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Properties and Structure of Laser Beam Welded Joints of S700MC Thermomechanically Treated Steel

Abstract: The article presents the structure and properties of joints welded using a laser beam without a filler metal, made of 10 mm thick thermomechanically treated high yield point S700MC steel. The related non-destructive tests have classified the joints described above as representing the quality level B in accordance with standard 13919-1. The destructive tests have revealed the joint characterised by the tensile strength approximately 5% higher than that of the parent metal. Laser welding without the filler metal increases the content of chemical elements responsible for steel hardening (Ti, Nb), which leads to a weld toughness decrease below the acceptable value of 27 J/cm^2.

Keywords: laser beam welding, S700MC steel, welding joints, destructive tests

Introduction

Laser welding, due to its advantages initially used for successful joining of simple and relatively small objects, now, thanks to technological development and increased laser power, is entering the area previously almost entirely reserved for conventional welding techniques. The replacement of "traditional" welding technologies is often dictated by the use of modern high-strength materials, the joining of which requires precise techniques and proper technologies which enable maintaining advantageous strength properties of the parent metal. Due to high power density obtained in the laser beam affected area, this process enables welding of sheets using just a single run. In addition, sheets can be set up without bevelling (square method) which makes a welding rate (efficiency) relatively high. As a rule, laser welding does not require the use of a filler metal and obtained welds are narrow and deep due to the partial melting of the edges of materials being joined. For this reason, the process requires very precise preparation of workpiece edges (workpieces should be set up without a gap) and ensuring proper positioning of workpieces to be welded and that of the welding head [1-5]. The technical and economic aspects resulting from the possibility of making products out of thermomechanically treated high yield point steels using energy-saving integrated production lines and the usability of such steels in the production of various structures, including those operated in extreme climate, arouse vivid scientific interest in this group of materials as well as in the improvement of their manufacturing and joining technologies, including laser beam welding [6-14].

Research

The objective of the research was to determine the effect of laser beam welding without a filler metal on the properties and structure of joints

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Table 1. Chemical composition according to PN EN 10149-2 and the mechanical properties of cold-formed thermomechanically rolled S700MC steel

Contents of chemical elements,%											
C max.	Si max.	Mn max.	P max.	S max.	$Al_{tot.}$ min.	Nb max*	V max.	Ti max.	B max.	Mo max.	Ce** max.
0.12	0.60	2.10	0.008	0.015	0.015	0.09	0.20	0.22	0.005	0.50	0.61
Mechanical properties											
Tensile strength Rm, MPa			Yield point Re, MPa			Elongation A5,%			Toughness, J/cm² (-20°C)		
822			768			19			135		
* - Sum of Nb, V and Ti contents should amount to max. 0.22%, ** Ce – carbon equivalent.											

made of 10 mm thick S700MC steel sheets. The chemical composition and mechanical properties of the steel are presented in Tables 1 and 2, whereas the structure of the steel is presented in Figure 1.

Table 2. Real chemical composition of 10 mm thick S700MC steel tested

Contents of chemical elements,%										
C	Mn	Si	S	P	Al	Nb	Ti	V	N*	Ce**
0.056	1.68	0.16	0.005	0.01	0.027	0.044	0.12	0.006	72	0.33
* - N: content in ppm, nitrogen was determined through high temperature extraction ** Ce – carbon equivalent.										

Welding Process

The research-related tests were carried out on a laser beam welded joint made of 10 mm thick S700MC steel using a TruDisk 12002 disc laser and the station presented in Figure 2. Table 3 presents process parameters selected on the basis of initial welding tests and the adopted welding rate of 1 m/min.

