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Effects of Laser Shock Peening Technology on Stress Corrosion Cracking of Austenitic Steel

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This article deals with the treatment of surface properties of austenitic steels using Laser shock peening (LSP) technology. It is a process in which the surface of the material is strengthened by a pulsed laser beam. The laser pulse generates a strong compression shock wave after impacting the component surface. This spreads through the material and introduces residual compressive stresses into the surface layer. These stresses improve the technical properties of the material, improving resistance to stress corrosion cracking. The aim of the tests was to influence the austenitic steel 08CH18N10T by LSP technology, to carry out a corrosion test under the action of a boiling $MgCl_2$ salt solution, and to subsequently evaluate these tests. $MgCl_2$-based salt is one of the candidate coolant media for new types of Generation IV nuclear reactors.

Furthermore, the hardness of the peened and non-peened part of the material was measured. These tests brought information about the resistance of the peened material to the non-peened material.

Keywords: LSP, 08CH18N10T, corrosion, stress corrosion cracking, residual stress

1 Introduction

It is well known that austenitic steels are resistant to corrosion, and with the ever-increasing demand for high quality materials, there is a growing need to develop new production technologies that can influence the mechanical properties of the material. The surface of the material has a great influence on its functionality and its treatment can be used to prevent its destruction, for example due to corrosion and related processes [1].

Therefore, the importance and use of laser technology has been growing in recent years. These technologies, replacing the still frequently used conventional methods of material treatment, have high quality, production speed, and often a high level of automation. One of the latest technologies is Laser shock peening [2,3,4,5,6,7].

The technology works on the principle of the interaction of a pulsed laser beam with the surface of the material to form a high - pressure plasma., which causes plastic deformation of the material and the formation of compressive stresses on the surface and under the surface of the material. These waves plastically deform the surface and compressive stresses are transmitted to the layers below the surface. The dynamic stress is highest on the surface of the processed material and decreases in the direction to its depth. When the amount of pressure on the surface of the material exceeds the dynamic yield strength of the metal, plastic deformation occurs [2,8].

To generate a shock wave with a laser, several requirements must be met. One of them is that the target surface must be covered with an absorbent layer. This layer evaporates under the action of the laser and creates a plasma on its surface and thus pressure during and shortly after the laser is applied. The absorption layer prevents melting and laser ablation of the base material, thanks to which it maintains high surface quality [1,2,3,5,6,7,8,9,10,11,12].

To prevent the plasma spreading away from the surface of the material, the use of a transparent overlay is necessary. Keeping the plasma on the surface significantly increases the intensity of the shock wave. This overlay layer, also known as the bonding medium, can be water, quartz glasses, borosilicate glasses, lead glasses, plexiglass, or silicone rubber. See Fig. 1. The choice of bonding medium depends on the application, after LSP it has a positive effect on corrosion resistance and corrosion under stress. It is also a suitable method of material modification to improve fatigue life, fatigue strength, microstructure refinement, thereby improving the mechanical properties of the surface layer with the subsequent creation of plastic deformation of the surface [1,2,3,5,6,7,8,9,10,11,12].

LSP technology is also effective on the microstructure of the material. Materials influenced by LSP technology are more resistant to corrosion cracking. Corrosion cracking is one of the types of corrosion attack on metal material, which is caused by the joint action of external and internal tensile stresses and an aggressive environment. It can also occur in a less aggressive environment containing chlorides and hydroxides [13, 14].

Corrosion cracking occurs when static tensile stress is applied to a metal material exposed in a specific environment (at certain temperatures and concentrations). It occurs only when the stress, the properties of the corrosion environment and the properties of the material simultaneously reach the limit values necessary for its formation [13,14].

LSP technology does not change the passivity of the material, the passivation layer is thinned due to the action of shock waves, but the layer becomes more compact and durable. The effects of LSP do not affect the corrosion activation energy. However, LSP-treated material that will has compressive residual stress in the surface and surface layer will resist corrosion better than the same but untreated material with tensile or low compressive residual stress at the same activation energy. The compressive stress closes the surface and thus prevents corrosion from progressing deeper into the material. On the contrary, tensile stress in the surface opens cracks and pores and was thus allows corrosion to spread into the materials [1].

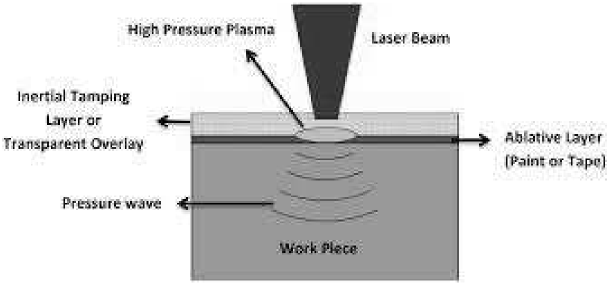


Fig. 1 *LSP principle [11]*

2 Experiment

08CH18N10T austenitic steel was used to perform the experiment, see in Tab. 1 and Tab. 2.

