Influence of resistance butt welding thermal cycle on structure and properties of termomechanically rolled steel

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Abstract. In this article examination of structure and properties of resistance butt welded joints from S700MC high strength steel. 10 mm thick including recording welding thermal cycle recording are presented. The thermal cycle acquisition was performed on purpose build rig with a thermographic camera and a computer. The thermal fields acquisition station consisted of Varocam Head HR thermal camera and computer with Ibris 3 plus software, which enabled control of thermal camera parameters and saving of acquired on a local storage media. Aside from environmental parameters, such as temperature and humidity of surrounding, transmissivity of atmosphere equal to 1 and mean emissivity of steel surface of 0.9 were set. Noticeable impact of welding thermal cycle on strength and plastic properties was observed.

1. Introduction
The resistance welding process is characterized by specific parameters, caused by an evolving temperature field and a wide range of physical and mechanical properties of material during the process. A wide range of structures is produced due to the welding thermal cycle, during heat-affected zone formation in resistance butt welding. Welding thermal cycle – changes of temperature in each point in a volume of welded joint during process caused by heat transfer and heat-activated processes. The structural and mechanical properties of the material in the weld metal and heat-affected zone are determined by the thermal cycle character. Understanding and controlling heat flow during resistance butt welding is vital for successful process applications. Temporary cooling speed is variable and decreasing with a reduction of temperature during the process. The most widely used parameter describing cooling conditions is cooling time from 800 to 500°C (t8/5). The type and extensivity of structural changes are mainly influenced by maximum thermal cycle temperature and cooling time t8/5. With the increase of maximum thermal cycle temperature austenite is overheated and as an effect dissolution of precipitation in the austenite matrix is increased. As a result, γ-α transformation during cooling is delayed and moved to a lower temperature. In thermomechanically rolled base material presence of vanadium, titanium, and niobium is beneficial due to the formation of fine titanium nitrides vanadium and niobium carbonitrides, which decrease the grain growth of austenite. Resistance butt welding process can lead to disturbance of this mechanism and uncontrolled precipitation of MX type phases. Moreover, high nitrogen content in base material with insufficient content of titanium and do some extent aluminium can lead to uncontrolled aging and as an effect decrease of weldability [1-23].
2. Experimental procedure
The aim of the experiment was the determination of structure and properties of resistance butt welded high strength steel S700MC joints 10 mm thick, as well as, assessment of the thermal cycle impact on plastic and strength properties of the joints. The thermal cycles were recorded by means of thermal imaging. The chemical composition of S700MC steel is presented in table 1 and the steel structure is presented in figure 1.

Table 1. The chemical composition of S700MC steel 10 mm plate.

| Chemical composition, wg. % | C   | Mn  | Si   | S   | P   | Al  | Nb  | Ti  | V   | N*  | Ce** |
|-----------------------------|-----|-----|------|-----|-----|-----|-----|-----|-----|-----|------|
|                             | 0.056 | 1.68 | 0.005 | 0.01 | 0.027 | 0.044 | 0.12 | 0.006 | 72  | 0.33 |

* - N: content in ppm, nitrogen measured by high-temperature extraction.
** Ce – carbon equivalent.

2.1. Welding process
The resistance butt welded S700MC joints subjected to testing were 10 x 10 mm in cross-section. Based on preliminary welding trials process parameters (consisting of welding current, welding time, welding force, stick-out from jaws, and shortening of joint during the process) were chosen based on criteria of visual examination. The welding process and the thermal image acquisition were performed on purpose build station consisting of resistance butt welder ZDZ-7, thermal camera Variocam Head HR and computer (figure 2). The thermal fields acquisition consisted of Variocam Head HR thermal camera and computer with Ibris 3 plus software, which enabled control of thermal camera parameters and saving of acquired on a local storage media. The camera lens had a focal length of 50 mm, which in conjunction with distance to measured plane of 460 mm enabled view field of 140 x 110 mm with a spatial resolution of the thermal image (IFOV) of about 0.25 mm. Aside from environmental parameters, such as temperature and humidity of surrounding, the transmissivity of atmosphere equal to 1 and mean emissivity of steel surface of 0.9 were set. The thermal camera was elevated 1550 mm from a laboratory floor and the main lens axis was parallel to the floor surface. The joining process and thermal image acquisition were performed with an environmental temperature of 23.7°C and humidity of 65.7%.
During the acquisition temperature field evolution in time was registered and following thermal cycle parameters were derived:

- $T_{\text{max}}$ – the maximum cycle temperature,
- $t_h$ – the heating time from 50°C to $T_{\text{max}}$,
- $t_8$ – the time in which temperature was reduced back to 800°C,
- $t_5$ – the time in which temperature was reduced back to 500°C,
- $t_{85}$ – the cooling time between 800-500°C.

Thermal images were presented in figure 3 and thermal cycles were presented in figure 4. Thermal cycle acquisition was performed for 3 joints and mean, as well as, maximal thermal cycle parameters were presented in table 2.

**Table 2. Thermal cycles parameters.**

| Parameter | Mean value | Maximal value |
|-----------|------------|---------------|
| The maximum cycle temperature $[°C]$ | 1332 | 1618 |
| The cooling time between 800-500°C $[s]$ | 12 | 11 |
| Time spent over 900°C $[s]$ | 17 | 22 |
| The heating rate $[°C/s]$ | ~95 | ~124 |
| The heating time from 50°C to $T_{\text{max}}$ $[s]$ | 14 | 13 |
Figure 3. Series of thermal images covering resistance butt welding of S700MC joint.

Figure 4. Minimal, maximal and mean thermal cycle acquired during the experiment.

2.2. Welded joints examination
The obtained welded joints after visual examination were subjected to destructive testing. To perform the above-mentioned tests butt welded joints were ground to remove a fin, formed by plastic deformation during the welding process. The range of destructive tests was:
- tensile test acc. to PN-EN ISO 6892-1:2010 using ZWICK/ROELL Z 330RED test machine,
bending test acc. to PN-EN ISO 5173:2010. The bending tests were performed on ZWICK/ROELL Z 330RED with an additional bending module. The bending tests were performed with a punch diameter of 30 mm and inter support distance was set to 60 mm. To reveal joint midplane Adler etchant was used;

- impact test acc. to PN-EN ISO 148-1:2010, on Charpy v-notch specimens, on impact hammer ZWICK/ROELL RKP 450. Test temperature was -30°C. Test were performed in joint midplane (specimen marking: A), on HAZ and joint border (marking: B), and in HAZ (marking C). To reveal joint macrostructure Adler etchant was used;

- macroscopic metallographic examination on Olympus SZX9 light stereoscopic microscope; Adler etchant was used to reveal joint macrostructure,

- microscopic metallographic examinations on NIKON ECLIPSE MA100 light microscope; Nital etchant was used to reveal microstructure,

- Vickers hardness testing on WILSON WOLPERT 430 in accordance with PN-EN ISO 9015-1 requirements. Hardness tests were performer along 3 test lines, 2 mm from upper and lower surface of the sample and in the middle of cross-section,

- chemical composition examinations in micro areas were performer on ZEISS SUPRA 35, with EDAX EDS addon, viewing of the sample was performed using back-scattered electrons (BSE),

- thin foil examinations were performed on high-resolution scanning-transmission microscope FEI (HR S/TEM) Titan 80-300 kV.

