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INFLUENCE OF PHASE TRANSFORMATIONS IN THE TEMPERATURE RANGERS OF 1250-1000 C AND 650-350 C ON THE FERRITE CONTENT IN AUSTENITIC WELDS MADE WITH T 23 12 LRM3 TUBULAR ELECTRODE

WPŁYW PRZEMIAN FAZOWYCH W ZAKRESIE TEMPERATURY 1250-1000 C I 650- 350 C NA OBJĘTOŚCIOWY UDZIAŁ FERRYTU W SPOINACH WYKONYWANYCH DRUTEM PROSZKOWYM TYPU T 23 12 LRM3

Theoretical basis of $\gamma \rightarrow \alpha$ transformation proceeding at the temperature below 700°C has been presented. The course of investigation consisted in the recording of welding thermal cycles directly in the weld pool and weld as well as the analysis of the influence of cooling times on ferrite volume fraction. The significance of $\gamma \rightarrow \alpha$ transformation proceeding at the temperature below 700°C for ferrite volume fraction at the room temperature has been indicated. The correcting nomogram for the Schaeffler diagram taking into account the chemical composition, welding energy input and the weld run sequence has been developed and presented.

Przedstawiono teoretyczne podstawy przemiany $\gamma \rightarrow \alpha$ zachodzącej w temperaturze poniżej 700°C. Omówiono tok badań polegających na rejestracji cykli cieplnych spawania bezpośrednio w jeziorku spawalniczym i spoinie oraz porównaniu wpływu czasów stygnięcia na jetościowy udział ferrytu. Wskazano na znaczenie przemiany $\gamma \rightarrow \alpha$ zachodzącej w temperaturze poniżej 700°C dla objętościowego udziału ferrytu w temperaturze pokojowej. Opracowano i przedstawiono nomogram korygujący do wykresu Schaefflera uwzględniający skład chemiczny, energie liniową spawania, kolejność układania warstw spoiny.

1. Introduction

The ferrite is formed in alloy steels during metal solidification. The microstructure of the steel varies in dependance on the content of austenite-forming elements (Ni,

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C, N, Mn, Cu, Co) and ferrite forming elements (Cr, Mo, Si, W, V, Al., Ti, Nb) [1]. According to the up-to-date state of the art the weld microstructure at room temperature depends on the content of ferrite, which had appeared at very high temperature (below liquidus line), that is the microstructure depends on the relation between austenite and ferrite-forming elements. Welds of 18-10 steel have austenitic- ferritic structure after cooling to the ambient temperature. This structure is formed mainly because of rapid cooling of the weld. For the 18-10 steel in the first part of the weld solidification period, a substantial amount of ferrite is formed. The transformation of ferrite into austenite during the cooling process is complete, only if metal stays long enough in the temperature range in which the transformation is possible [1].

In the publication [4] the phenomena occurring at the temperature range below 800°C have been analysed. In this publication it has been assumed, that just after solidification there is only δ phase, which is transformed into phase γ in the welds of acid resistant steels with Cr/Ni > 3. Phase γ can be partly transformed again into ferrite α at lower temperature. This secondary $\gamma \rightarrow \alpha$ transformation can be shifted to the lower temperature range or restricted. It happens especially during rapid cooling of the weld (Fig. 1) [4]. The indication of the existence of $\gamma \rightarrow \alpha$ transformation at the temperature below 800°C and the influence of the weld cooling rate on the depression of temperature in which this transformation takes place is very important.

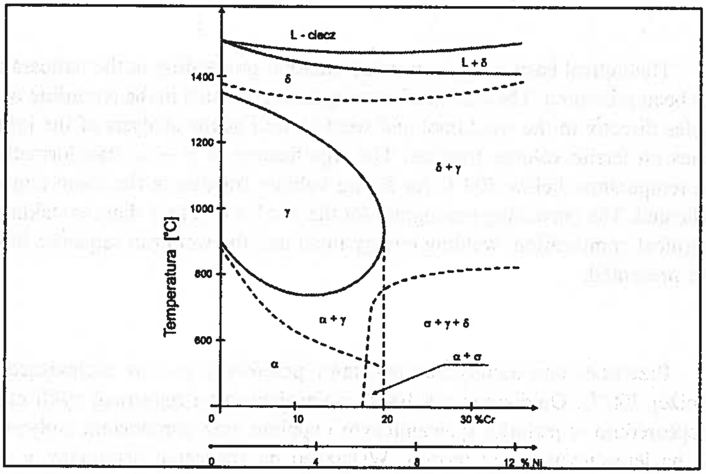

Fig. 1. Fe – Cr – Ni at Cr/Ni = 3/1 phase equilibrium diagram [4]

The secondary $\gamma \rightarrow \alpha$ transformation occurring at the temperature about 550°C is presented on a Fe-Cr-Ni phase equilibrium ternary diagram (Fig. 2) [5, 6].