Tab. 1 *Chemical composition of 08CH18N10T*

Element	C	Mn	Si	P	S	Cr	Ni	Cu	Mo	Ti
[wt %]	0.05	1,68	0.57	0.02	0.001	17.5	9.9	0.06	0..06	0.47

Tab. 2 *Mechanical properties of 08CH18N10T*

	At 20 °C	At 350 °C
Re [MPa]	248	213
Rm [MPa]	565	425
A [%]	54.5	31
Z [%]	76	69

The test specimens for the corrosion cracking test in boiling $MgCl_2$ solution were made of a tube of austenitic steel 08CH18N10T with a length of 240 mm, a diameter of 32 mm and a wall thickness of 2 mm. The pipe surface was not further treated, ground or polished. One part was left in the initial state and the other was reinforced with LSP technology.

The surface treatment of the experimental material was performed with a pulsed laser L2-BIVOJ (HILASE Center-Dolní Břežany).

LSP process parameters:

- Pulse energy: 5.5 J,
- Pulse length: 14 ns,
- Repeat frequency: 10 Hz,
- Pulse density 6.25 GW / cm^2.

The surface of the pipe with an area of about 40 x 110 mm was shelled with a laser three times with 50 % overlap of each subsequent spot in a row. The size of the laser trace was 2 x 2 mm and black vinyl tape was chosen as the ablation layer.

2.1 Sample prepared

The samples were cut from a piece of pipe reinforced with LSP technology and from a pipe without LSP reinforcement using LSP technology for live corrosion cracking tests and hardness tests. See in Fig. 2.

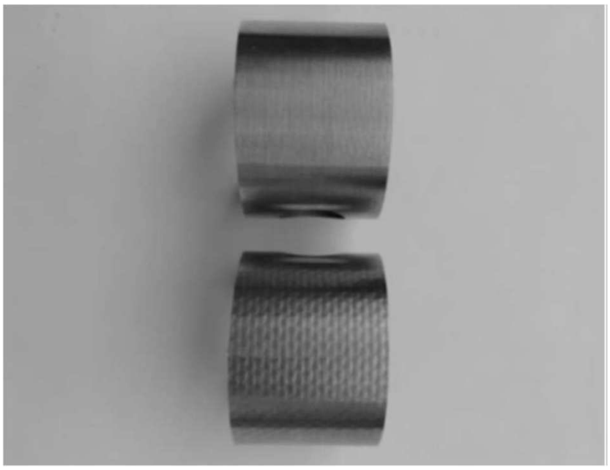


Fig. 2 *Sample made LSP application at the top and after LSP application at the bottom of the image*

Two holes with a diameter of 10.2 mm were drilled in each axis on the opposite sides for the M10 clamping screw. Shape C of the sample was created by cutting out a part of the pipe corresponding to a section at an angle of 60 °. See Fig 3.

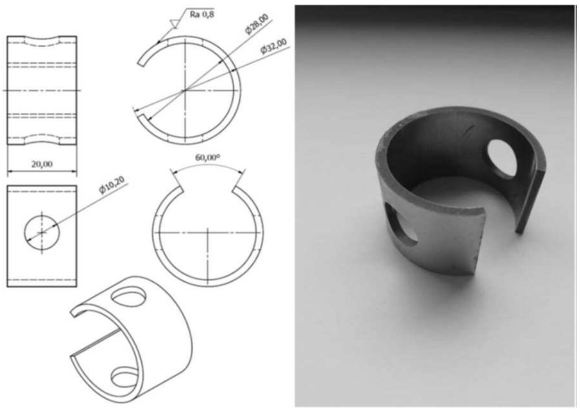


Fig. 3 *Required dimensions and appearance of the produced C-shaped sample*

Fig. 4 *Prepared sample*

A C-shaped sample was chosen for the tests, which is suitable for stress corrosion cracking tests on pipes. Circuit voltage is the most important for this C-shape. However, the stress in this experiment varies from the maximum tensile stress on one surface to the maximum compressive stress on the opposite surface. Furthermore, the tension varies around the circumference of the C-ring from zero at each bolt hole to a maximum in the middle of the arc against the tension bolt.

Prior to the start of the experiment, the individual samples were degreased in acetone, a clamping screw was threaded through them, and the sample was subjected to a constant load. With a torque wrench, the clamping screw was tightened to a tightening torque of 0.250 Nm. See Fig. 4. This value was determined based on the yield strength so that no plastic deformation occurred in the material. The samples were marked A for the starting material, i.e., without LSP reinforcement and B for the pipe after LSP reinforcement.

