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Research on the Assessment of Selected Austenitic Stainless Steels Hot Crack Susceptibility

Abstract: The article presents the results concerning hot crack susceptibility of selected steels having an austenitic structure. The tests were based on the analysis of the chemical composition of these steels and utilising special stations for the Transvarestraint tests and the Blanchet method. During the tests it was possible to observe cracks in the liquid-solid area. The results obtained indicate the existence of an area free from solidification cracks for a certain strain value at a pre-set welding rate. It was also possible to observe the absence of a distinct boundary between such areas, which was reflected in the crack length.

Keywords: hot crack susceptibility, austenitic steel, Transvarestraint tests, Blanchet method,

Introduction

Operational requirements for equipment used at a higher temperature and corrosive environment have tasked engineer-constructors and technologists with selecting engineering materials characterised by high mechanical properties. Such requirements are satisfied by, among others, austenitic steels and nickel-based alloys making these materials particularly popular in the aviation, space, chemical and power industries [1÷4] due to their unique properties such as high strength and creep resistance at high temperatures (even up to 1100°C) and corrosion resistance in aggressive environments [4, 5]. However, it has proved problematic to select an appropriate welding technology from a metallurgical point of view. Welding consumables available on the market enable making welded joints, yet the metallurgical properties of welds during solidification are not entirely known. The formation of cracks during welding of both thin and thick elements has necessitated the assessment of hot crack susceptibility of selected chromium-nickel steels.

In order to test the hot crack susceptibility of selected austenitic steels it was necessary to develop a test programme including the following:
– chemical composition assessment utilising spark spectrometry,
– assessment of microstructure using light microscopy,
– hot crack susceptibility assessment of thick sheets in the Transvarestraint test,
– hot crack susceptibility assessment of thin sheets in the Blanchet test.

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Test Materials

The tests involved the use of 1, 3 and 5 mm thick AISI/ASTM 304 (X5CrNi18-10, 1.4301 according to EN 10088) and 314 (X6CrNi25-20, 1.4842 according to EN 10088) austenitic steels of chemical compositions presented in Table 1. These steels have an austenitic structure (Fig. 1) and are characterised by good anticorrosive properties due to high contents of chromium (min. 16% by weight) and nickel (min. 6% by weight). The microstructure of these steels, particularly after welding, can also contain ferrite δ. An excessively high ferrite delta content, i.e. above 10%, can reduce ductility or corrosion resistance, whereas overly low ferrite δ content, i.e. below 5%, increases hot crack susceptibility of steels during welding [6].

Table 1. Results of chemical composition analysis of X5CrNi18-10 (304) and X6CrNi25-20 (314) (% by weight) performed using a spark spectrometer.

Alloying element	Steel 304	Steel 314
Fe	71.1	53
C	0.0507	0.0957
Si	0.432	1.89
Mn	1.39	1.47
P	0.0282	0.0254
S	<0.005	<0.005
Cr	17.6	23.1
Mo	0.189	0.191
Ni	8.68	19.3
Al	0.0372	0.068
Co	0.0532	0.339
Cu	0.148	0.165
Nb	0.0166	0.0407
Ti	0.0035	0.0602
V	0.114	0.103
W	<0.02	0.0396

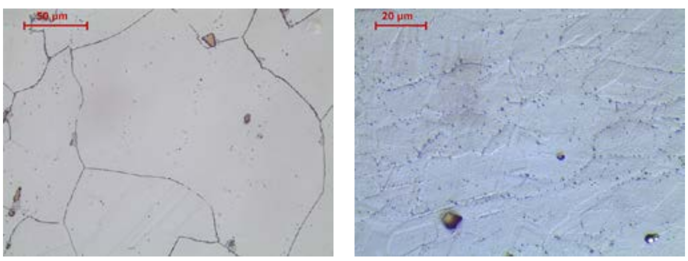

Fig. 1. Austenitic structure of 304 (a) and 314 (b) steels

Hot Crack Susceptibility Assessment

The solidification crack susceptibility of austenitic steels is assessed on the basis of their **chemical composition** presented in Table 1. The theoretical analysis of crack susceptibility involves the determination of a chromium – nickel equivalent ratio on the basis of the formula (1) as well as the determination of phosphorus and sulphur contents.

$$\frac{R_{Cr}}{R_{Ni}} = \frac{Cr + Mo + 0{,}7Nb}{Ni + 35C + 2N + 0{,}25Cu} \tag{1}$$

where R_{Cr} – chromium equivalent; R_{Ni} – nickel equivalent; Cr, Mo, Nb… – mass content of the alloying elements in the weld.

