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Microstructure and texture welds of 15-7Mo steel after heat treatment

Mikrostruktura i tekstura spoin stali 15-7Mo po obróbce cieplnej

Abstract
This paper presents the results of determining the effect of heat treatment after welding X8CrNiMoAl15-7-2 steel (commercial name: PH 15-7Mo steel) on the microstructure and texture of the welds. XRD studies showed the presence of the two phases in the welds of 15-7Mo steel; i.e., δ ferrite and austenite. Annealing at a temperature of 400°C/1 h and 550°C/1 h results in changes of the intensities for individual peaks derived from austenite and ferrite. Microstructure investigations carried out by LM and TEM indicated that the austenite and δ ferrite coexist in the microstructure of 15-7Mo steel in as-welded condition. Annealing at a temperature range of between 400–620°C after welding causes small changes in the microstructure. The hardness of the welds after annealing in that temperature range increases.

Keywords: semi-austenitic PH steels, XRD, welds, heat treatment, 15-7Mo steel

Streszczenie
W artykule zostały zaprezentowane wyniki badań wpływu obróbki cieplnej po spawaniu stali X8CrNiMoAl15-7-2 (nazwa handlowa: PH 15-7Mo) na mikrostrukturę i teksturę spoin. Badania XRD wykazały obecność dwóch faz w spoinach stali 15-7Mo, tj. ferrytu δ i austenitu. Wyżarzanie w temperaturach 400°C przez 1 h i 550°C przez 1 h powoduje zmiany intensywności poszczególnych pików pochodzących od austenitu i ferrytu. Badania mikrostrukturalne (mikroskopia świetlna i transmisyjna mikroskopia elektronowa) potwierdziły obecność ferrytu δ i austenitu w stali 15-7Mo w stanie po spawaniu. Wyżarzanie po spawaniu w temperaturach pomiędzy 400°C a 620°C powoduje małe zmiany w mikrostrukturze. Twardość spoin po wyżarzaniu w zakresie tych temperatur wzrasta.

Słowa kluczowe: stale półaustenityczne umacniane wydzieleniowo, XRD, spoiny, obróbka cieplna, stal 15-7Mo

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1. Introduction

PH 15-7Mo is a semi-austenitic precipitation-hardening stainless steel that provides high strength and hardness, good corrosion resistance, and minimum distortion upon heat treatment. It is easily formed in the annealed condition and develops an effective balance of properties by simple heat treatments. For applications requiring exceptionally high strength, PH 15-7Mo Stainless Steel in cold rolled delivery conditions (which is later aged) is particularly useful for applications allowing for limited ductility and workability. In its heat-treated condition, this alloy provides excellent mechanical properties at temperatures of up to 482°C. Its corrosion resistance is superior to that of the hardenable chromium types. In some environments, corrosion resistance approximates that of austenitic chromium-nickel stainless steels [1].

Although these steels have been used for a long time, studies are still being carried out regarding the optimal parameters of their heat treatment [2]. Most studied have focused on the influence of heat treatment on the microstructure or properties of the base material [3]. There are only a few works concerning the microstructure of the welded joints of semi-austenitic PH steels [4, 5]. Semi-austenitic steels are considered to be weldable, although their weldability is slightly worse than martensitic PH steels. The precipitation-hardening class of stainless steels is generally considered to be weldable by common welding techniques. Special consideration is required to achieve optimum mechanical properties by considering the best heat-treated conditions in which to weld and which heat treatments should follow the welding. This particular alloy is generally considered to have poorer weldability compared to the most common alloys of this stainless class (e.g., 17-4PH stainless steel). A major difference is the high Al content of this alloy, which degrades penetration and enhances weld slag formation during arc welding. Also, the austenite conditioning and precipitation hardening heat treatments are both required after welding to achieve high strength levels [1, 6–8].

Thus, it is especially important to choose the appropriate parameters of heat treatment in order to achieve optimal microstructure and, owing to this, the best combination of material plastic and mechanical properties. The aim of the present work was to study the influence of heat treatment after welding on the microstructure and texture of 15-7Mo welds.

2. Experimental

The investigations were carried out on sheets of 15-7Mo commercial steel (the chemical composition of the steel is given in Table 1). The thickness of the sheets was 2.5 mm.

The sheets were cut into smaller pieces, and autogenous welding by GTAW was made using the following parameters: welding current – 35 A; arc voltage – 12 V; and welding speed – 1.5 mm/s. After this processing, the welded joints were cut into samples with the dimensions of 20 × 40 × 2.5 mm. The samples was aged within a temperature range of 400–620°C for one hour. Argon was used as a shielding gas.