2.2 Used equipment

The experiment was performed according to the ASTM G36 standard, where the mechanically stressed sample is exposed to a boiling $MgCl_2$ solution at a temperature of 155 ± 1 °C. An apparatus was used for the tests, which consisted of a 6 litter sulfonation flask with outlets for a thermometer, condenser, and sample sockets. This flask was placed in a heating nest. See Fig 5. The test solution was prepared of dissolving 3000 g $MgCl_2.6H2O$ in 75 ml distilled water. The boiling point of $MgCl_2$ solution is strongly dependent on its concentration in water. Therefore, as the solution began to boil vigorously, a small amount (4 to 5 ml) of water was slowly added until the temperature stabilized at 155 ± 1 °C. The sample was then added to the solution. The test solution was kept boiling at 155 ± 1 °C. The vapours generated during the boiling of the solution condensed back thanks to the added condenser. The volume of the $MgCl_2$ solution was constant during the test.

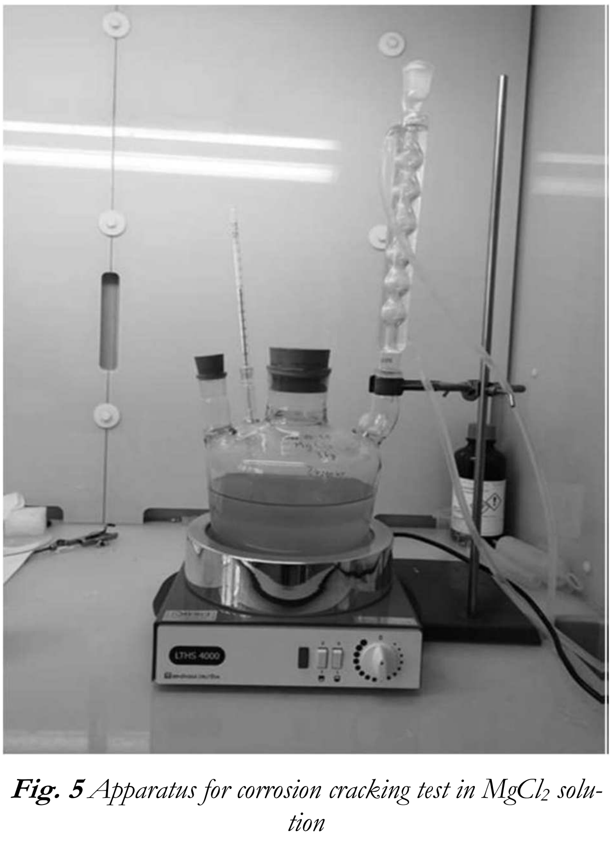


Fig. 5 *Apparatus for corrosion cracking test in $MgCl_2$ solution*

Tab. 3 *Sample designations and experiment conditions*

Sample identification	Material modification	Sample control	Total exposure time $MgCl_2$
A	Unpaved LSP	After 10 minutes	120 minutes
A2	Unpaved LSP	After 20 hours	20 hours
B2	Reinforced LSP	After 20 hours	20 hours
A4	Unpaved LSP	After 3 hours	24 hours
B4	Reinforced LSP	After 3 hours	24 hours

The samples marked A2 and B2 were tested first. After baseline preparation and documentation, the samples were placed in a boiling $MgCl_2$ bath for 20 hours. Throughout the test, the samples were immersed in a still boiling $MgCl_2$ solution. At the end of the predetermined experiment time, each sample was removed from the corrosion solution, cleaned, and checked for light microscopy for cracks, and photo documentation was obtained. See Fig. 6 to Fig. 9.

