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WELD JOINTS FATIGUE PROPERTIES OF THIN CARBON STEEL SHEET TREATED BY NITROOXIDATION

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Original scientific paper

Low carbon steel DC 01 (EN 10130-91) treated by the process of nitrooxidation significantly increased its mechanical properties as well as the resistance to atmospheric corrosion. The high increase was due to the presence of the surface nitridic and oxidic layers. Previous outcomes dealt with suggesting a suitable welding method for steel sheets treated in this way, the solid-state laser beam welding being marked as the most suitable. The aim of this paper was to determine the fatigue properties of laser beam welded joints of material treated by nitrooxidation. The fractographic analysis was carried out as well. The fatigue tests were carried out under bending load with frequency of 20 kHz and sinusoidal symmetric cycle. The results proved that the process of nitrooxidation had a great positive effect on the weld joints ultimate fatigue properties.

Keywords: *nitrooxidation, fatigue, S-N diagram*

Zamorna svojstva zavarenih spojeva tankog lima od ugljičnog čelika obrađenog nitrooksidacijom

Izvorni znanstveni članak

Nisko ugljični čelik DC 01 (EN 10130-91) obrađen postupkom nitrooksidacije značajno je povećao mehanička svojstva kao i otpornost na atmosfersku koroziju. To je povećanje nastalo zbog postojanja površinskih nitridnih i oksidnih slojeva. Do sada su predlagani odgovarajući postupci zavarivanja za tako obrađivane čelične limove, od kojih se zavarivanje čvrstog tijela laserskim snopom (solid-state laser beam welding) smatralo najpogodnijim. Cilj je ovoga rada bio odrediti zamorna svojstva laserom zavarenih spojeva materijala obrađenog nitrooksidacijom. Provedena je i fraktografska analiza. Ispitivanja na zamor su se provodila kod opterećenja pri savijanju s frekvencijom od 20 kHz i sinusoidalnim simetričnim ciklusom. Rezultati su dokazali da se postupkom nitrooksidacije značajno poboljšavaju zamorna svojstva zavarenih spojeva.

Ključne riječi: *nitrooksidacija, zamor, S-N dijagram*

1 Introduction

Nitrooxidation is a method of steel sheets surface treatment, which significantly increases their corrosion resistance together with the increase of mechanical properties [1, 2, 3]. It consists of surface nitridation with subsequent oxidation.

The fatigue degradation process and the initiation of fractures are in close connection with the surface, as well as the subsurface properties of a steel sheet. The priority of surface or subsurface fracture initiation with regard to the number of cycles is often discussed.

The previous research activity [4, 5, 6] dealt with the welding possibility as well as the forming properties of this type of treated steel sheets. Because of potential practical applications, further attention was focused on fatigue behaviour [7, 8, 9]. This paper deals with the comparison of fatigue behaviour of the steel sheet DC 01 EN 10130-9 treated by nitrooxidation to that of the identical sheet without treatment.

2 Materials and methods used for research

Experiments were carried out on a thin steel sheet DC 01/DIN EN 10130-9 of 1 mm in thickness. Chemical composition of the experimental sheet is shown in Tab. 1. The steel sheet was nitrooxidized in fluidized bed, which was performed in Kaliareň, PLC in Považská Bystrica. The nitridation fluid environment consisted of Al_2O_3 grains of 120 μm in diameter wafted by gaseous ammonia. After the nitridation, oxidation process started immediately. Oxidation itself was carried out in vapours of distilled water. Nitrooxidation parameters are presented in Tab. 2.

Experimental activity was carried out at the Faculty of Mechanical Engineering at the University of Žilina, Slovakia. As a testing device, the ultrasonic fatigue machine KAUP-ŽU (see Fig. 1), consisting of piezoceramic converter, booster, horn and ultrasonic generator was used. The fatigue experiments were carried out in condition of bending loads with frequency of 20 kHz. All specimens were tested to the failure point.