Table 1. Chemical composition of 15-7 Mo (X8CrNiMoAl15-7-2) steel

Chemical composition [wt.%]								
C	**Mn**	**P**	**S**	**Si**	**Cr**	**Ni**	**Mo**	**Al**
0.09 max.	1.00 max.	0.04 max.	0.03 max.	1.00 max.	14–16	6.5–7.75	2–3	0.75–1.5

The X-ray diffraction study was made on selected samples after welding and annealing at 400°C and 550°C. The HZG4 diffractometer equipped with a Co lamp ($\lambda_{K\alpha}$ = 1,79Å) was used. The diffraction pattern was obtained using the Bragg–Brentano method and step-counting ($\Delta 2\theta = 0.02°$; time per step – $\tau = 5$ s) within a range of a 2θ angle from 40° to 80°. The texture measurements were carried out using cobalt lamp radiation ($\lambda_{K\alpha}$ = 1.79 Å), the diffractometric Schulz reflection method, and a D8 Advance Bruker diffractometer equipped with a Eulerian cradle. The pole figures of {111} and {200} for austenite and {110} and {200} for ferrite were recorded, and then the orientation distribution function (ODF) was calculated [9].

In order to observe the changes in hardness for the different variants of heat treatment, the Vickers hardness measurements were carried out using an HPO-250-type durometer. The hardness measurements were performed on a cross-section of the welded joint. The applied load was 98.07 N.

Examinations of the microstructure of the steel welds was carried out using a Leica DMLM light microscope. The samples were electro-polished and etched in a 10% aqueous solution of CrO_3. Thin films for TEM were prepared by slicing, grinding, and ion milling. The observations were performed on a JEOL 200CX transmission electron microscope.

3. Results and discussion

X-ray diffraction studies showed the presence of austenite and delta ferrite in the steel microstructure of the 15-7Mo weld in the as-welded state (Fig. 1).

The strongest diffraction peak is 200_{δ}, next to which there is a relatively strong peak (200_{γ}). Annealing at 400°C does not cause significant changes. Further annealing at 550°C reduces the peak intensity of the 110 line derived from the ferrite. The $111_{\gamma}/200_{\gamma}$ intensity ratio for the austenite and $110_{\delta}/200_{\delta}$ intensity ratio for the ferrite were calculated and compared to the intensities of the standard sample. The results are shown in Table 2. The differences in intensities between the theoretical and experimental values indicated a stronger texturing of the material.

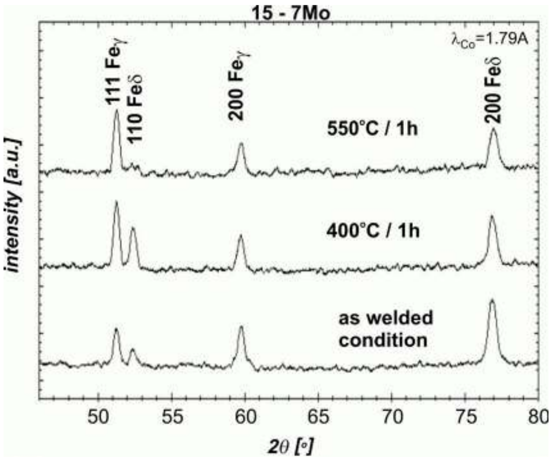

Fig. 1. XRD patterns for welds of 15-7Mo steel

Table 2. Intensity ratios of XRD peaks for 15-7 Mo (X8CrNiMoAl15-7-2) steel

Heat treatment	$I_{\gamma111}/I_{\gamma200}$	$I_{\delta110}/I_{\delta200}$
Reference sample	2	5
As-welded condition	0.4	0.3
400°C/1 h	1.7	0.7
550°C/1 h	1.7	0.2

The orientation distribution functions (ODF) for the ferrite and austenite of the 15-7Mo steel weld are shown in Figure 2. The strongest component of ferrite for the as-welded state is the twisted cubic {001} <110> component, which is a part of the α_1 fiber. However, no cubic {001} <100> orientation is observed. Annealing at 400°C/1 h resulted in a large increase in the intensity of the ferrite texture, a shift of the maximum intensity to the {115} <110> orientation, the reinforcement of the fiber α_1 component, and the appearance of the cubic {001} <100> orientation. Annealing at 550°C/1 h resulted in a slight decrease in the ferrite texture as compared to the sample annealed at 400°C/1 h.