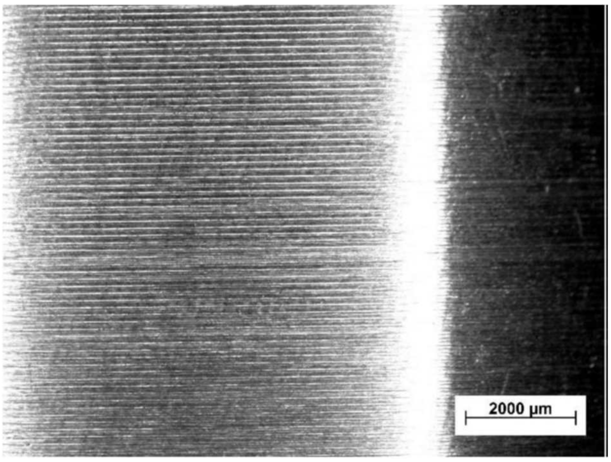


Fig. 6 *Sample A2 before the $MgCl_2$ bath test*

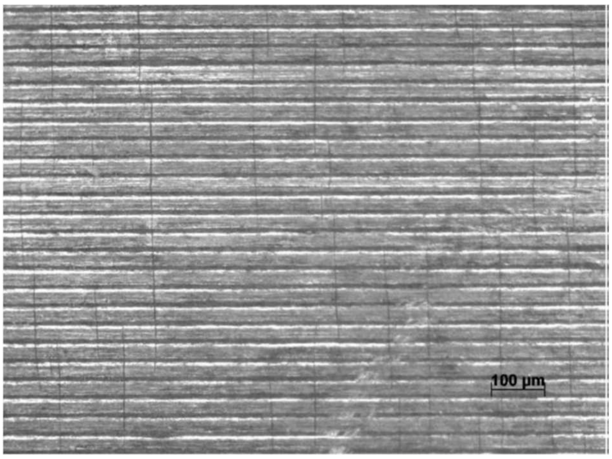


Fig. 7 *Sample A2 after 20 hours in a $MgCl_2$ bath*

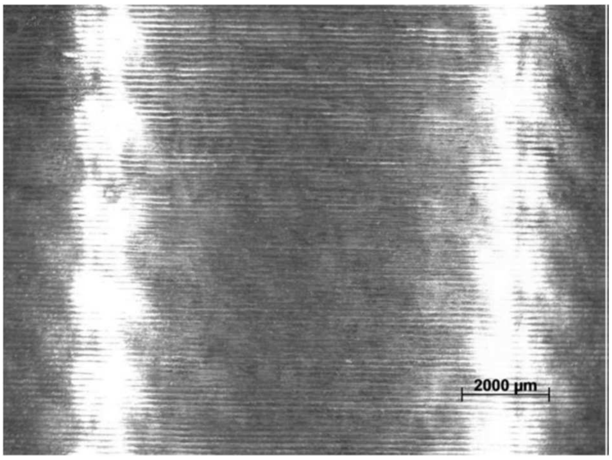


Fig. 8 *Sample B2 before testing in $MgCl_2$ bath*

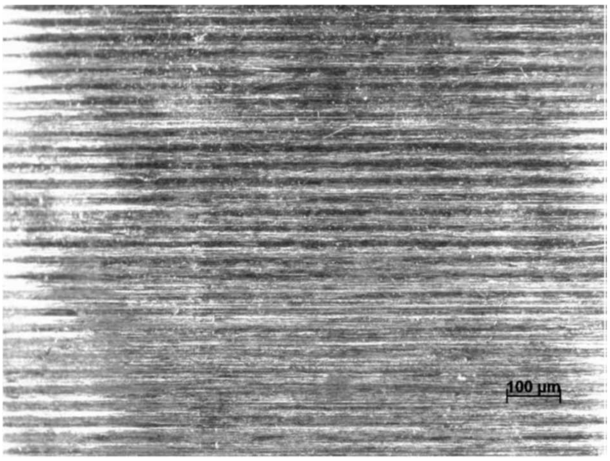


Fig. 9 *Sample B2 after 20 hours in a $MgCl_2$ bath*

The initial test found that the unreinforced LSP sample showed traces of corrosion cracking after 20 hours of exposure to the boiling $MgCl_2$ solution compared to the consolidated LSP sample, where no cracks were visible. To determine the time of the first occurrence of cracks on the surface of the material, another pair of samples A4 and B4 were tested. The samples were in a boiling bath of $MgCl_2$ for 24 hours and were removed from the solution every 3 hours during the ongoing experiment. to determine after which time of action of the corrosion solution $MgCl_2$ corrosion cracking cracks develop on the surface of the material. Subsequently, the surface was checked under a stereomicroscope and photo documentation was obtained. As the cracks of corrosion cracking appeared in the unconsolidated sample A4 after 3 hours of the action of the corrosion solution $MgCl_2$, the testing of the unconsolidated piece of pipe marked A was started. The objective of this was to find out after what time the corrosion cracks would develop on the surface of the sample pipe. The sample was placed in a boiling bath for another 10 minutes and then examined under a light microscope. These individual steps were repeated until the first cracks of corrosion cracking were detected. It was after 120 minutes of exposure in a boiling $MgCl_2$ bath. The test was not continued after this.

3 Evaluation of surface topography of samples

A scanning electron microscope from TESCAN was used to evaluate the surface structure of individual samples A2, B2, A4, B4 after exposure to $MgCl_2$ solution and to determine the structure of cracks caused by stress corrosion cracking. In figure 10 is sample A2, which was in a boiling bath of $MgCl_2$ for 20 hours. There is a clear view of the upper part of the unconsolidated sample, on which cracks of various sizes and widths are visible. A detailed picture of the cracks is shown in Fig. 11 and Fig. 12.

In contrast, no cracks are seen in the images of sample B2, which is a sample of a reinforced pipe exposed for 20 hours in a boiling $MgCl_2$ solution. See Fig. 13 and Fig. 14.

The following Fig. 15 shows the stress corrosion cracking cracks in the unconsolidated sample A4, after 3 hours in a boiling $MgCl_2$ bath. Figures 16 and 17 then show detailed images of these cracks.

In the case of the consolidated sample B4, which was in a boiling $MgCl_2$ solution for 24 hours and checked every 3 hours, no cracks are visible at 13x magnification. See Fig. 18. But at higher magnifications, cracks are visible, as can be seen in Fig 19 and in Fig. 20 is a detailed image of the crack.