Austenitic steels tend to develop solidification cracks for $R_{Cr}/R_{Ni} \leq 1.5$ and resistance for $R_{Cr}/R_{Ni} > 1.5$. Another important solidification crack resistance indicator is the content of phosphorus, sulphur (P and S) and ferrite δ (defined by a ferrite number (FN)) in the weld. Hot crack resistance criteria are the following:

- (P+S) ≤ 0.02% and an austenitic structure,
- (P+S) ≤ 0.03% and FN ≥ 4,
- (P+S) ≤ 0.04% and FN ≥ 8,
- (P+S) ≤ 0.05% and FN ≥ 12.

The values of chromium and nickel equivalents along with their ratio as well as phosphorus and sulphur contents are presented in Table 2.

The values of chromium and nickel equivalents indicate that the welds of 304 and 314 steels tested are characterised by an austenitic structure with a lattice of ferrite δ precipitates on the boundaries. Because of relatively low phosphorus and sulphur contents, as well as due to a high ferrite number and $R_{Cr}/R_{Ni} > 1.5$, 304 steel should not reveal hot crack susceptibility. It is expected that 314 steel will be susceptible to solidification cracking.

The Transvarestraint test consisted in setting a variable strain by using matrix blocks of various rounding radiuses. During welding, a specimen undergoes a significant strain the size of which in the area of extreme fibres depends on the specimen thickness and the matrix block rounding radius and is determined from a simplified formula (2):

$$\varepsilon = \frac{g}{2R} \qquad (2)$$

where ε – strain, g – specimen thickness [mm], R – radius of matrix block upper plane curvature [mm].

The strain set is thus a parameter independent of welding process parameters, chemical composition and other quantities affecting the microstructure of a joint or of an overlay weld. While setting a strain it is possible to observe cracks formed in the overlay weld or in the partially melted zone of the parent metal. The direction of the cracks is usually perpendicular to the weld axis. The scheme of the Transvarestraint test is presented in Figure 2.

The assessment of the technological metal strength is based on three criteria:

1. minimum strain necessary for triggering a crack, so-called crack threshold,
2. total length of all cracks,
3. maximum crack length.

The tests involved sheets having thicknesses of 1, 3 and 5 mm and being 40 and 60 mm in width. The results obtained indicate the crack formation in the liquid-solid (L+S) zone with a solidifying weld pool. In consequence, the results concerning the longest crack are very similar irrespective of the matrix block rounding radius. The examples of fusion faces are presented in Figures 3 and 4.

Table 2. Value of chromium and nickel equivalents and the content of ferrite measured using a ferrite meter (magnetic phase volume)

Steel grade	R_{Cr}	R_{Ni}	R_{Cr}/R_{Ni}	P+S	% of ferrite	According to Schaeffler diagram
304	17.80	10.49	1.70	0.033	0.5-2.7	up to approx. 3%
314	23.32	22.69	1.03	0.030	0.1-0.2	0%