Specimens without treatment as well as specimens from a sheet treated by nitrooxidation were subsequently

Table 1 Chemical composition of steel DC 01, wt. %

C	Mn	P	S
max. 0,10	max. 0,45	max. 0,03	max. 0,03

Table 2 Parameters of nitrooxidation

Nitridation temperature / °C	Nitridation time / min	Oxidation temperature / °C	Oxidation time / min
540	45	380	5

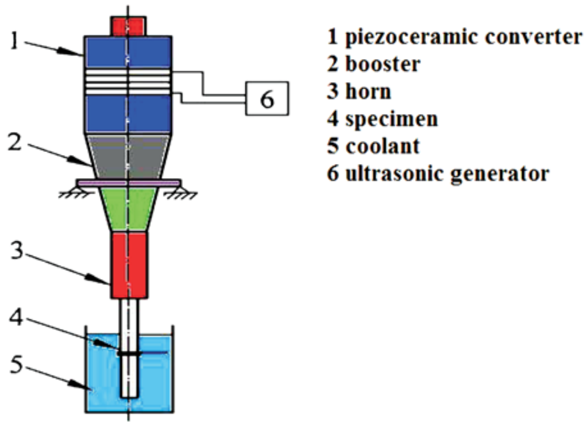

Figure 1 Scheme of KAUP-ŽU ultrasonic testing device

welded lengthwise as it is shown in Fig. 3 by TRUMF TruDisk 1001 laser according to the parameters provided in Tab. 3.

The shape and dimensions of the specimens (see Fig. 2) were designed in regard to the high-frequency load requirements. All tests were performed at the room temperature (20 °C). To keep constant temperature during the fatigue tests the water cooling was used.

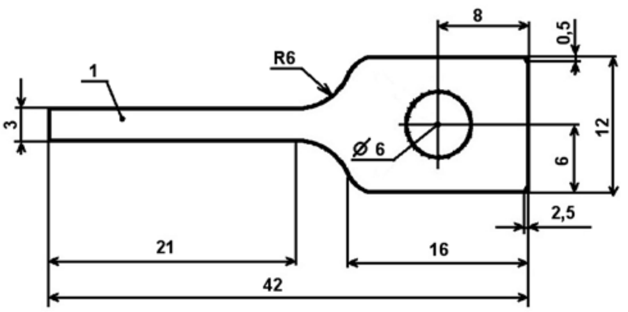

Figure 2 The shape and dimensions of a fatigue test specimen

The analysis of the fatigue fracture character was done by the fractographic analysis of the fracture surfaces of broken specimens.

Specimens in basic state as well as specimens treated by nitrooxidation were subsequently welded lengthwise as it is shown in Fig. 3 by TRUMF TruDisk 1001 laser according to the parameters provided in Tab. 3.

Table 3 Parameters of welding process

	Specimens treated by nitrooxidation	Non-treated specimens
Focus	On surface	On surface
Mode	Continual	Continual
Wavelength / μm	1,06	1,06
Power / W	740	770
Focal length /mm	140	140
Spot size	420	420
Welding speed /mm/s	20	20
Welding time / ms	3000	3000
Energy / J	2166	2268
Specific heat input / J/mm	34,29	27,21
Frequency / Hz	0,01	0,01
Shielding gas	Ar	Ar
Gas flow / l/min	10	7

Figure 3 A test specimen

The differences in parameters of welding result from the physical properties of the surface layer as it is darker with sheet-surface in comparison to non-treated sheet. The laser beam efficiency was confirmed in previous research by measuring the reflection from both surfaces. The results of this test are shown in Tab. 4.

Table 4 Laser beam efficiency

	Laser efficiency / %
Sheet in basic state	95
Sheet treated by nitrooxidation	72

The macrostructure of the specimens made from sheet treated by nitrooxidation (Fig. 4) did not show any abnormalities in weld shape nor any defects. The weld metal width on the surface was approx. 1,2 mm and approx. 0,6 mm in the root part of the weld. In case of the welding non-treated specimens, the size of weld metal was approx. 20 % bigger.