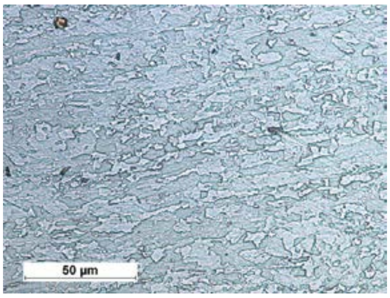


Fig. 1. Bainitic-ferritic structure of S700MC steel

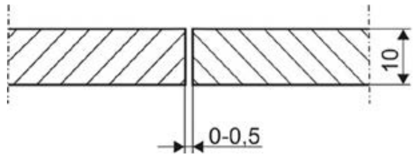
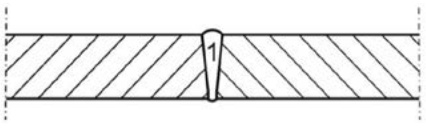

welding station

welding process

post weld joint view

Fig. 2. Making a test joint using a TruDisk 12002 disc laser

Table 3. Parameters of laser beam welding of 10 mm thick S700MC steel using, linear energy: 5 kJ/cm

Pre-weld sheet preparation			Welding sequence		
					
Run	Beam power, W	Location of focus in relation to sheet surface, mm	Welding position	Welding rate v, m/min	Welding linear energy E, kJ/cm
1	8400	0	PA	1	5
Shielding gas - helium. Gas flow rate -20 dm³/min. Drying preheating temperature: 65°C.					

Tests of Welded Joints

The test joints underwent the following NDT:

- visual testing in accordance with the requirements of standard PN-EN ISO 17637:2011;
- magnetic particle testing in accordance with the requirements of standards PN-EN ISO 3059:2005, PN-EN ISO 9934-2:2003 and PN-EN ISO 9934-3:2003. The tests involved the use of white contrast MR 72, magnetic powder MR 76S and a yoke electromagnet;
- radiographic testing in accordance with the requirements of standard PN-EN 1435 using a CERAM 235 lamp, X-ray beam having a diameter $d = 2$ mm, voltage $U = 180$ kV, current $I = 3$ mA and intensifying screens OW – 0.15 mm. The test results were recorded on a photographic plate AGFA C5 using the exposure time $t = 2.3$ min and the focal length f = 700 mm. The image quality was assessed using a 13FEEN wire type image quality indicator.

Following NDT test joints were subjected to the following destructive tests:

- tensile tests in accordance with the requirements of standard PN-EN ISO 6892-1:2010 using a ZWICK/ROELL Z 330RED testing machine and test pieces sampled in accordance with the requirements of standard PN-EN ISO 4136:2011;
- face bend test of butt joint (FBB) and root bend test of butt joint (RBB) in accordance with the requirements of standard PN-EN ISO 5173:2010. The bend tests were conducted using a ZWICK/ROELL Z 330RED testing machine provided with an additional module for bend tests utilising a bending mandrel with a diameter of 30 mm. The distance between the rolls amounted to 60 mm. In order to determine the position of the weld axis the fronts of test pieces were etched with Adler's reagent;
- impact tests in accordance with the requirements of standard PN-EN ISO 148-1:2010, using V-notch test pieces, a ZWICK/ROELL RKP 450 impact testing machine and temperature of -30°C. Due to the thickness of sheets being welded (10 mm) and the necessity of performing pre-weld machining the cross-section of test pieces was reduced and amounted to 7.5 mm; the test pieces underwent etching in Nital;
- macroscopic metallographic examination using an Olympus SZX9 light stereoscopic microscope; the test pieces were etched with Adler's reagent,
- microscopic metallographic examination using a NIKON ECLIPSE MA100 light microscope; the test pieces underwent etching in Nital,
- Vickers hardness test using a WILSON WOLPERT 430 testing machine in accordance with the requirements of standard PN-EN ISO 9015-1.
- quantitative measurements determining the contents of S700MC steel hardening microadditions using a JEOL-manufactured JXA-8230 X-ray microanalyser and wavelength dispersion spectroscopy (WDS),
- testing thin films using a FEI-manufactured Titan 80-300 kV high resolution scanning electron microscope (HR S/TEM) equipped with an XFEG electron gun with higher brightness Schottky field emission,
- X-ray phase analysis using an X'Pert PRO diffractometer and X'Celerator strip detector.