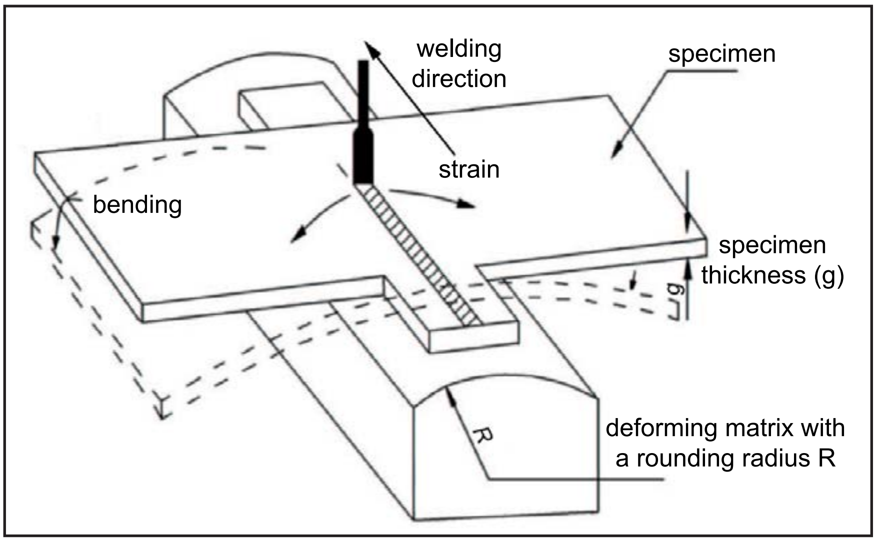

Fig. 2. Scheme of hot crack susceptibility assessment using the Transvarestraint method

Fig. 3. 5 mm thick 304 (155) steel, bend radius of 135 mm. Fusion face. Cracks in the L+S zone. The longest crack of 1 mm, LM, mag. 10x,

Fig. 4. 3 mm thick 314 (335) steel, bend radius of 135 mm. Fusion face. Cracks in the L+S zone. The longest crack of 2 mm, LM, mag. 10x

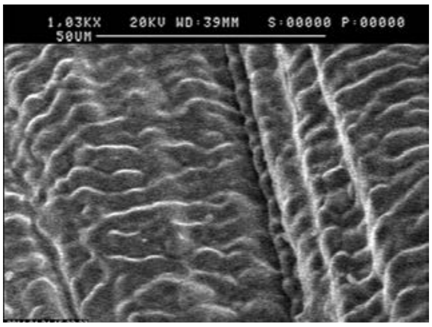

Fig. 5. Hot crack in 304 steel after fracturing the specimen. The crack surface with parallel arranged dendrites, the free surface of a crack. SEM image

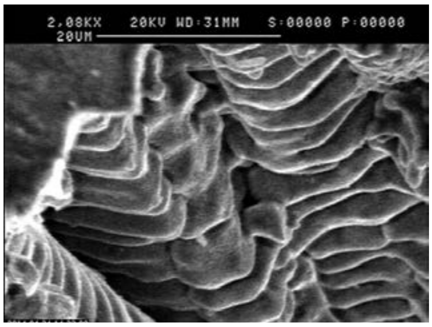

Fig. 6. Hot crack in 314 steel after fracturing the specimen. The crack surface with parallel arranged dendrites, the free surface of a crack. SEM image

The microscopic observations of the crack bottom revealed the structure of the parent metal indicating crack propagation only in the liquid presence area in the weld pool and in the adjacent area. Figures 5 and 6 present the crack edges with visible dendrites in a parallel arrangement. It is possible to notice free spaces between the dendrites, formed due to the strain applied and the presence of liquid.

Figures 7÷9 present the results of hot crack susceptibility assessment in the Transvarestraint test. The horizontal axis represents the percentage strain value.

The Blanchet method is used for assessing the hot crack susceptibility of thin sheets. The tests involve circular specimens fixed rigidly in a special clamp. The initial stage involves applying an initial strain (stress) with a ball probe; the measure of the strain is the deflection. The next stage involves annular overlay welding or parent metal remelting of a minimum diameter of 60 mm. The state of stresses obtained corresponds to the strength model of a circumferentially-fixed sheet affected by a concentrated force F. The disadvantage of the test is the variable state of stresses; the initial state of stresses is not strictly specified and changes during welding. The initial stress can be obtained from the following formula (3):

$$\sigma = \frac{3F}{2\pi g^2}\left(1-\frac{b^2}{a^2}\right) \qquad (3)$$

where b – diameter of the probe touching the sheet surface, a – specimen diameter counted from the fixing edge, F – concentrated force in N, g – sheet thickness in mm.