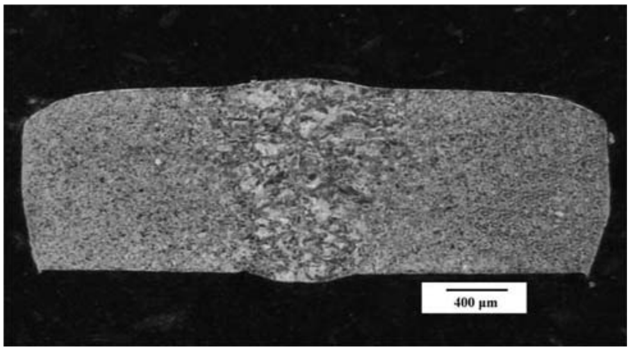

Figure 4 Welded joint macrostructure of specimen treated by nitrooxidation

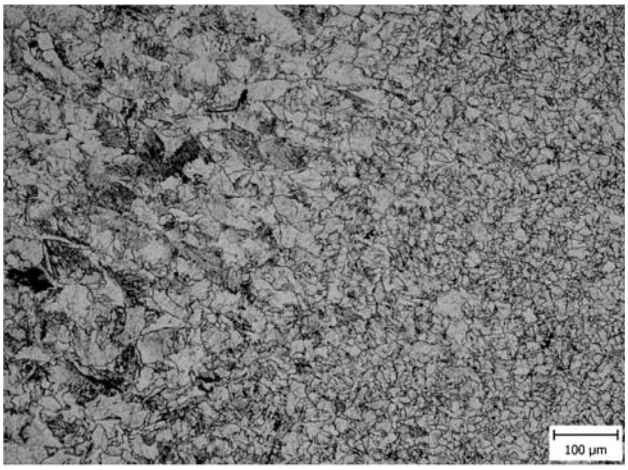

Figure 5 Microstructure of WM-HAZ of specimen from non-treated sheet

Figure 6 Microstructure of weld metal of specimen from non-treated sheet

The weld metal microstructure of the non-treated specimens was formed mainly by acicular and polygonal

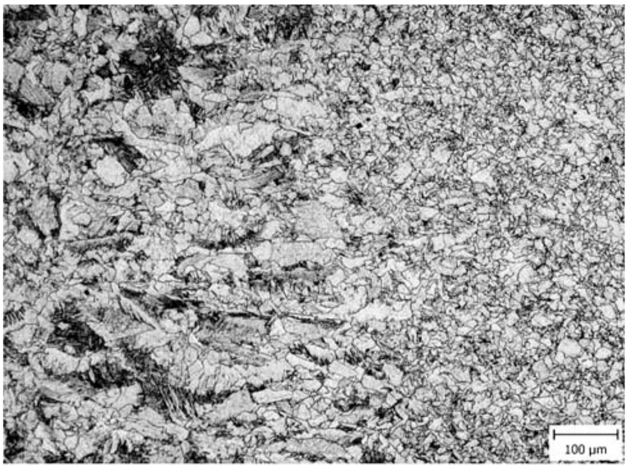

Figure 7 Microstructure of WM-HAZ of specimen from sheet treated by nitrooxidation

Figure 8 Microstructure of weld metal of specimen from sheet treated by nitrooxidation

ferrite with the occasional presence of upper bainite (Fig. 5). The heat affected zone was mainly formed by polygonal ferrite with the occasional presence of acicular ferrite (Fig. 6).

The microstructure containing polygonal and acicular ferrite as well as a small amount of upper bainite was observed in weld metal of specimens treated by nitrooxidation (Fig. 7). The microstructure was very similar to that of the non-treated specimens meaning that the heat affected zone was formed by the polygonal ferrite with the occasional presence of acicular ferrite (Fig. 8). The presence of particular phases was confirmed by microhardness measurement.