Analysis of Test Results

The conducted visual tests and magnetic particle tests of the welded joint did not reveal such surface welding imperfections as cracks, porosity, incomplete fusions or lacks of penetration. The radiographic tests did not reveal any internal welding imperfections. The welded joint satisfied the requirements of the quality level B in accordance with ISO 13919-1. The macroscopic examination did not reveal the presence of imperfections in the weld area and HAZ (Fig. 3).

The microscopic tests revealed the presence of bainitic-ferritic structure in the weld area. In the HAZ no clearly visible grain size changes were observed, which can be ascribed to the very low heat input to the welded joint (Fig. 4).

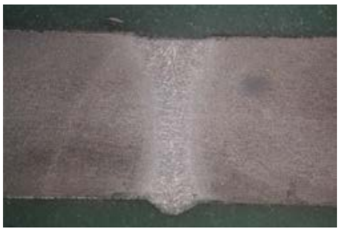
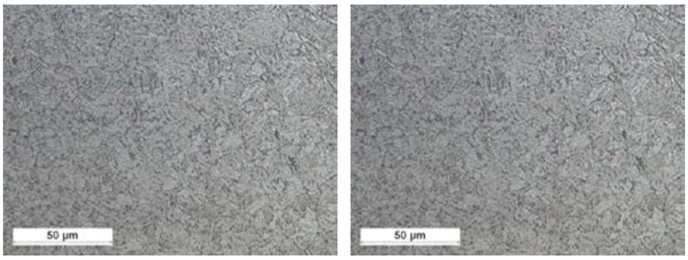


Fig. 3. Macrostructure of the laser beam welded joint made of S700MC steel



weld HAZ

Fig. 4. Microstructure of the laser beam welded joint made of S700MC steel

The analysis of the destructive test results related to the laser beam welded butt joint revealed the significant effect of the welding method on the mechanical and plastic properties of the joint (Table 4). Laser beam welding decreased tensile strength to approximately 790 MPa, in relation to that of the parent metal (830 MPa). The weld ruptured in the fusion line area, where a structural projection was formed. The decrease in tensile strength can be attributed to the loss of properties provided to S700MC steel through thermomechanical rolling (local heat treatment as a result of thermal cycle). During the bend test the bend angle of 180° was reached, both in FBB and RBB tests. Unfortunately, the impact test at the temperature of -30°C revealed very low toughness values. The toughness in the weld area amounted to 20 kJ/cm², which is significantly lower than the acceptable level of 27 J/cm². The welded joint hardness measurements revealed that the weld was characterised by hardness comparable with that of the parent metal. The hardness in the HAZ was lower by approximately 30 HV if compared with the parent metal hardness.

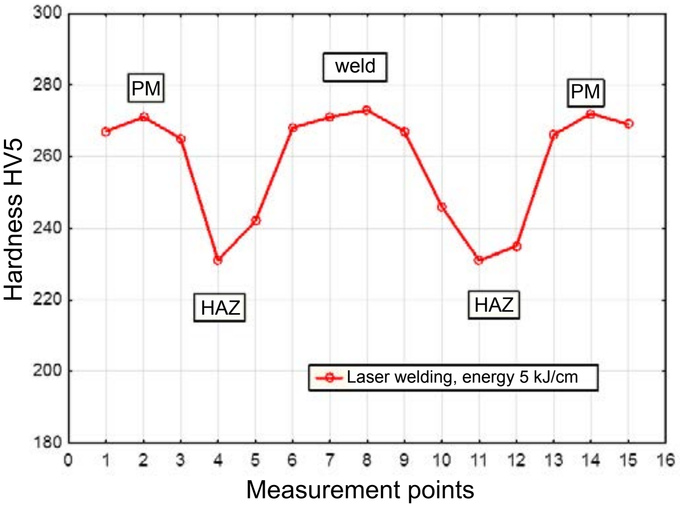


Fig. 5. Hardness distribution in the laser beam welded joint

The X-ray phase analysis revealed that the parent metal and the weld made with a laser beam were fully composed of the ferritic phase (Fig. 6).