The measure of hot crack resistance is the value of specimen initial deflection at which cracks are formed during welding. The test scheme is presented in Figure 10.

The tests were conducted using a special device for the Blanchet method-based hot crack susceptibility assessment; the device was mounted on a welding positioner. Specimens having a diameter of 136 mm sampled from 1 mm thick sheets were melted using the TIG method gas-shielded electric arc. The constant welding process parameters included a shielding gas flow rate of 12 l/min (argon 4.8), welding current of

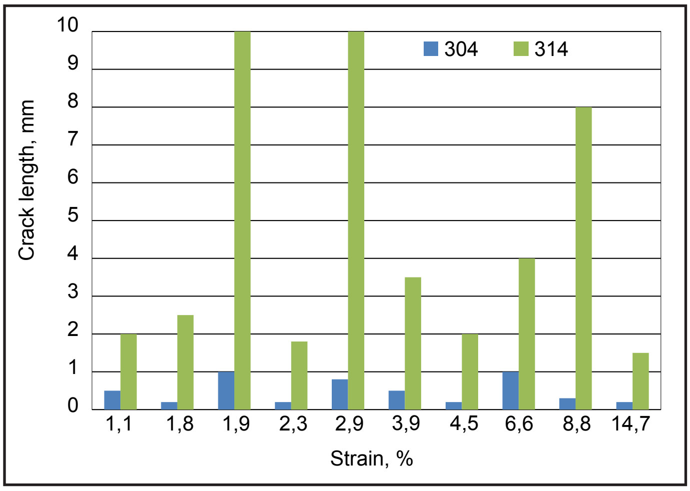

Fig. 7. Dependence of the longest crack on strain for 304 and 314 steels in Transvarestraint test

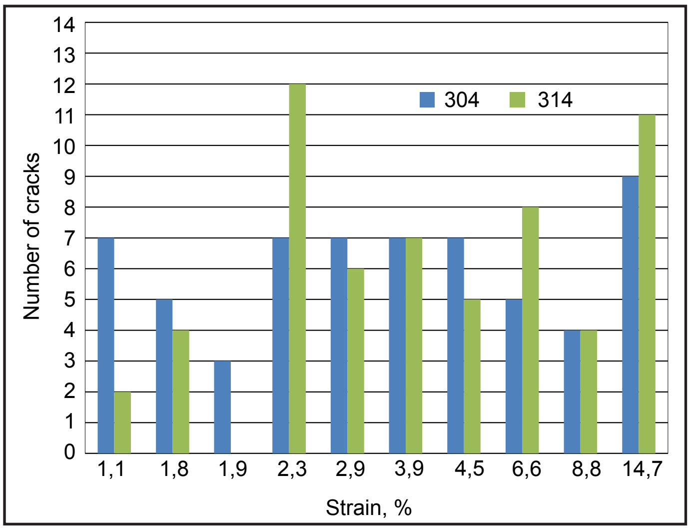

Fig. 8. Dependence of the number of cracks on strain for 304 and 314 steels in Transvarestraint test

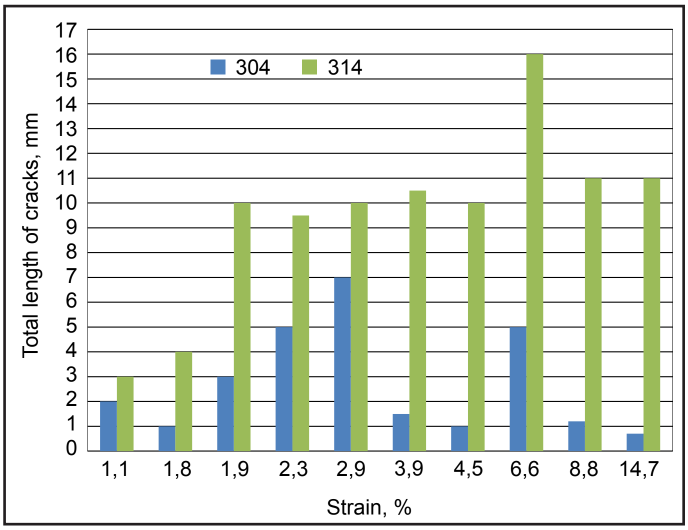

Fig. 9. Dependence of the total length of cracks on strain for 304 and 314 steels in Transvarestraint test