The total transformation of ferrite formed at high temperature into phase γ and than transformation of this phase into phase α is shown on vertical section of the Fe-8Ni-Cr space diagram (Fig. 3) [6, 7].

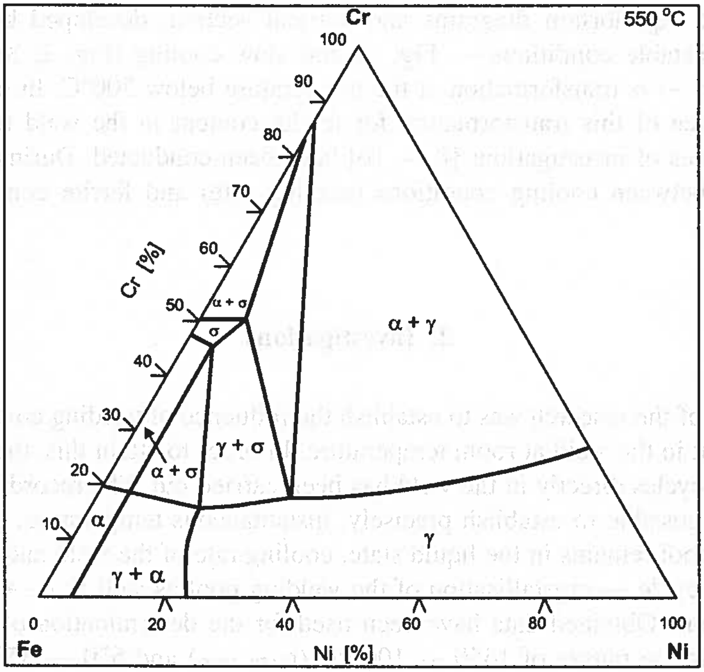

Fig. 2. Ternary Fe – Cr – Ni phase equilibrium diagram at temperature of 550°C [5, 6]

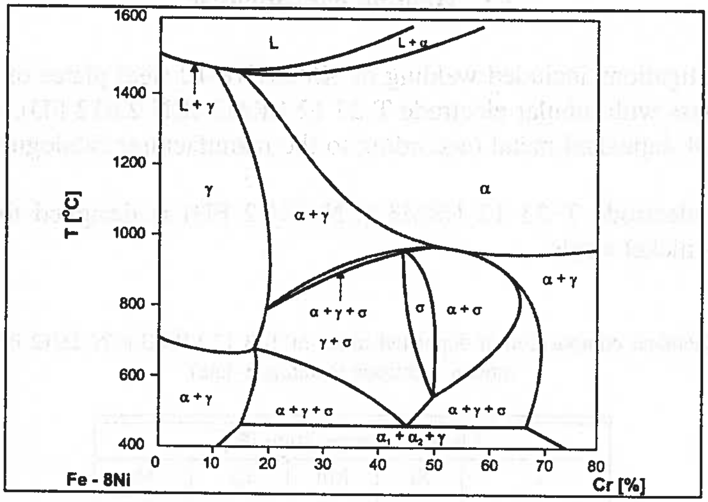

Fig. 3. Vertical section of Fe – 8Ni – Cr phase equilibrium diagram [6, 7]

Presented equilibrium diagrams and vertical section, developed both for rapid cooling (metastable conditions — Fig. 1) and slow cooling (Fig. 2, 3) indicate the existence of $\gamma \rightarrow \alpha$ transformation at the temperature below 700°C. In order to prove the significance of this transformation for ferrite content in the weld (at room temperature), series of investigations [8 — 16] have been conducted. During the research the relation between cooling conditions (cooling rate) and ferrite content has been examined.

2. Investigations

The aim of the research was to establish the influence of welding conditions on the ferrite content in the weld at room temperature. In order to attain this, the recording of real welding cycles directly in the weld has been carried out. The recording of thermal cycles made possible to establish precisely: instantaneous temperature, time in which the welding pool remains in the liquid state, cooling rate of the weld and characteristic points of the cycle — crystallisation of the welding pool as well as $\delta \rightarrow \gamma$ and $\gamma \rightarrow \alpha$ transformations. Obtained data have been used for the determination of cooling time in the temperature ranges of 1450 — 1000°C ($t_{1450-1000}$) and 650 — 350°C ($t_{650-350}$). In particular for the determination of:

- the cooling time in the temperature ranges of 1450 — 1000°C ($t_{1450-1000}$) and 650 — 350°C ($t_{650-350}$) on the basis of thermal cycles recorded in the real welding conditions as a parameter characterising the cooling rate;
- the relation between the cooling rate and the ferrite content.