3. Results and discussion

Carried out visual examinations failed to find imperfection such as: cracks, porosity or overlap. Macroscopic examinations did not reveal any imperfection in welded joint and HAZ as well (figure 5). Microscopic examinations revealed coarse grained ferritic-bainitic structure of weld material. In HAZ noticeable change of grain size was visible. This is due to heat input during resistance butt welding (figure 6). Destructive test result analysis yielded the influence of welding thermal cycle on the strength and plastic properties of the joint, table 3. As a result of the welding process, the ultimate tensile strength is reduced to 660 MPa, from a level of 820 MPa in base material. The Fracture was formed in the weld metal as a result of a structural notch. The reduction of strength parameters is due to the loss of properties acquired by S700MC steel in the thermo-mechanical rolling process. The bending tests resulted in a bend angle of 130° and visible cracks in weld material. Charpy pendulum impact testing in temperature of -30°C indicates a significant loss of plastic properties of S700MC welded joint in comparison to the base material. In each area of welded joints, brittle fractures were observed, figure 7. The lowest toughness value was that of weld metal, with a value of 6 J/cm². With an increase of the distance from the welded seam plane toughness is slightly rising, and reaches 8 J/cm² on weld metal/HAZ border, 11 J/cm² in HAZ figure 8. Temperature measurement, with the use of the thermal camera, enabled determination of the maximum temperature of welding thermal cycle of 1300°C. Such high temperature neutralizes the beneficial effect of strengthening phases on austenite grain growth reduction and as a result, reduces joint plasticity. The loss of plastic properties should be connected with an increase of strengthening phases dissolution in the metal matrix, followed by uncontrolled precipitation of fine particles, figure 9.

Table 3. The resistance welded joint destructive test results.

| Tensile test* | Bending* | Toughness KCV**, J/cm² (test temperature -30 °C) |
|---------------|-----------|-----------------------------------------------|
| Rm, MPa       | Fracture  | Bend angle°   | Fracture | Weld | Weld/HAZ | HAZ   |
|               | Fracture | KCV, J/cm²   | Fracture | KCV, J/cm² | Fracture | KCV, J/cm² | Fracture |
| 660           | Weld     | 130         | Weld     | 6     | Brittle  | 8 | Brittle  | 11 | Brittle |

* - mean of two tests, ** - mean of three tests.
Figure 5. Macrostructure of S700MC steel resistance butt welded joint.

Figure 6. The microstructure of S700MC resistance butt welded joint: (a) Weld metal; (b) HAZ; (c) Weld metal – HAZ border; (d) HAZ – Base material.
Figure 7. The fractures after impact testing: (a) Weld metal fracture; (b) Weld metal/HAZ border fracture; (c) HAZ fracture.

Figure 8. S700MC welded joint toughness.
Figure 9. (NbTi)C carbide precipitation in weld metal: (a) Bright field; (b) Dark field; (c) Difractogram; (d) Resolved difractogram; (e) EDX spectrum.

The hardness tests results demonstrated a noticeable decrease of HV1 hardness of weld metal (215 HV1) in comparison with the base material (280 HV1). In the HAZ hardness was around 235 HV1, figure 10.

Figure 10. The hardness of S700MC steel resistance butt welded joint.

4. Conclusions
The S700MC steel is characterized by a highly defective bainitic-ferritic structure. The very low carbon content (0.05%), which is mostly bonded with Ti and Nb, results in a decrease of carbon impact on steel strengthening and reduces its impact on phase and structural changes. The analysis of butt welded S700MC steel joints indicates the possibility of producing said joints free of welding
defects. However, the resistance butt welding process reduces the plastic and strength properties of the welded joint area. High thermal input and plastic deformation in the joint area resulted in a loss of properties acquired by the material in the thermo-mechanical rolling process. The impact toughness KCV is reduced to the level of 6-11 J/cm², which is unacceptable in a structural joint. In the welded joint area maximal temperature reaches 1300°C. As a result, not only structural changes but also uncontrolled MX precipitation formation causes a sharp decrease in plastic properties. Simultaneously reduction of strength properties, in the form of ultimate tensile strength (660 MPa in the welded joint from 820 MPa in the base material) and hardness. Hardness values were lower both in weld material and HAZ (215 HV1 and 235 HV1 correspondingly) compared to 290 HV1 in the base material.

5. References

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