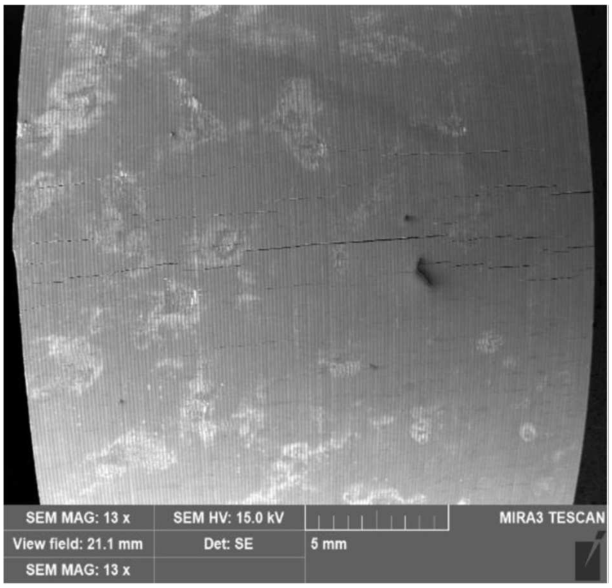


Fig. 10 *View of the upper part of the unengined sample A2 with visible cracks*

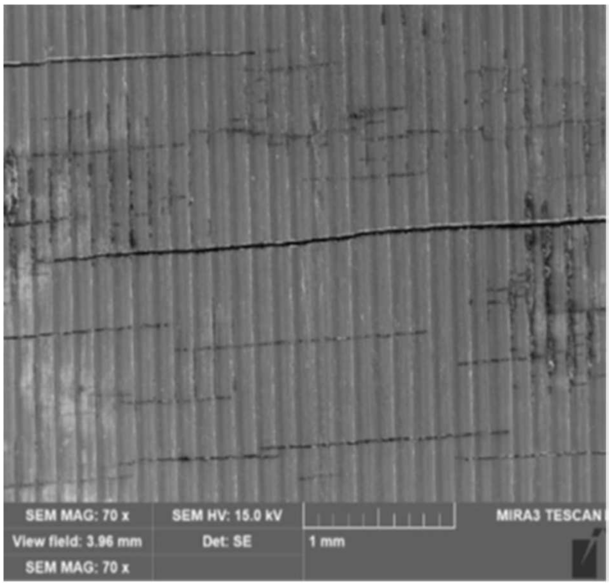


Fig. 11 *Detailed views of cracks in sample A2*

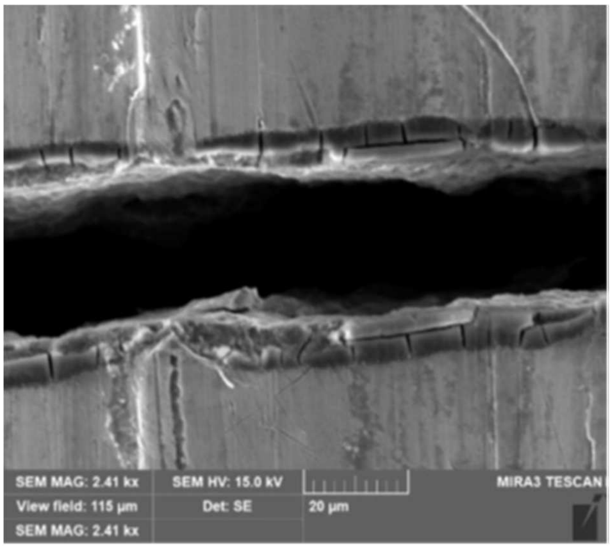


Fig. 12 *Detailed views of cracks in sample A2*

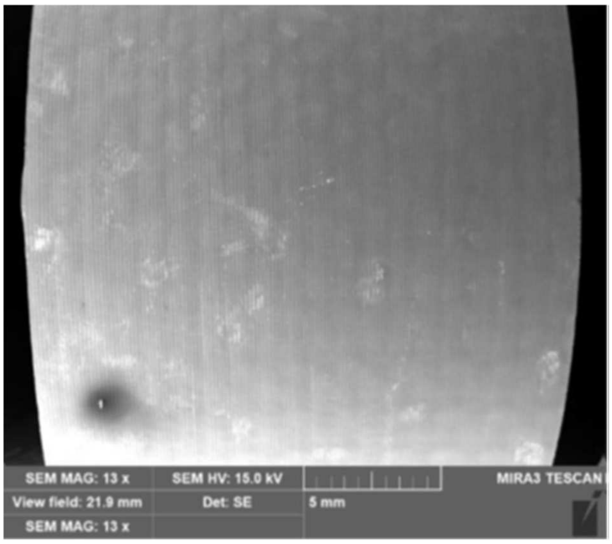


Fig. 13 *Detail of the view of the reinforced sample B2*

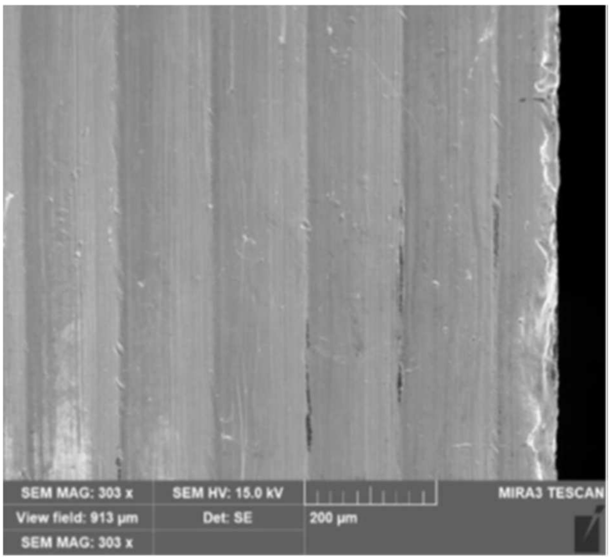


Fig. 14 *Detail of the view of the reinforced sample B2*

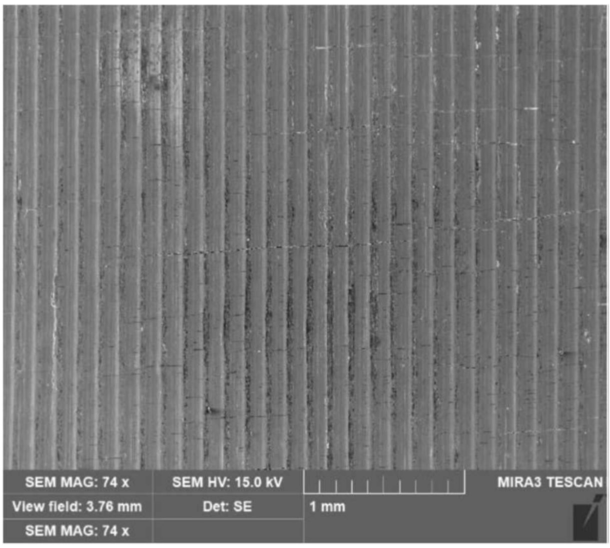


Fig. 15 *View of the upper part of a non-peening sample A4 with obvious cracks*

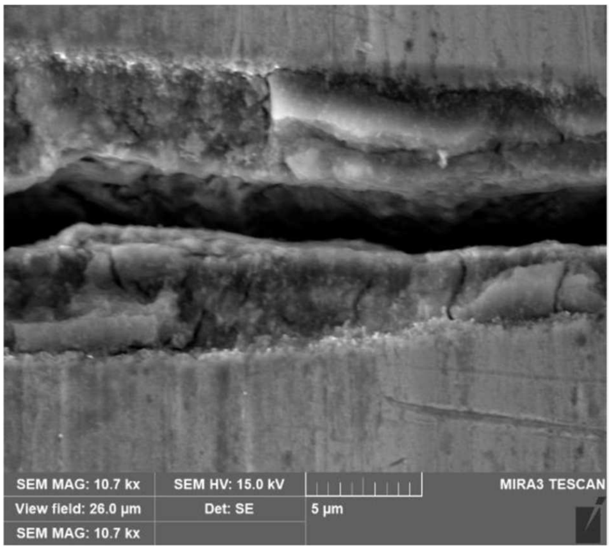


Fig. 16 *Detailed view of cracks in sample A4*

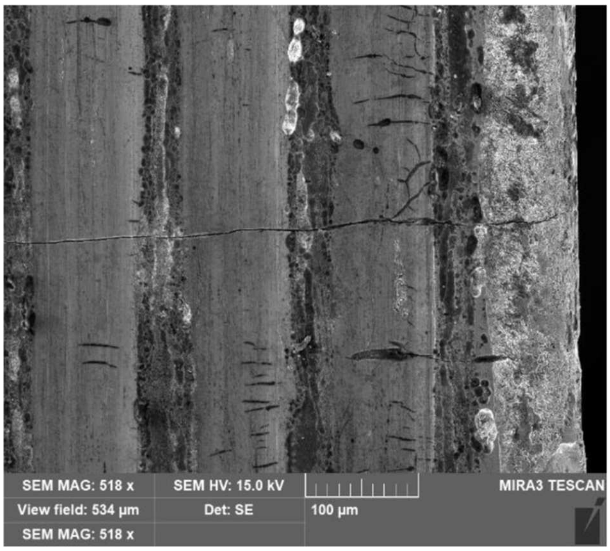


Fig. 17 *Detailed view of cracks in sample A4*

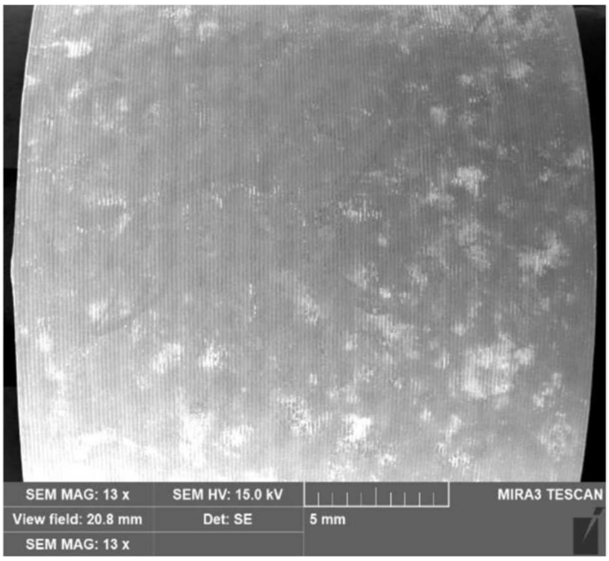


Fig. 18 *View of the upper part of the reinforced sample B4*

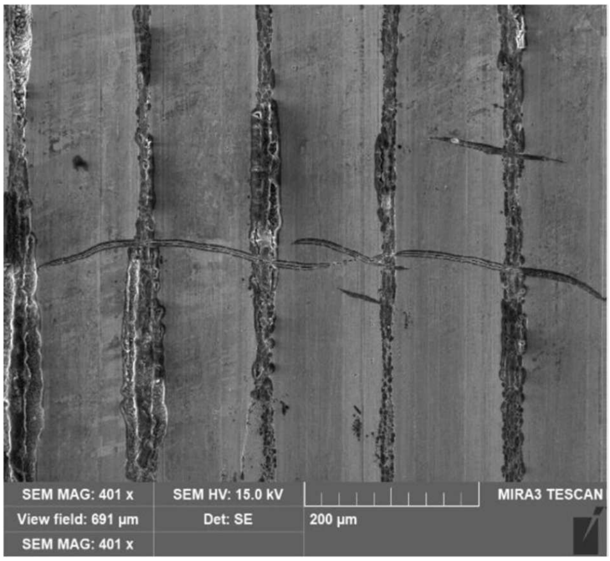


Fig. 19 *Detailed view of cracks in reinforced specimen B4*

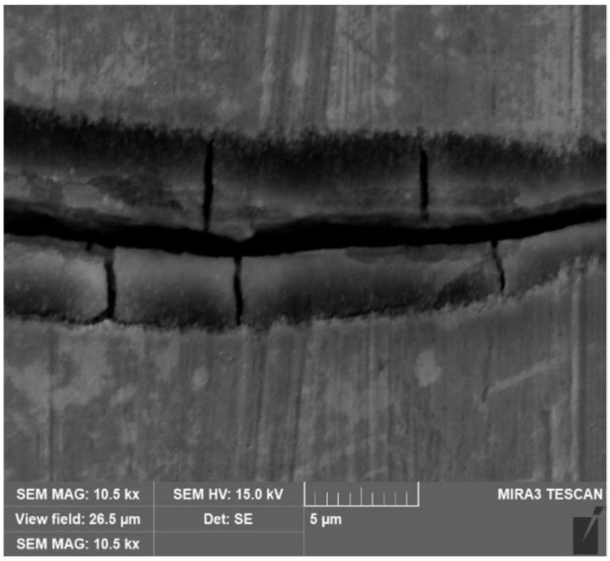


Fig. 20 *Detailed view of cracks in reinforced specimen B4*