2.1. Welding consumables

The investigations included welding of X5CrNi18-10 steel plates of 8, 16 and 24 mm in thickness with tubular electrode T 23 12 LRM3 (CN 23/12 FD). The chemical composition of deposited metal (according to the manufacturer catalogue) is shown in Table 1.

Rutile cored electrode T 23 12 LRM3 (CN 23/12 FD) is designed for welding of chromium — nickel steels.

TABLE 1

Chemical composition of deposited metal of T23 12 LRM3 (CN 23/12 FD) tubular electrode (catalogue data)

Chemical composition [%]				
C	Si	Mn	Cr	Ni
Max 0.03	0.6	1.5	22.8	12.5

2.2. Measurement and recording of thermal cycles directly in the weld pool and weld (with use of W –Re thermoelement)

The investigation consisted in welding of restraint plates, 8, 16 and 24 mm in thickness, with the energy input of 8 – 24 kJ/cm. In each sample a groove was milled, in which the W – Re thermoelement (in ceramic insulation) was placed. The groove made possible to locate in a reproducible way the thermoelement tip in the succesive weld beads. W – Re thermoelement enabled weld thermal cycles to be recorded directly in the weld pool and than in the cooling weld. The records of weld thermal cycles revealed the transformations which occurred in the temperature range of 1450 – 1000°C and 650 – 350°C and made possible to determine the cooling times $t_{1450-1000}$ and $t_{650-350}$ in these temperature ranges. An example of a weld thermal cycle is shown in Fig. 4. On the surface of each run of the weld the measurement of ferrite content was conducted (in accordance with [17]). The measurement was made with the use of a ferrite meter with the inductance method of measuring.

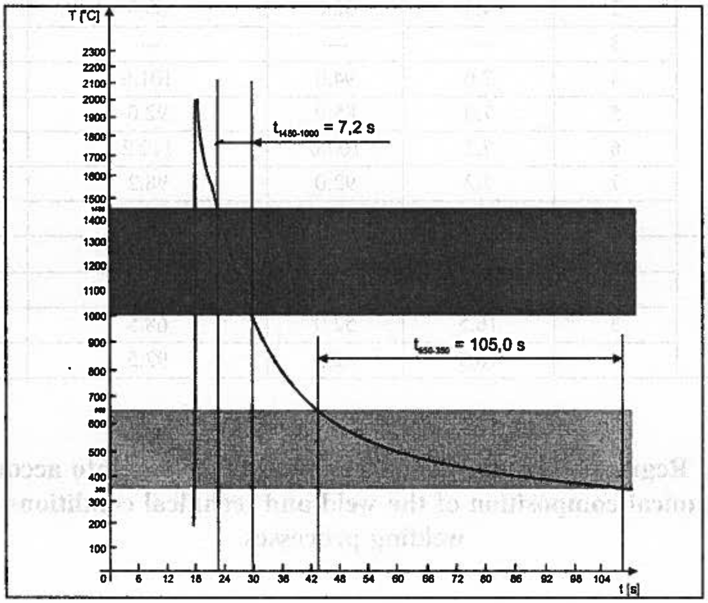

Fig. 4. En example of welding thermal cycle

TABLE 2

Results of measurement

Sample No	Weld bead No	$t_{1450-1000}$ [s]	$t_{650-350}$ [s]	$t_{1450-1000} + t_{650-350}$ [s]	Ferrite [%]
1	1	7.2	88.0	95.2	14.20
	2	7.2	90.0	97.2	14.00
2	1	12.6	93.0	105.6	9.50
3	1	10.1	96.0	106.1	16.42
	2	11.4	118.0	129.4	15.68
	3	7.4	90.0	97.4	14.50
	4	6.8	81.0	87.8	12.74
4	1	9.4	96.0	105.4	15.24
	2	11.6	90.0	101.6	15.70
5	1	8.5	94.0	102.5	16.00
	2	4.8	62.0	66.8	10.50
	3	—	—	—	10.90
	4	7.6	94.0	101.6	14.80
	5	7.0	85.0	92.0	14.28
	6	7.2	105.0	112.2	15.24
	7	7.2	92.0	98.2	14.68
	8	—	—	—	14.30
6	1	—	—	—	10.90
	2	5.5	42.0	47.5	9.64
	3	16.5	52.0	68.5	10.92
	4	10.5	82.0	92.5	14.56