3 Results and achievements

The results of high-frequency fatigue tests, presented in the form of S-N diagram, are shown in Fig. 9 ÷ Fig. 12. The measurements were performed in the interval of the stress amplitude $\sigma_a = 260 \div 80$ MPa, which represented the $N_f \approx 8 \times 10^5$ to $N \approx 2 \times 10^8$ cycles to failure. The fatigue characteristics of tested sheet before and after the process of nitrooxidation are compared in the graph. Conventional fatigue limit stated at $N \approx 2 \times 10^8$ is provided in Tab. 5.

In case of both series of specimens, a continuous decrease of fatigue life from high-cycle fatigue to ultra-high-cycle fatigue was observed. The fatigue life of the sheet without treatment was significantly lower in comparison to the sheet treated by nitrooxidation.

The results of fractographic analysis showed that in the sheet without treatment fracture propagation was observed from both upper and bottom steel sheet sides (Fig. 13). The transcrystalline character of the fracture was observed. Compared to that, the fracture initiation and propagation in

Table 5 Measured fatigue strength as the dependence on surface treatment

Specimen, $N = 10^8$ cycles	σ_c /MPa
Without treatment	90
Treated by nitrooxidation	160
Without treatment/welded	70
Treated by nitrooxidation /welded	100

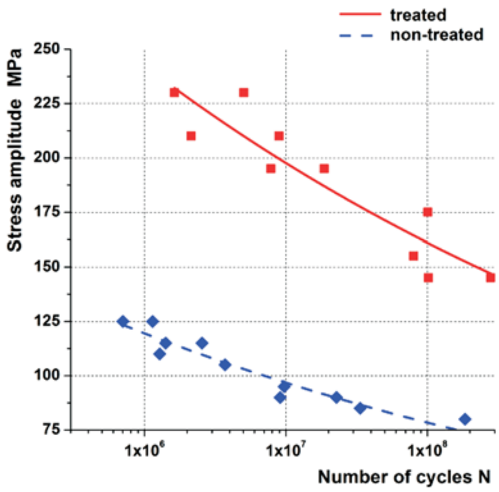

Figure 9 The S-N curves of non-treated sheet and sheet treated by nitrooxidation

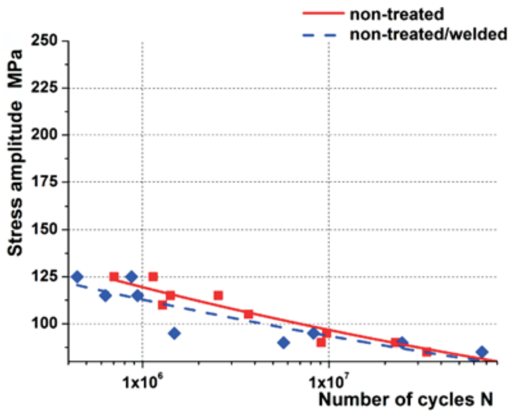

Figure 10 The S-N curves of non-treated and non-treated welded sheets

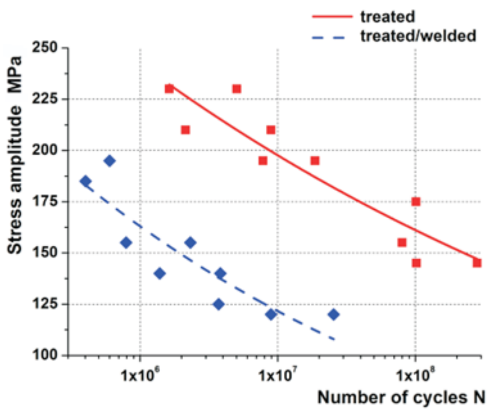

Figure 11 The S-N curves of welded and non-welded sheets treated by nitrooxidation