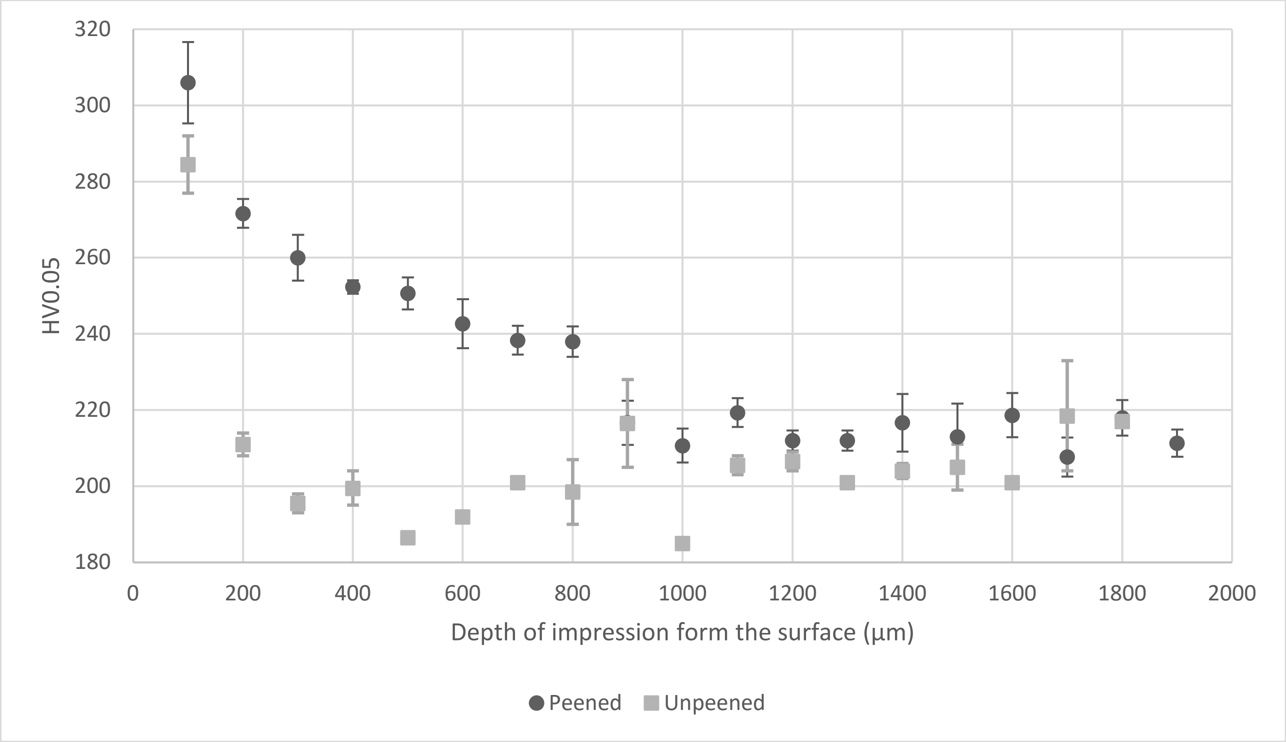
4 Microhardness measurement to the standard ČSN EN ISO 6507-1

The purpose of measuring microhardness was to verify the depth to which the material can be strengthened using LSP technology. Vickers microhardness was measured on a polished cut in the peened part using LSP technology and unpeened part. The reinforced part of the pipe is located in its center and the unpeened part is at the edges, The measurement was performed on a DuraScan microhardness tester. For measuring the course hardness for different parts of the pipe, the Vickers method was chosen, HV 0.05. In the area, which was strengthened by LSP technology, 3 series of measurements were performed. Each row counted 19 identical impressions at 0.1 mm intervals. Measurements were made at opposite points on the unpeened part of the tube, which counted 17 and 18 impressions of the identifier. These impressions were also 0.1 mm apart.

The following Graph 1 and Table 4 show the measured Vickers hardness values from peened and unpeeled pipe sections using LSP technology.