2.3. Regression equitation and nomogram taking into account the chemical composition of the weld and technical conditions of the welding processes

On the basis of received results of ferrite volume fraction measurements and examination of weld thermal cycles (Table 2) linear regression equitations have been developed. The equitation take into account the chromium and nickel equivalents as well as the cooling time. The developed equitation include summarised cooling time in two temperature ranges 1450 – 1000°C ($t_{1450-1000}$) and 650 – 350°C ($t_{650-350}$). Independent variables are as follows:

— the difference of chromium and nickel equivalents — (Cr_{eq} - Ni_{eq})

— the sum of cooling times in two temperature ranges 1450 – 1000°C ($t_{1450-1000}$) and 650 – 350°C ($t_{650-350}$).

The dependent variable is the volume ferrite content measured at room temperature — $V_{ferrite}$.

The linear regression equation (weld made with tubular electrode CN 23/12 FD, time $t_{1450-1000}$ and $t_{650-350}$) is the following:

$$V_{ferrite} = 3.9352(Cr_{eq} - Ni_{eq}) + 0.0299(t_{1450-1000} + t_{650-350}) - 22.90 \qquad (1)$$

$\alpha = 0.05$

R = 0.99

Standard error = 3.56

The developed multiple regression equation has been applied for the construction of the nomogram in the Cartesian co-ordinate system (Fig. 5 upper part) [18-20]. The nomogram is valid only for ($Cr_{eq} - Ni_{eq}$) and ($t_{1450-1000} + t_{650-350}$) values specified during the research. The nomogram consists of the family of parallel lines ($Cr_{eq} - Ni_{eq}$) = $\alpha\%$ = constant and two co-ordinate axis. On the X-axis the sum of cool

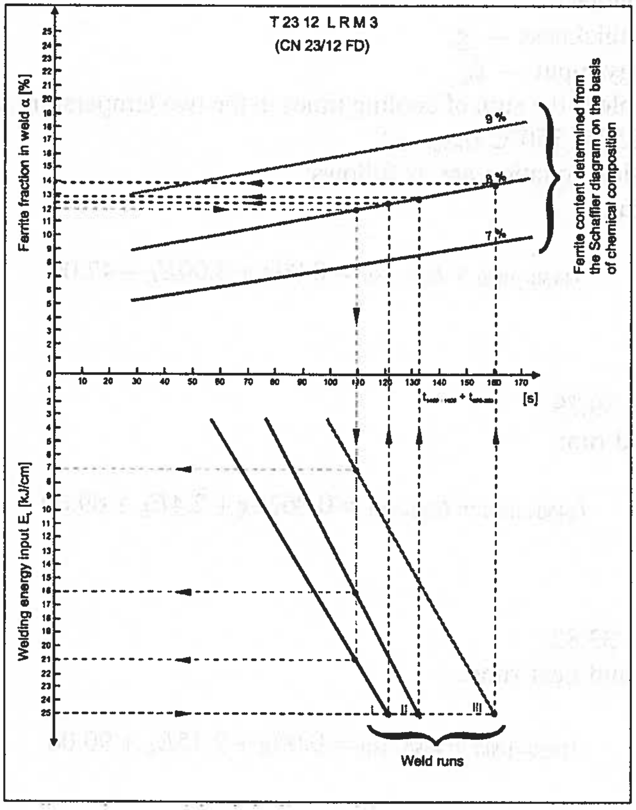

Fig. 5. Nomogram for more accurate determination of ferrite content

ing times $t_{1450-1000}$ + $t_{650-350}$ (technological parameter characterising cooling rate) is marked. The Y-axis shows corrected ferrite fraction. The nomogram takes into account the weld cooling rate and makes possible to specify precisely the ferrite fraction determined on the basis of Schaeffler diagram. It is possible to estimate the ferrite content with the accuracy of ± 2%.

The obtained results enable to develop the multiple regression equitation, which take into account the influence of the welded plate thickness (g) and the welding energy input (E_L) on the summarised cooling time in two temperature ranges 1450 – 1000°C ($t_{1450-1000}$) and 650 – 350°350 ($t_{650-350}$).

In order to increase accuracy of the determined relation, the multiple regression equitation have been formulated separately for the first, second, third and the following runs because of different volume ferrite contents.