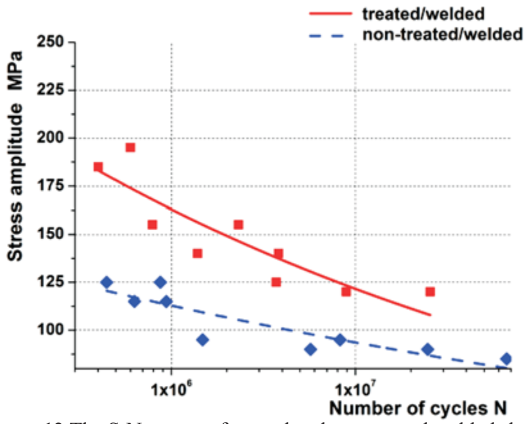

Figure 12 The S-N curves of treated and non-treated welded sheets

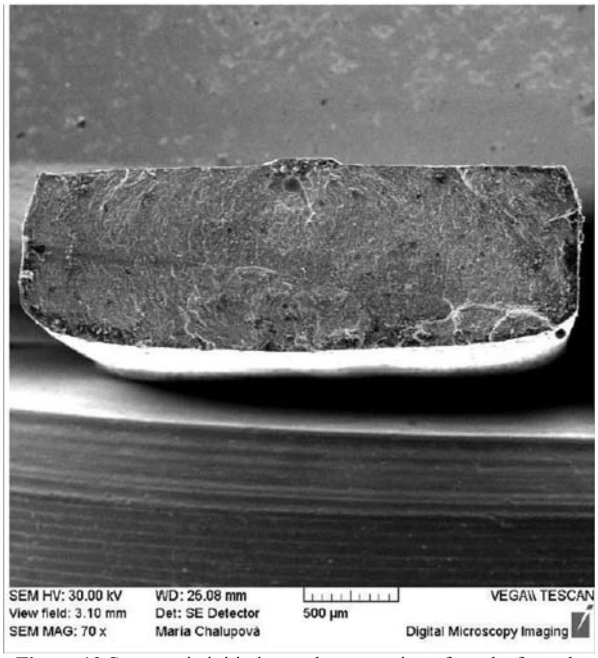

Figure 13 Symmetric initiation and propagation of cracks from the upper and the bottom side of sheet. Welded specimen without treatment.

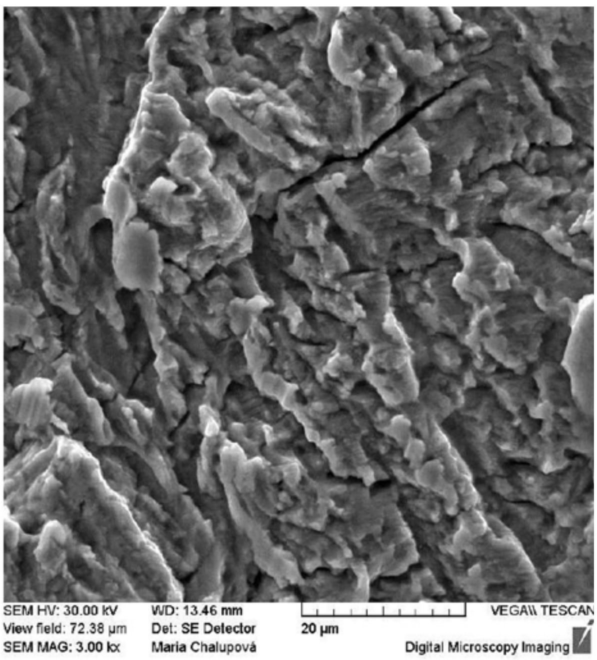

Figure 14 A close-up of transcrystalline fatigue fracture in the area of stabile fatigue crack propagation of fatigue crack through the cross-section. Welded specimen without treatment.

the case of the sheet treated by nitrooxidation was mostly multiple. There were sporadically observed pores in weld metal. The presence of pores can be explained by the surface layer deterioration during the laser beam welding process resulting in the generation of gaseous products.