For the as-welded 15-7Mo stainless steel, the texture of the austenite has a strong η fiber component with a maximum close to {012} <100>. There is also a strong Goss component, and no {110} <112> component is observed. There are strong orientations of the τ fiber {113} <332> and Cu-type {112} <111> orientation. Annealing at 400°C/1 h resulted in lengthening and strengthening the α fiber as well as the appearance of a relatively strong {110} <112>-type component. A higher annealing temperature (550°C/1 h) will further strengthen the α fiber constituent. The maximum intensity corresponds to the Goss {110} <001> orientation. The fiber τ {112} <111> and {113} <332> orientations were weaker.

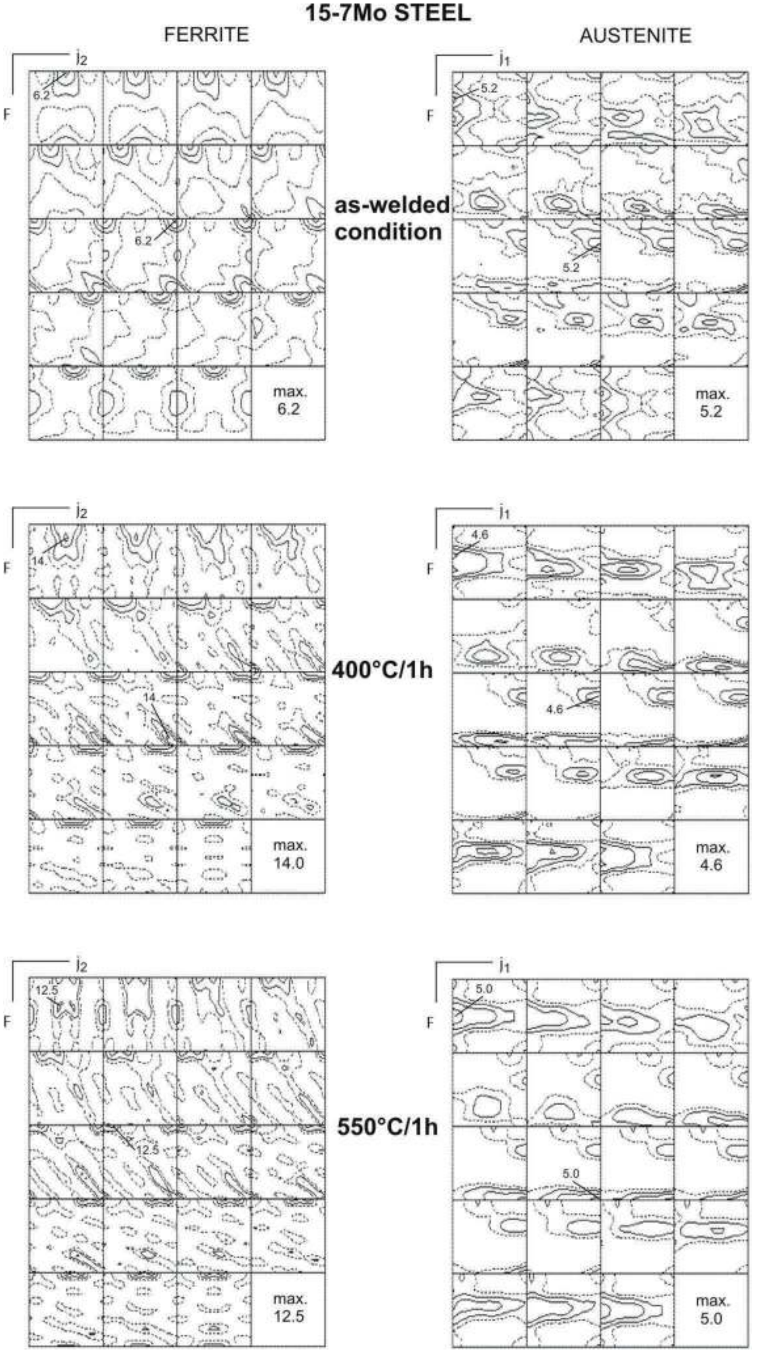

Fig. 2. Orientation distribution functions in sections φ_1=const for δ-phase and in sections φ_2= const for γ-phase in as-welded condition and after heat treatment for welds of 15-7Mo steel

The sample of as-welded 15-7Mo steel has a hardness of 240 HV10. During annealing within a temperature range of 400–620°C, a continuous increase of 475 HV10 in the hardness is observed (Fig. 3).

