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Integrated Assessment of Weldability of Steel with Increased Strength

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Abstract. Modern production of agricultural equipment and facilities, hulls of ships, stationary oil drilling platforms, wind energy installations and other metal structures makes extensive use of sheet steel of increased strength. The main manufacturing process is welding, the quality of which depends on multiple factors, including the ability of steel to resist welding. It is known that the properties of the thermal influence zone are highly dependent on phase transformations, the nature of which is determined by the intensity and development of diffusion processes of carbon redistribution and alloying elements under the impact of the welding thermal cycle. Therefore, it is necessary to evaluate the weldability of the steel of a certain chemical composition, in order to choose the optimal method and the technological parameters of the welding mode for the manufacture of a specific metal structure. In order to reduce material costs, you can use analytical calculation methods that were developed at the E.O. Paton Electric Welding Institute. They are based on the analysis of the literature and the study of about 150 diagrams of the thermokinetic decomposition of austenite. Mathematical models make it possible to predict with a sufficient degree of accuracy the phase composition and mechanical properties of the high-temperature thermal influence zone depending on the chemical composition and cooling time of the metal, heated to a maximum temperature of 1350ºC, in the temperature range 850-500ºC. However, such tests are quite expensive and do not allow optimization of weld properties when the welding mode, mode, welding materials and other underlying technological factors change. In this connection, the objective was to assess the reliability of the proposed methodology in the study of weldability of shipbuilding steel of the increased strength of the category E36, for the weakest T(transverse) – the orientation of the sheet of 50 mm thickness. A high performance of the steel category is achieved by a limited increase in the aluminium content or other grain-crushing elements (Nb, V, Ti), which ensures that the size of the austenitic grain is not greater than the fifth point. The research showed that analytical methods for calculating the mechanical characteristics of high temperature HAZ sites by chemical composition, taking into account the cooling rate after welding, provide a level of confidence sufficient for practical application and can be recommended for the primary evaluation of the properties of welded compounds of high-thickness steel plates of category E36 (T-orientation). The impact work (KV-40) of the high-temperature sections of the high-temperature thermal influence zone is not subject to an analytical evaluation with the degree of accuracy required for production practice

Keywords: steel of category E36, analytical calculation methods in welding, complex mechanical tests, mechanical characteristics, impact viscosity, steel hardness

INTRODUCTION

Modern production of agricultural equipment and facilities, hulls of ships, stationary oil drilling platforms, wind energy installations and other metal structures makes extensive use of sheet steel of increased strength. The main manufacturing process is welding, the quality of which depends on multiple factors, including the ability of steel to resist welding. It is known that the properties of the thermal influence zone are highly dependent on phase transformations, The nature of which is determined by the intensity and degree of development of diffusion processes of carbon redistribution and alloying elements under the impact of the welding thermal cycle [2; 3; 5; 16-20]. Naturally, the concentration of alloying elements and cooling rates have a significant

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impact on the diffusion mobility of carbon. Therefore, it is necessary to evaluate the weldability of the steel of a certain chemical composition, in order to choose the optimal method and the technological parameters of the welding mode for the manufacture of a specific metal structure.

In practice, as a rule, the development of a certain welding technology is carried out in accordance with the requirements of the ISO 15609 – ISO 15614 series of international standards [23; 24], which allows to record the properties of welds with a high degree of confidence. In order to reduce material costs, it is possible to use the analytical methods of calculation developed in the E.O. Paton Electric Welding Institute (PWI), based on the analysis of literary data and the study of about 150 thermocynthetic decay diagrams of austenite. Mathematical models (see formulas 1-4) allow to predict with a sufficient degree of accuracy the phase composition and mechanical properties of the high-temperature heat-affected zone (HAZ) depending on the chemical composition and cooling time of the metal, heated to a maximum temperature of 1350°C, within a temperature range of 850-500°C [1-3]:

Vickers hardness number (with correlation coefficient of R=0.95) [1-3] (1):

$$HV=M(309+494C+622C^2+17.7Mn)+B(234+122C)+ \\ +[F+P](98+275C+15.4Mn) \qquad (1)$$

where F, P, B and M are quantities of ferrite, pearlite, bainite and martensite. Ultimate tensile strength (with correlation coefficient of R=0.91) (2):

$$\sigma_t\,(MPa)=M(798+3215C)+B(590+960C+39.7Mn+ \\ +200V)+[F+P](297+1360C+60Mn+140V) \qquad (2)$$

Yield strength (with correlation coefficient of R=0.90) (3):

$$\sigma_{0.2}\,(MPa)=M(662+1610C)+B(500+460C-120C^2+ \\ +150V)+[F+P](187+925C+47Mn+90V) \qquad (3)$$