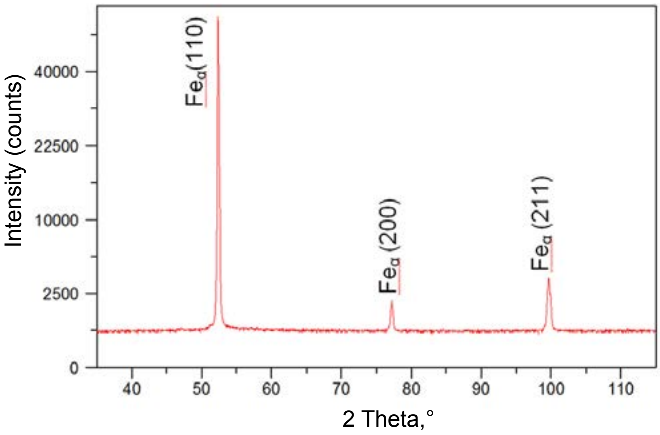


Fig. 6. X-ray diffraction pattern of the weld of the laser beam welded joint made of S700MC steel

During laser beam welding, in spite of very low welding linear energy, toughness was very low – below 20 J/cm². In laser welds made without a filler metal the content of Ti and Nb was considerably higher than in arc-made welds (filler metal does not contain Ti or Nb).

Table 4 Strength and plasticity of the laser beam welded joint

Method/ welding linear energy, kJ/cm	Tension*		Bending*, bend angle, °		Toughness KCV**, J/cm2 (testing temperature -30 °C)			
					Weld		HAZ	
	Rm, MPa	Rupture site	Face	Root	KCV, J/cm²	Fracture	KCV, J/cm²	Fracture
Laser/5	790	FL	180	180	20	brittle	-	-

* - average result of two measurements, ** - average result of three measurements.

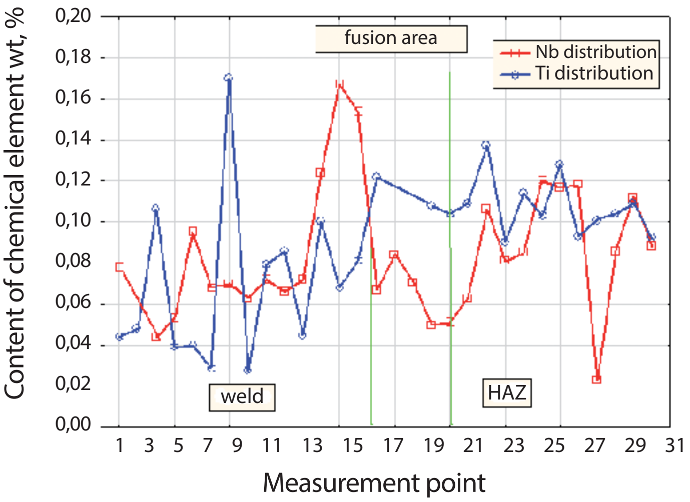
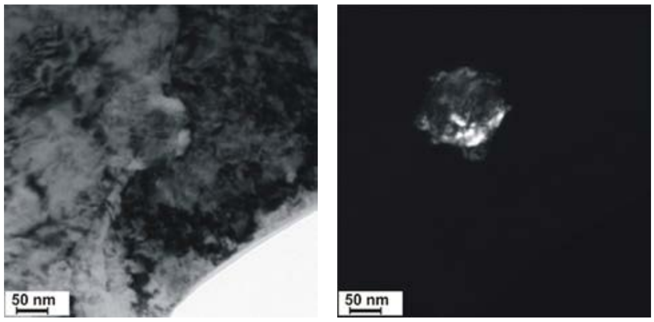
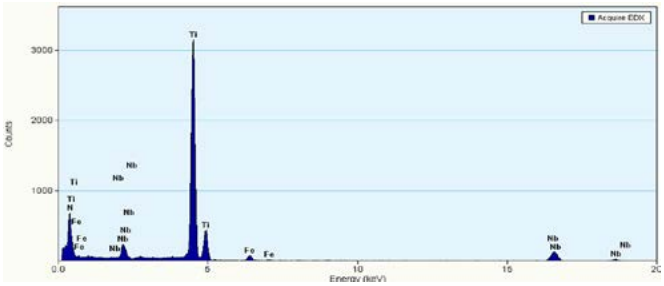