Independent variables:
— welded plate thickness — g,
— welding energy input — E_L.

Dependent variable is the sum of cooling times in the two temperature range 1450 - 1000°C ($t_{1450-1000}$) and 650 – 350°C ($t_{650-350}$).

Multiple regression equation are as follows:
— for the first run

$$t_{1450-1000} + t_{650-350} = 0.00g + 3.00E_L + 47.00 \tag{2}$$

$\alpha = 0.05$
R = 0.77
Standard error = 39.79.
— for the second run:

$$t_{1450-1000} + t_{650-350} = 0.0625g + 2.4E_L + 69.00 \tag{3}$$

$\alpha = 0.05$
R = 0.75
Standard error = 33.82.
— for the third and next runs:

$$t_{1450-1000} + t_{650-350} = 0.00g + 2.75E_L + 90.00 \tag{4}$$

$\alpha = 0.05$
R = 0.77
Standard error = 36.48.

On the basis of the regression equitation (1-4) the nomograms taking into account the influence of the plate thickness and welding energy input on the weld cooling time (Fig. 5 lower part) have been developed. The developed nomogram is valid for plate

thickness (g) and welding energy input (E_L) applied in the investigation. On X-axis the summarised cooling time $t_{1450-1000} + t_{650-350}$ (technological parameter characterising the cooling rate) is marked. The Y-axiss represents welding energy input (E_L).
The nomograms developed on the basis of carried out experiments enable the influence of plate thickness and welding energy input on weld cooling time to be estimated. The connection of the nomogram which make possible the determination of corrected ferrite content on the basis of the weld chemical composition ($Cr_{eq} - Ni_{eq}$) and summarised cooling times $t_{1450-1000} + t_{650-350}$ with the nomogram for the determination of the plate thickness (g) and welding energy input (E_L) influence on the cooling time, represented by the parameter $t_{1450-1000} + t_{650-350}$, made possible to construct the composite correcting nomogram (Fig. 5). In the composite nomogram the common time axis $t_{1450-1000} + t_{650-350}$ connects the nomograms constructed on the basis of multiple regression equitation (1) and (2-4). The time axis ($t_{1450-1000} + t_{650-350}$) is the X –axis for the nomogram constructed on the basis of equitation (1) and the Y-axis — for the nomogram constructed on the basis of equitations (2-4). The composite nomogram enables to estimate the ferrite content in the weld on the basis of the welding energy input, the weld run sequence and chemical composition. The nomogram, which takes into account not only (as before) the influence of chemical composition on the ferrite content, but also the cooling rate represented by ($t_{1450-1000} + t_{650-350}$) can be used to develop the technology of welding of stainless steels. The part of the nomogram, which is constructed on the basis of linear regression equitation (1), enables more accurate determination of the ferrite content in the weld. In this case measurement of the times ($t_{1450-1000} + t_{650-350}$) is required. For technological purposes, the received results make possible to assume the simplification ($t_{1450-1000} + t_{650-350}$) $\approx 1{,}1 t_{650-350}$ in order to facilitate time and temperature measurements.

The way of reading of the nomogram is the following:
For the required ferrite content in the weld the approximate ferrite content resulting from chemical composition should be estimated on the basis of the Schaeffler diagram. Welding consumables should be selected with use of the Schaeffler diagram taking into account the approximate ferrite content. On the basis of expected ferrite content and ferrite content resulting from chemical composition the welding energy input for particular weld runs should be selected.

3. Summary

The developed nomogram, which takes into account the influence of chemical composition, cooling rate represented by ($t_{1450-1000} + t_{650-350}$), welding energy input and weld run sequence on the volume fraction of ferrite, enables the results determined on the basis of the Schaeffler diagram to be specified more accurate. It can be applied while developing the welding technology for stainless steels.

Conducted investigation and received results have revealed the significance of cooling rate (especially in temperature range of 650 – 350°C) for the volume ferrite content in weld at room temperature. The course of investigations has shown the importance of $\gamma \rightarrow \alpha$ transformation in these temperature ranges as well as enabled the specification of a technological parameter connecting the cooling rate with the volume ferrite content. The presented nomogram, developed on the basis of obtained examination results, is an example of technological presentation of the issues concerning the influence of the weld cooling rate on the volume ferrite fraction.

The development of the family of nomograms enabling the accurate determination of volume ferrite content at the whole range of the Schaeffler diagram would require further extensive and expensive research, including testing of a wider range of weld chemical composition ($Cr_{eq} - Ni_{eq}) = 6 \div 30$.

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