Impact toughness of specimens (4):

$$KCV(T)=(KCV_{max}-KCV_o)\Phi(u)+KCV_o \qquad (4)$$

where KCV_o is the minimum value of impact toughness at low temperatures (0.01…0.02KCV_{max}); $\Phi(u)$ – normal distribution function ($\Phi(u)=0.5(1+\mathrm{erf}(u/\sqrt{2}))$) (5):

$$\ln(KCV_{max})\ (MJ/m^2)=1.29-3.85C-0.181Si-0.204Cr- \\ -1.04Mo-0.328Ni-1.51V-1.67Ti-1.60Nb-0.285W+ \\ +0.160Co-2.49Zr-2.62S-5.84P-15.8N-10.7O- \\ -1.19C\cdot Mn+0.052Mn\cdot Cr-0.104Si\cdot Cr+0.062Cr\cdot Mo+ \\ +0.581C\cdot Ni-6.51C^2+0.038Cr^2-0.030Mo^2- \\ -0.229V^2+(0.028+0.954C-0.048Cr+0.356Mo+ \\ +0.455V+0.077Ni)\cdot \ln_t,\ (R=0.93) \qquad (5)$$

They can be used for steels containing not more than (% by mass 0.4C; 2Mn; 0.8Si; 2Cr; 1Mo; 1.5Ni; 0.3V; 0.06Ti; 0.06Al; 0.1Nb; 0.5W; 0.5Cu, in thermal cycles that provide a cooling time t within a specified temperature range of 5 to 200 s. It is also possible to determine the properties of a molded metal.

The most reliable way of assessing the weldability of sheet metal is the comprehensive testing of welded welds according to the requirements of the Qualification Societies Regulations (Lloyd's Register (LR), Bureau Veritas (BV), Det Norske Veritas (DNV), Germanischer Lloyd (GL), American Bureau of Shipping (ABS), Shipping Register of Ukraine (SRU)) [14]. However, such tests are quite expensive and do not allow optimization of weld properties when the welding mode, mode, welding materials and other underlying technological factors change. In this connection, the objective was to assess the reliability of the proposed methodology in the study of weldability of shipbuilding steel of the increased strength of the category E36, for the weakest T(transverse) – the orientation of the sheet of 50 mm thickness. The regulated requirements of the Qualification Societies Regulations for the mechanical performance of the specified thickness rolling stock are at the following level (T-orientation time resistance Rm=490-620 MPa, yield strength ReH 355 MPa, elongation A 21%, impact operation KV-20 24 J, hardness HV 350 Unit. A high performance of the steel category is achieved by a limited increase in the aluminium content or other grain-crushing elements (Nb, V, Ti), which ensures that the size of the austenitic grain is not greater than the fifth point. In addition, it is known that impact viscosity is a structurally sensitive characteristic and depends on the state of the grain boundary, the morphology of structural constituents including micro excretion (carbides, nitrides, MAC phase), chemical and structural microheterogeneity, content of impurities and dissolved gases whose permissible concentration, including nitrogen, is not always regulated by the DA Regulations [5; 22-25].

The purpose of this paper was to assess the validity of the proposed the analytical methods of calculation in the study of weldability of shipbuilding steel of the increased strength of category E36, for the weakest T (transverse) – the orientation of sheets of 50 mm thickness.

MATERIALS AND METHODS

Blanks of 50 mm thickness sheet metal (% by mass) were selected as the main metal as follows: 0.11C; 1.56Mn; 0.23Si; 0.003S; 0.010P; <0.005As; 0.03Cr; 0.02Ni; 0.03Cu; <0.005Ti; 0.025Al; 0.033Nb; 0.007N; <0.065V; <0.005Mo; <0.0005B; 0.0015Sn; <0.001Sb. The chemical composition and mechanical characteristics of the selected blanks were fully compliant with the requirements of the DA Regulation for steel of category E36, as confirmed by the standard set of mechanical tests [14].

Analytical evaluation of the properties of metal HAZ (R_m, R_{eH}, KV_{-40}, HV), depending on a given chemical composition and duration of metal cooling from a maximum heating temperature of 1350°C, in a temperature range of 850-500°C, using a dependency of 1-4. The pre-heating requirement for a thickness of 50 mm was taken into account. The calculated heating temperature was ~150°C.

Test specimen welding was performed automatically under the flux, a continuous cross-section wire (121 welding code) on the calculated linear energy HI=2.5 kJ/mm (I=550 A; U32 V; v=6.67 mm/s; η=0.95) and HI=4.2 kJ/mm (I=800 A; U=36 V; v=6.57 mm/s; η= 0.95) with the use of welding wire OK Autrod 12.20 (S), 4 mm and flux OK Flux 10.71, SA AB 1 67 AC H5 (EN 760) vacuum packaging. The pre-heating was in both cases up to a design temperature of ~150°C. The intergrading temperature was controlled at <200°C. After each welding, the welding direction was reversed. The ambient temperature during welding was +21 cc, relative humidity ~68%, atmospheric pressure ~1.013 10^5 Pa.