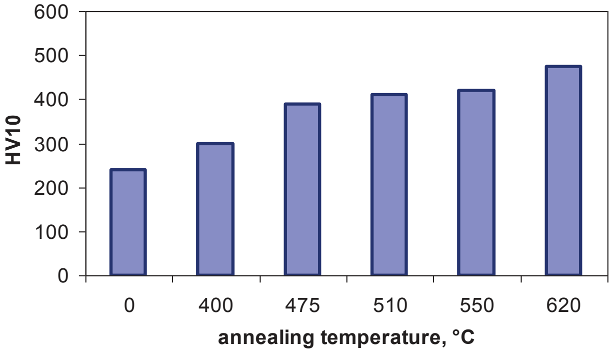

Fig. 3. Hardness of welds vs. annealing temperature for 15-7Mo steel

a) b)

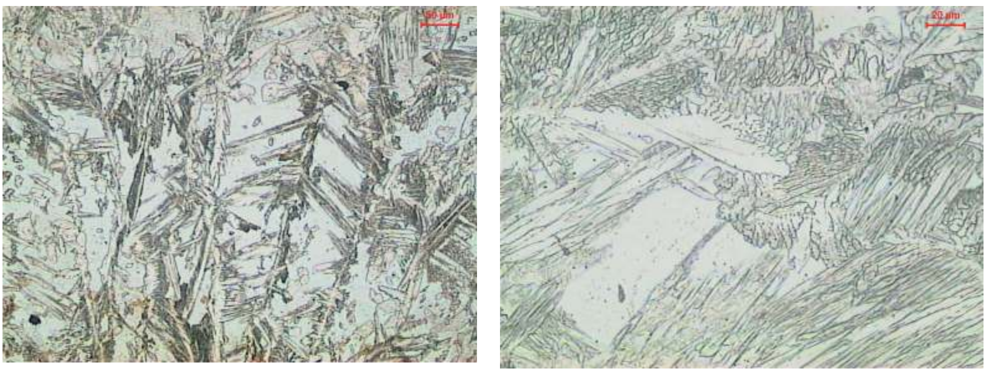

Fig. 4. LM microstructures of welds of 15-7Mo steel: a) in as-welded condition; b) welding and subsequent annealing at 550°C/1 h

The LM and TEM observations confirmed that the as-welded 15-7Mo steel microstructure consists of austenite and delta ferrite (Fig. 4a). The morphology of this ferrite is mostly skeletal and lath-like. There are also certain areas of blocky ferrite. Heat treatment at temperatures between 400–620°C did not significantly change the appearance of the microstructures when observed under a light microscope. Figure 4b shows an exemplary appearance of the as-welded microstructure after annealing at 550°C. There are ferrite, austenite, and carbide precipitations in the microstructure. Carbide precipitation is observed by TEM (Fig. 5); however, they could not be identified by electron diffraction due to their high dispersion.

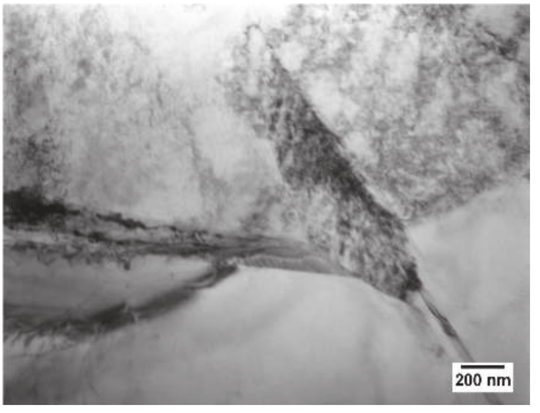

Fig. 5. TEM microstructures of welds of 15-7Mo steel. Fine carbide precipitates on δ/γ boundary and between δ subgrains

4. Summary

The microstructure of the 15-7Mo steel in as-welded condition was composed of austenite and ferrite δ. An analysis of the 15-7Mo steel welds indicates that δ ferrite occurring in the welds has a lathy and skeletal morphology. There are also some areas of blocky ferrite. After heat treatment at temperatures within a range of 400–620°C, the microstructure of the weld is not significantly changed. There is austenite, ferrite, and carbide precipitation in the microstructure. The ferrite phase predominated in the texture of the 15-7Mo steel in as-welded condition. After annealing, the ferrite texture is stronger than the fibrous austenite texture for the welds of the studied steel. After welding and aging within a temperature range of 400–620°C, the 15-7Mo steel exhibited an increase of 475 HV10 in the hardness.

Acknowledgements

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