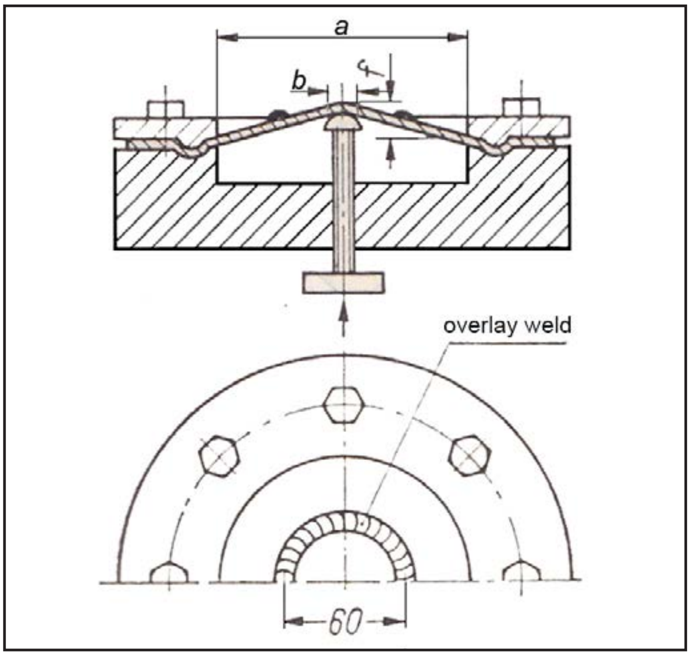

Fig. 10. Scheme of testing the hot crack susceptibility assessment using the Blanchet method

50 A and arc voltage of approximately 23 V. The arc length amounted to approximately 1.5 mm. A variable parameter was a linear velocity set on the welding positioner.

The test results are presented in Figures 11-14. The tests conducted enabled determining the area of welding parameters and permissible strain (stress) of the parent metal in which hot cracks are not present. Steel 304 did not reveal the presence of hot cracks.

In addition, for the results obtained, a crack indicator (W) was developed. The crack indicator value was established as follows:

$W = 1$	for the crack-free specimen;
$W = 1 + \dfrac{2\alpha}{360}$	for the specimen with a crack from the 0° - 360° range where α – crack angular length;
$W = 3$	for the specimen with a crack on the whole circumference.

The use of the crack indicator enabled the determination of crack-free, short crack and circular crack areas. Circular cracks were not observed for 304 and 314 steels as the specimen underwent corrugation for excessively high deflections. The results in the form of diagrams are presented in Figures 13-14.

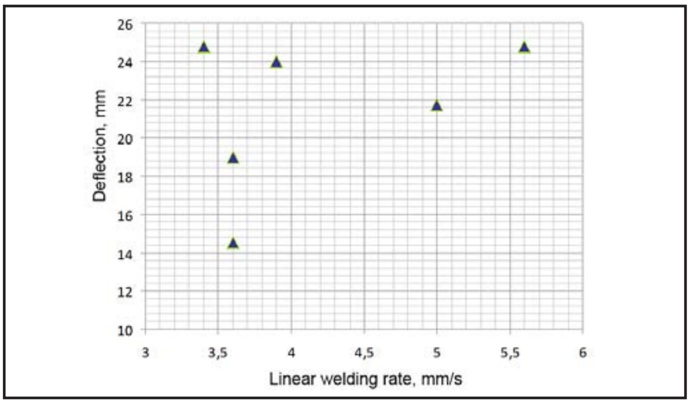

Fig. 11. Hot crack susceptibility tests results obtained using the Blanchet method for 304 steel. The whole area was free from cracks