In order to assess the impact of the actual thermal welding cycle on the properties of the metal T of the given chemical composition, standard reference samples were welded in accordance with the requirements of DNV GL [21]. Size of welded plates: 50 mm thick; 200 mm wide; 2000 mm long. Type of weld connection: 2.5.5 ISO 9692-2 [25]. Welding was carried out in parallel to rolling the sheet to provide tenderloins for tensile and impact tests in the transverse direction of rolling (T-orientation).

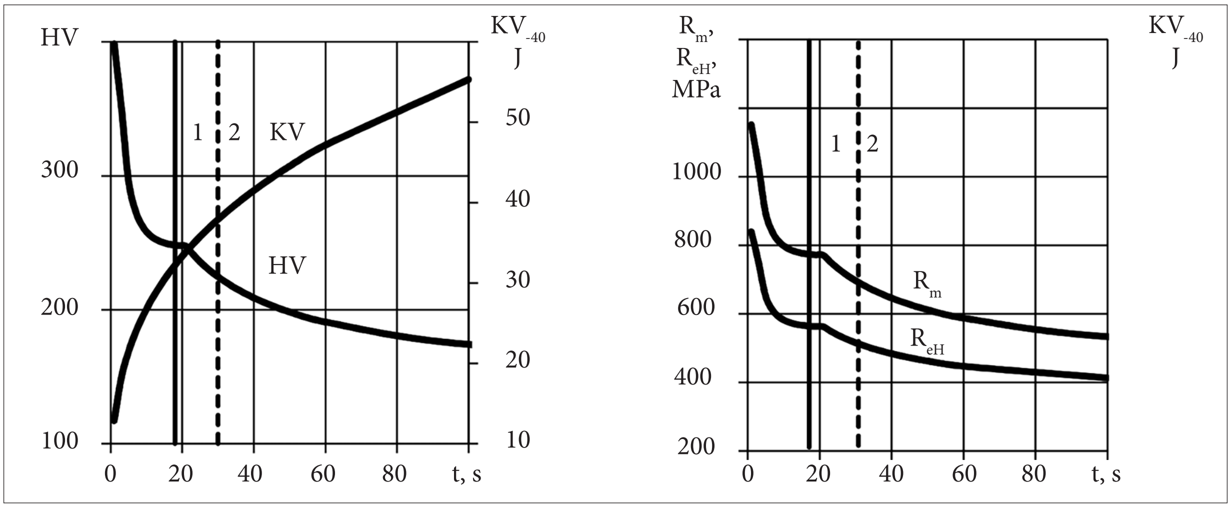
After welding, the welds were stretched and impacted. The tensile tests were carried out on cylindrical samples with a diameter of 14 mm with a linear base of five diameters.

Hardness measurements for different weld joints were performed using the Wickers method (HV10).

In order to determine the impact viscosity of the metal HAZ, we have carried out comprehensive impact bending tests in different areas of test welds (T-orientation of rolled sheeting). Five sets of standard samples (consisting of 3 samples with a V-cut for the Sharpe impact bend test) were tested for each weld joint. The incision was located along the metal of the seam, along the mold line and 2.5 and 20 mm from the mold line. The samples were cut from the straight edge of the weld.

RESULTS AND DISCUSSION

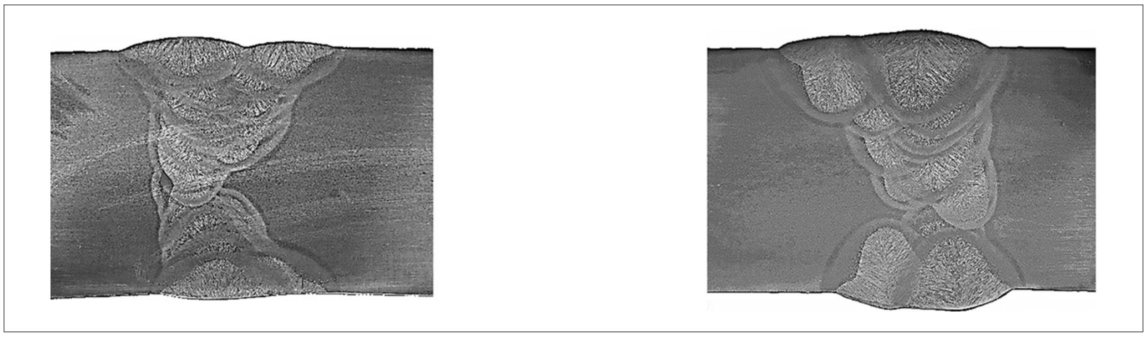
The results of calculations according to the above formulas 1-4 are presented in graphs in Fig. 1 (a. b).



