FORECASTING THE CONTENT OF σ-PHASE IN THE HAZ OF WELDED JOINTS OF DUPLEX STEELS IN ARC WELDING

V.I. MAKHNENKO, S.S. KOZLITINA and **L.I. DZYUBAK**
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Numerical algorithm is suggested for calculation of the content of σ-phase in HAZ metal of multipass butt-welded joints on duplex steel DSS 2205. Experimental temperature-time diagrams of formation of σ-phase under isothermal conditions at different temperatures are used in combination with thermal cycles of points of welded joint HAZ.

Keywords: *arc welding, duplex steels, butt joints, heat-affected zone, σ-phase, temperature-time diagram*

Over the last decades chromium-nickel duplex steels have become ever wider accepted in engineering owing to their properties, which are due to the initial structure (50 wt.% of ferrite and 50 wt.% of austenite). In connection with the high resistance to intercrystalline pitting corrosion in an aggressive medium in combination with good weldability and comparatively high fracture resistance, as well as moderate cost, this class of stainless steels is widely used to develop various-purpose critical structures.

However, alongside acquiring the above advantages, these steels partially inherited also the disadvantages of stainless steels of both austenitic and ferritic classes. The most significant disadvantage at 50 wt.% of initial ferrite content in the structure is their sensitivity to temperature impact, when ferrite decomposes with formation of σ-phase, which abruptly lowers the steel mechanical properties. This problem is quite well-studied in terms of service loading of structures from such steels. Respective temperature-time diagrams (TTD) allowing evaluation of the probability of appearance of intermetallic formations of σ-phase type under isothermal service conditions were plotted. As regards welding heating, there is a number of publications ([1], etc.), where this issue is studied experimentally on samples cut out of HAZ metal that allowed defining certain limitations on heat input in welding [2]. Nonetheless, at present there is no calculation procedure for forecasting (with a certain degree of validity) the extent of the influence of specific modes and conditions of welding on σ-phase content in the HAZ, thus limiting the effectiveness of predictive estimates at selection of technological modes and conditions of welding specific components.

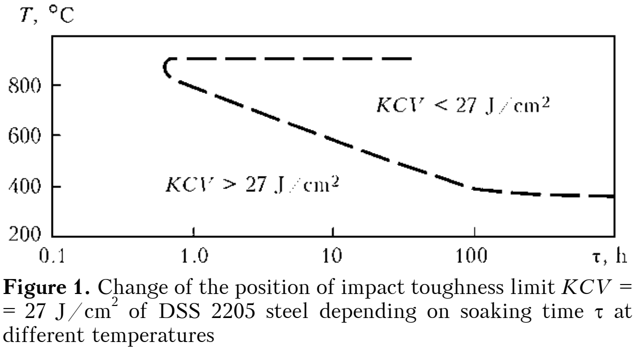

Figure 1. Change of the position of impact toughness limit KCV = = 27 J/cm^2 of DSS 2205 steel depending on soaking time τ at different temperatures

This work is an attempt to develop a procedure based on calculated thermal cycles in specific points of the HAZ and experimental data of TTD, plotted for specific steel. The idea of such an approach was tried out to a certain extent at prediction of the degree of sensibilization of HAZ metal of chromium-nickel steels with an increased content of carbon at formation of intercrystalline corrosion cracks.

Samples of butt-welded joint of pipes of 271 × × 20 mm cross-section from duplex steel DSS 2205 of the following composition [3], wt.%: 22.43 Cr; 1.88 Ni; 3.13 Mo; 0.14 Mn; 0.07 Si; 0.18 N; 0.023 C, were selected as the object for procedure development. The above steel composition ensures a high resistance to pitting corrosion in chloride solutions. Respective equivalent PRE = Cr + 3.3 wt.% Mo + 16 wt.% N = = 35.64, that is quite close to limit value PRE = 40 [2]. DSS 2205 steel similar to other duplex steels is sensitive to heating above 475 °C in connection with a high ferrite content (50 wt.%) that is manifested in considerable embrittlement. In duplex steels at more than 538 °C temperature part of ferrite is transformed into σ-phase, which combines different intermetallics, promoting a lowering of steel ductility, particularly at temperatures below −40 °C.

Figure 1, based on the data of [2], presents the change of the position of impact toughness limit KCV = 27 J/cm^2 of DSS 2205 steel, depending on soaking time at different temperature. At superposition of these data on experimental data [3] on the change of the content of σ-phase in DSS 2205 steel (Figures 2, 3) it is seen that lowering of KCV value occurs at the content of σ-phase of 15–18 wt.%.