Tab. 4 *HV0.05 microhardness measuremtent results*

	Peened specimen				Unpeened specimen		
Depth of impression from the surface [mm]	**Series 1 HV 0.05**	**Series 2 HV 0.05**	**Series 3 HV 0.05**	**Average value**	**Series 4 HV 0.05**	**Series 5 HV 0.05**	**Average value**
0.1	307	321	290	**306±11**	292	277	**285±8**
0.2	274	275	266	**272±4**	208	214	**211±3**
0.3	265	251	264	**260±6**	198	193	**196±3**
0.4	251	251	255	**252±2**	204	195	**200±5**
0.5	248	247	257	**251±4**	186	187	**187±1**
0.6	233	245	250	**243±6**	192	192	**192±0**
0.7	244	235	236	**238±4**	200	202	**201±1**
0.8	243	232	239	**238±4**	207	190	**199±9**
0.9	208	218	224	**217±6**	228	205	**217±12**
1.0	204	214	214	**211±4**	184	186	**185±1**
1.1	215	218	225	**219±4**	203	208	**206±3**
1.2	209	211	216	**212±3**	209	204	**207±3**
1.3	210	210	216	**212±3**	201	201	**201±0**
1.4	210	212	228	**217±8**	202	206	**204±2**
1.5	203	226	210	**213±9**	199	211	**205±6**
1.6	210	220	226	**219±6**	202	200	**201±1**
1.7	200	210	213	**208±5**	233	204	**219±15**
1.8	225	218	211	**218±5**	217	-	**217±0**
1.9	206	214	214	**211±4**	-	-	



***Graph 1** Comparison of hardnesses peened and unpeened part of the pipe*

5 Conclusion

From the experiment it was found that cracks caused by corrosion cracking appeared in the unconsolidated sample after only 120 minutes in the boiling $MgCl_2$. After 24 hours, only small cracks appeared in the boiled sample in the boiling $MgCl_2$ solution, which were visible only by SEM microscopy. Another part of the ongoing experiments was the measurement of microhardness on a sample, the surface area of which was strengthened by LSP technology. This measurement provided information on how the surface hardness of the peened and unpeened specimens differed. From the performed measurements it was found that the strengthening of the material affects the surface of the material to a depth of about 1 mm. The results of the experiment show that the surface treatment of 08CH18N10T steel with LSP technology strengthens the surface due to the introduced residual compressive stresses. This steel then shows better resistance to stress corrosion cracking than unreinforced material.

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