The pores due to their round shape did not manifest dangerous notch effect and the crack propagation was observed from the corner sides of the steel sheet (Fig. 14). Therefore it is possible that the deterioration of the surface layer in the specimen preparation process could affect the fatigue life properties as well. Despite this, the fatigue life of weld joints of the specimens from treated sheet was approximately 43 % higher than nontreated ones (Fig. 12).

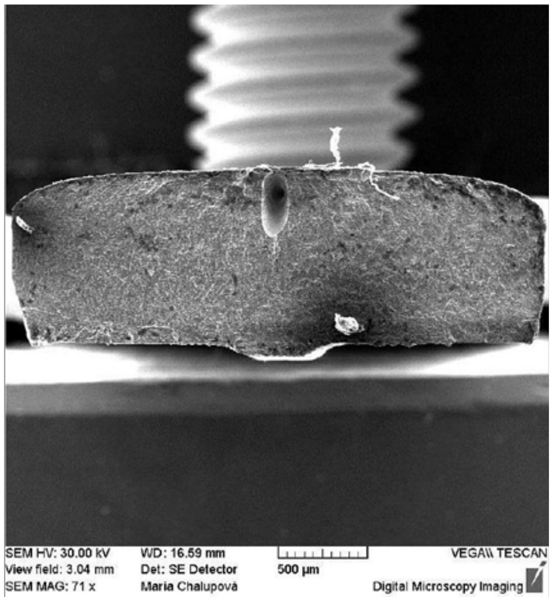

Figure 15 A macroscopic view of fatigue fracture with the presence of pores. Welded specimen with previous nitrooxidation treatment.

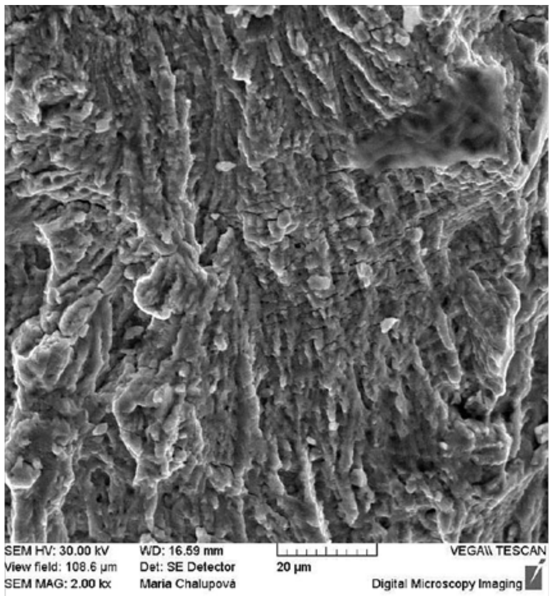

Figure 16 Transcrystalline fatigue fracture with the presence of striation fields. Welded specimen with previous nitrooxidation treatment.

The SEM macroscopic view of weld joint of treated sheet with the presence of pores is shown in Fig. 15. Fig. 16 represents the close-up of transcrystalline fatigue fracture with the presence of striation fields. This type of fatigue fracture mechanism was typical in the case of specimens treated by nitrooxidation and consequently welded sheet.

4 Conclusion

Based on the results, it can be stated that the process of nitrooxidation has a positive influence on fatigue life of the thin steel sheets. The fatigue strength of the sheet treated by nitrooxidation was two times higher in comparison to the sheet without treatment. Based on the fractographic analysis, it can be concluded that the nitrooxidic layer particularly prolonged the fatigue initiation period and therefore the overall fatigue life of this type of treated steel sheets was extended as well.

The influence of nitrooxidation in regard to fatigue life of weld joints was not as significant as the influence of nitrooxidation of non-welded specimens. A possible reason could be in the weld metal porosity making the weld cross-section area smaller. However the fatigue life of weld joints of specimens treated by nitrooxidation was higher than the fatigue life of welded specimens without treatment. One of the possible ways to increase the fatigue life of weld joints is the optimization of welding parameters leading to pore-free welds.

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