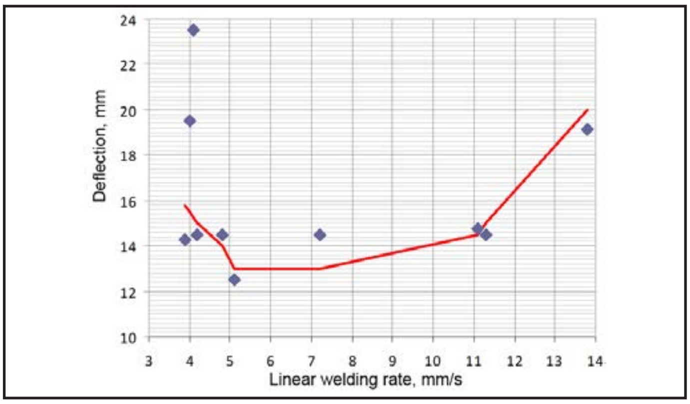

Fig. 12. Hot crack susceptibility tests results obtained using the Blanchet method for 314 steel. The area above the broken curve - hot crack susceptibility area

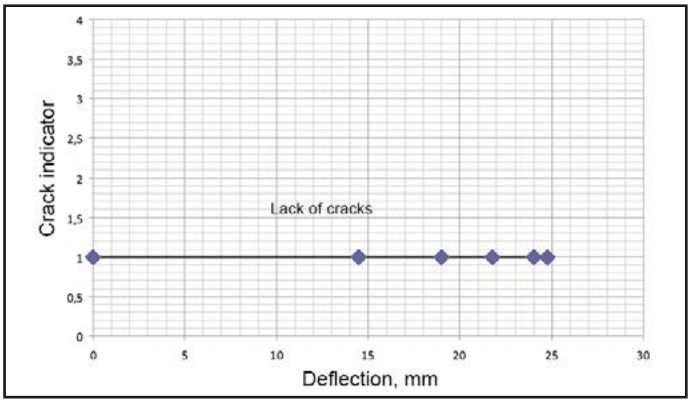

Fig. 13. Dependence of the crack indicator on the deflection for 304 steel

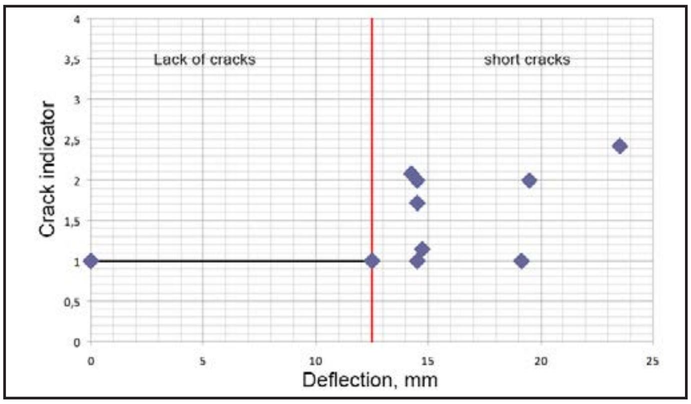

Fig. 14. Dependence of the crack indicator on the deflection for 314 steel

Conclusions

The analysis concerning the hot crack susceptibility of 304 and 314 type austenitic steels demonstrated that these steels should not reveal hot crack susceptibility or such a susceptibility should be low. The tests involved three materials of various thicknesses, i.e. 1, 3 and 5 mm, utilising the Blanchet and Transvarestraint methods. The tests performed revealed that

- 1 mm thick 304 steel sheets did not reveal any hot crack susceptibility. For 314 type steels it was possible to determine crack areas in the function of strain and welding rate. For 314 type steels it was not possible to obtain cracks in the whole penetration area as the area where such cracks were present was outside the measurement range of the measuring equipment;
- an increase in strain was accompanied by an increase in hot crack susceptibility of the steels tested. The cracks were formed in the solid-liquid area, in which it was possible to observe an increase in dendrites in the metallic liquid. The presence of liquid metal among dendrites decreases the plasticity and strength of a solid-state metal.

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