Proceeding from the data of Figures 2 and 3, obtained for HAZ specific thermal cycles $T(\tau')$, V of σ-phase, wt.%, can be calculated as follows:

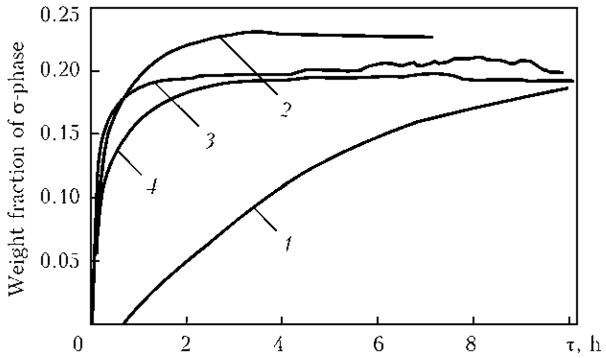

Figure 2. Kinetics of the change of σ-phase content at isothermal soaking of samples of DSS 2205 steel at temperature T = 700 (*1*), 750 (*2*), 800 (*3*) and 859 (*4*) °C by the results of experimental measurements

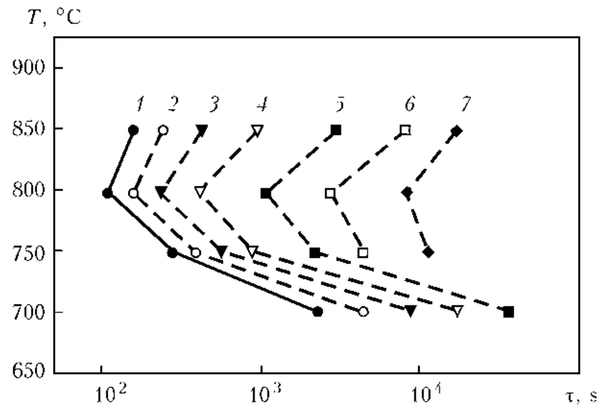

Figure 3. C-shaped curves of the change of σ-phase content depending on temperature T and soaking time τ: *1* — 1; *2* — 10; *3* — 25; *4* — 50; *5* — 75; *6* — 90; *7* — 99 wt.%

$$V = \sum_j \int_{T_{st}}^{T_{end}} \frac{(V_j - V_{j-1})\dfrac{V^{max}(T)}{100}}{\tau_j(T) - \tau_{j-1}(T)}\, d\tau'(T),$$

where j = 1, ..., 7 is the number of C-shaped curves (Figure 3); V_j = 1, 10, 25, 50, 75, 90, 99 wt.% is the

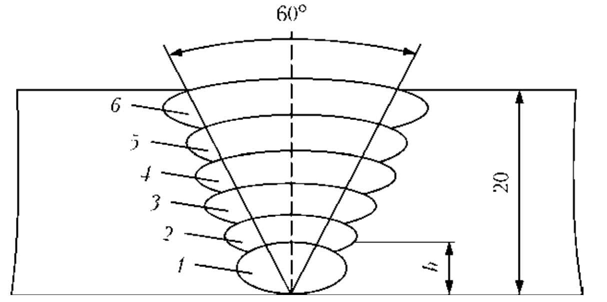

Figure 4. Schematic of layer-by-layer welding-up of butt joint by multipass arc welding: *1–6* — number of passes

Results of calculation of σ-phase content

No. of welding mode variant	Welding procedure	H, J/mm	η_s	$q_{h.i}$, J/mm	T_0, °C	V^{max}, wt.%
1	MIG	2270	0.75	1700	20	1.0–1.2
2		2270	0.75	1700	150	2.0–2.4
3	TIG	5000	0.60	3000	20	3.5–4.0
4		5000	0.60	3000	150	5.6–6.4

«price» of this curve from maximum value $V^{max}(T)$ at $T_{st} > T > T_{end}$ (here T_{st}, T_{end} is the temperature of the start and end of tracing the thermal cycle $T(t')$); and τ′ is the current time.

