	201
3	208	200	203	199
4	193	192	199	201
5	178	183	180	181
6	168	175	192	172
7	200	198	206	193

3. CONCLUSIONS

The conducted tests of the influence of thermal gouging processes (oxygen jet, plasma arc, covered electrode, arc-air) on thermomechanically treated S420 steel showed the possibility of obtaining grooves of high quality and correct geometry. The highest quality is characteristic of grooves obtained by oxygen jet gouging, while the lowest quality is characteristic of coated electrodes gouging. It should be noted that if the gouging process is carried out incorrectly, there will be streaks at the bottom of the gouge groove. It is a melted and recrystallized metal that can become highly saturated with nitrogen in the air atmosphere. This layer may cause porosity in the material prepared for welding. Magnetic particle tests have shown that in the case of gouging with coated electrodes, holding the electrode for too long at the starting point of the gouging process may cause cracks. As a result of the thermal cycle of thermal gouging processes, structural changes occur at the cutting surface. In this area, a ferritic-bainitic structure appears, which is characterized by a hardness of around 260 HV1 (the hardness of S420 MC steel is about 200 HV1).

The tests carried out on the MAG surfacing process of thermally grooved grooves with the removed and unremoved oxide layer of S420 MC steel showed that because of the repeated action of the surfacing thermal cycle, the HAZ area of the surfacing welds becomes softer. In this area, the properties created during thermomechanical processing are lost. Microscopic examinations revealed partial recrystallization and even grain growth in the SWC area, which may significantly reduce the impact strength. The hardness of the HAZ was about 180 HV1. The surfacing welds made in grooves with the oxides removed are characterized by much better quality (no welding defects). Surfacing welds made in grooves without removing oxides tend to form defects such as sticking and porosity. Therefore, it is recommended to remove oxides and other gouging residues from the groove surface before starting the welding or surfacing process.

In summary, although thermomechanically treated steels are well weldable (due to their poor chemical composition and low carbon equivalent), special attention should be paid to the unfavorable effect of multiple thermal cycles on the properties of thermomechanically treated steels, especially in the HAZ area.

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