Fig. 7. Distribution of Ti and Nb in the fusion area of the laser beam welded joint made of S700MC steel using the linear energy of 5 kJ/cm

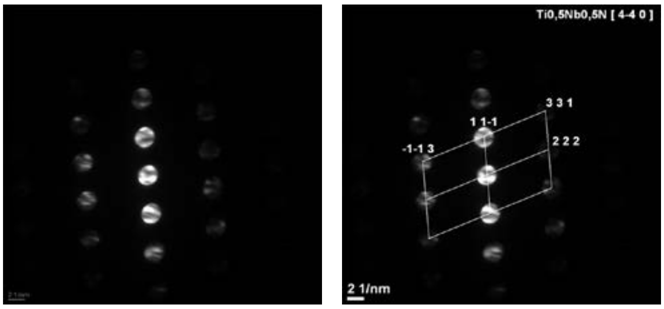


light field

dark field



EDX spectrum



Diffraction pattern

Diffraction pattern solution

Fig. 8. Precipitation of nitride (Ti,Nb)N with fine spherical hardening precipitates in the weld of S700MC steel welded using a laser beam

The increased content of hardening agents decreased toughness in the weld area in relation to that of the parent metal. The increased content of hardening agents was particularly visible near the fusion line, which was confirmed by the detailed chemical composition analysis carried out using the X-ray microanalyser (Fig. 6). Some areas of the weld near the fusion line revealed very high titanium and niobium contents, which reflected the presence of clustered carbonitride precipitates which had not entirely dissolved in the liquid metal pool. The excessively high concentration of hardening phases in the fusion area can significantly deteriorate weld plastic properties.

The significant fraction of hardening phases in the weld during cooling led to the strong precipitation hardening due to fine-dispersive (Ti,Nb)(C,N) precipitates of several nm located near greater (Ti,Nb)N particles of 100 nm (Fig. 8), which led to reduced plastic properties.

Summary

Steel S700MC is characterised by strongly damaged bainitic-ferritic structure. The very low carbon content (0.05%), largely bounded by Ti and Nb decreased carbon contribution to steel hardening and limited its effect during phase and structural transformations. The basic problems encountered during welding of thermomechanically treated steels were the following:

- loss of properties obtained during thermomechanical treatment through the effect of a welding thermal cycle which can cause partial dissolving of fine-dispersive hardening precipitates (carbides, carbonitrides Nb, Ti, V) and their uncontrolled re-precipitation,
- excessive growth of hardening precipitates and their loss of ability to inhibit grain growth,
- passage of alloying agents to the weld during welding, a difference in carbon equivalent between the parent metal and the weld.

During laser welding the content of alloying agents Ti and Nb in the weld was the same as that in the parent metal (during welding without a filler metal). A significant amount of precipitates containing hardening chemical elements adversely affected the plastic properties of welds. For welds made with a laser beam, in spite of low linear energy (5 kJ/cm) and low carbon equivalent (0.33%) toughness proved unsatisfactory, i.e. below 20 J/cm². The amount of microadditions in the weld made with a laser beam was significantly higher than that in welds made using arc welding processes [15]. This resulted in the increased amount of dispersive precipitates in the weld. The high content of hardening phases in the weld during cooling led to strong precipitation hardening through several nm sized fine-dispersive precipitates (Ti,Nb)(C,N) and decreased plastic properties. In order to improve weld toughness it seems advantageous to use hybrid welding as it decreases the content of alloying agents Ti and Nb in the weld.

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