The modes of multipass arc welding were selected using the recommendation of [2] as regards the applied electric heat input:

$$H = 60\,\frac{IU}{v},$$

where I is the welding current; U is the arc voltage; v is the welding speed. According to [2], H values are in the ranges of $512 < H < 2520$ J/mm under the

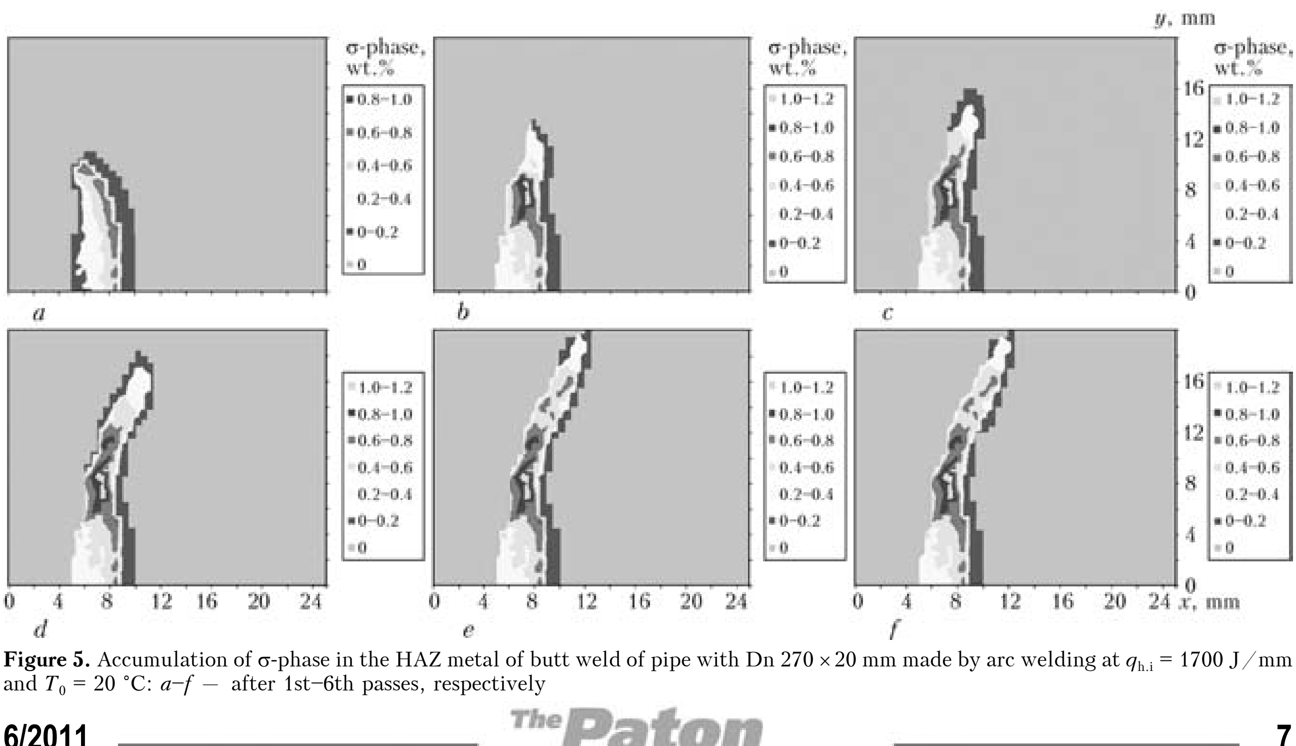

Figure 5. Accumulation of σ-phase in the HAZ metal of butt weld of pipe with Dn 270 × 20 mm made by arc welding at $q_{h.i}$ = 1700 J/mm and T_0 = 20 °C: *a–f* — after 1st–6th passes, respectively

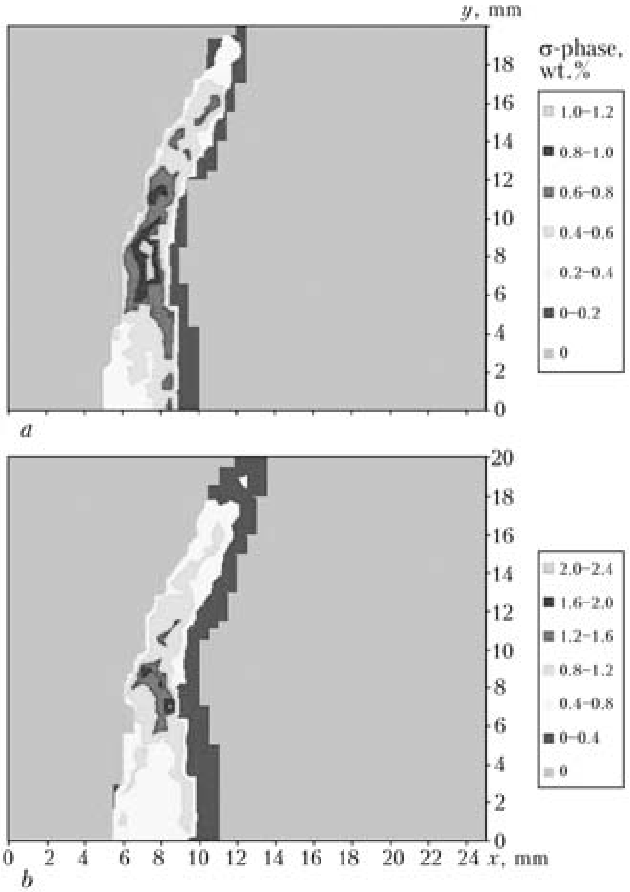

Figure 6. Distribution of σ-phase in the metal of the HAZ and butt weld of a pipe with Dn 270 × 20 mm from DSS 2205 steel made by six-pass MIG welding (after 6th pass) at $q_{h.i}$ = 1700 J/mm: *a* — T_0 = 20; *b* — 150 °C

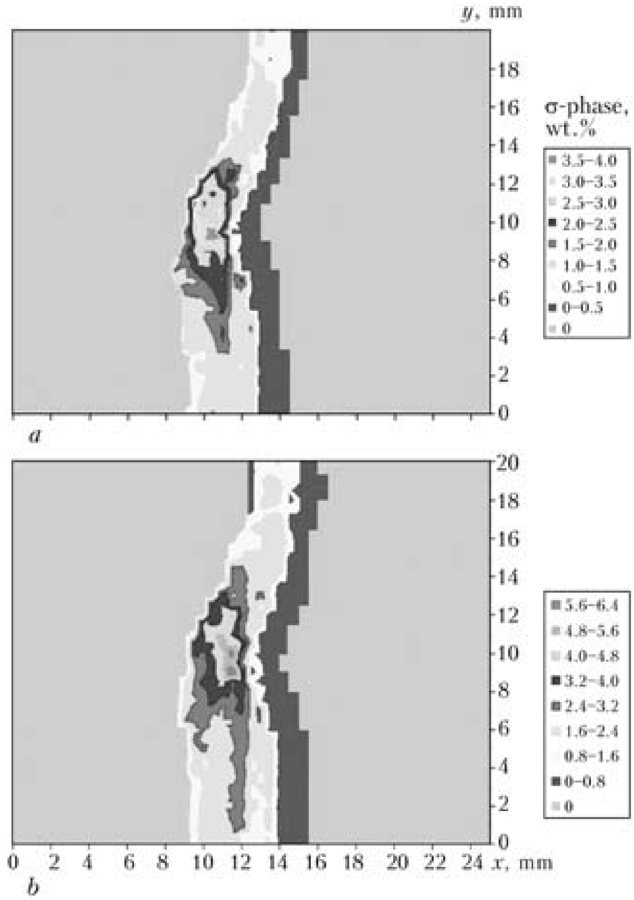

Figure 7. Distribution of σ-phase in the metal of HAZ and butt weld of a pipe with Dn 270 × 20 mm from DSS 2205 steel made by six-pass TIG welding (after 6th pass) at $q_{h.i}$ = 3000 J/mm (for *a* and *b* see Figure 6)

condition of preheating application before each pass (T_0 = 150 °C).

Let us consider the following variants of welding butt joints in six passes (Figure 4). Section of each bead is equal to F = 25–35 mm^2. Its thickness (height) h_i at groove angle α = 60° varies in the range of 7–1.8 mm, and width a_i — in the range of 7–20 mm.

Calculation results for the above heat input variants are given in Figures 5–7. It follows from the obtained data that increase of the heat input up to $q_{h.i} \leq 1700$ J/mm at T_0 = 20 °C has only a minor influence on the content of σ-phase in welding of the considered joint. However, at higher heat input ($q_{h.i}$ > > 3000 J/mm) content of σ-phase of HAZ metal is close to the level, at which, according to Figures 1–3, the value of impact toughness decreases to 27 J/cm^2 that is by almost an order of magnitude lower than that in the absence of σ-phase in the HAZ metal of butt joint of the above-mentioned steel. The given data are indicative of the influence of preheating (interpass temperature) on the intensity of σ-phase formation in the HAZ metal, which determines preservation of joint ductility at subsequent technological treatments or in service. It follows that repair of welded joints of duplex steels, at which σ-phase accumulates in the HAZ metal, requires discretion and appropriate predictive estimates. Estimates obtained on the basis of the proposed procedure (Table) agree quite well with the recommendations of work [2] as regards limitations of heat input in welding steels of the considered class.

CONCLUSIONS

1. Formation of σ-phase promotes an abrupt lowering of duplex steel ductility at thermal impact, in particular in welding, and thus limits application of these materials in modern structures.

2. Using standard TTD it is possible to quite effectively forecast the content of σ-phase in the HAZ metal at welding thermal cycle of multipass welding of duplex steels.

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