a) b)

***Figure 1**. Relationship of the properties of the experimental steel metal HAZ to cooling time in the range 850... 500ºC (1–HI=2.5 kJ/mm; 2–HI=4.2 kJ/mm): a) HV hardness and operation of KV-40; b) time resistance, MPA and yield stress*

The macrostructure of the investigated welded joints is shown Figure 1, 2. In all cases, the metallographic analysis confirmed the formation of the flat metal with a smooth interface with the base metal. Macro-rodefects such as unproves, cracks, slags, pores and similar have not been found. The geometrical dimensions of the weld were in accordance with the welding procedure [8-13].



a) b)

***Figure 2**. Macro-structure of welded joints of steel of category E36: a) HI=2.5 kJ/mm; b) HI=4.2 kJ/mm (x1.5)*

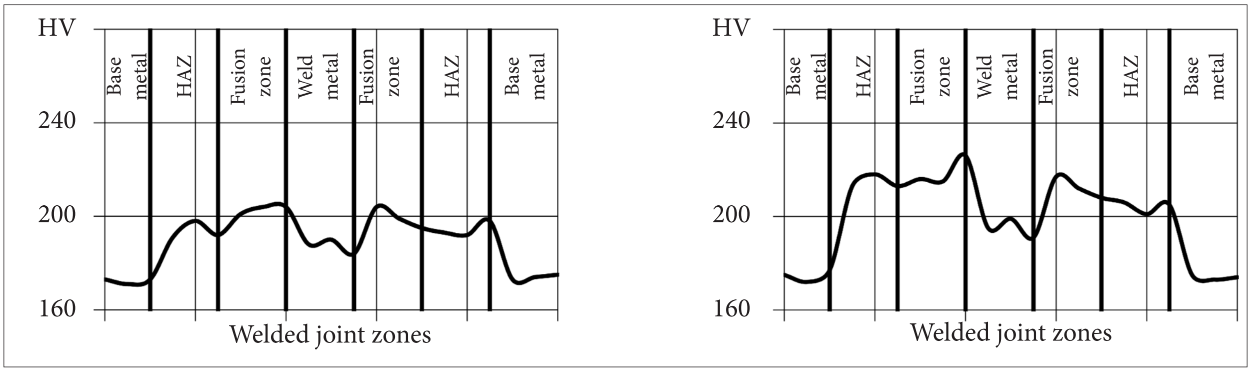
The results of tensile tests performed on cylindrical samples are presented in Table 1. Given the fact that the cylindrical tensile samples included parts of metal with different properties (ABS, base metal, seam metal), the only valid value is the temporal resistance of the base metal, as it is the cause of destruction in all cases. The analysis of the results showed that the properties of welded joints fully met the qualification requirements of the DA Regulation for steel of category E36 (T-orientation) [14] (Table 1).

The results of hardness measurements of the investigated welded joints are shown in Figure 3.

Table 1. *Results of tensile tests (d=14 mm)**

Steel category (static energy)	R_m, MPa	R_{eH}, MPa	A_5, %	Z, %
E36 (HI=2.5 kJ/mm)	507	355	23.6	72.0
	500	362	25.7	77.8
E36 (HI=4.2 kJ/mm)	510	369	24.7	70.5
	512	367	24.3	72.8

Note*: * – the tensile tests were carried out on cylindrical samples with a diameter of 14 mm with a linear base of five diameters*



a) b)

Figure 3*. Hardness distribution (HV10) in welded compounds E36 steel category: a) HI=2.5 kJ/mm; b) HI=4.2 kJ/mm*

Analysis of the hardness measurements showed that the HAZ of welds hardened the base metal and a good correlation of hardness with the thickness of the rolled metal. Increasing the torque energy of welding from 2.5 kJ/mm to 4.2 kJ/mm slightly equalizes the hardness of the metal HAZ. A comparison of the calculated and actual hardness of the HAZ in the heating of the main metal above 1350°C (the main metal adjacent to the molding line) shows that there is a fairly high degree of coincidence. For example, for welded 2.5 kJ/mm welded linear energy, the design hardness of the metal HAZ is 230 HV (see Fig. 1, a). The average effective hardness for a HAZ welded compound is 210 HV (see Fig. 3, a). In this case, the calculation error is +8.7%. For welding stroke energy 4.2 kJ/mm, the design hardness of the metal ABS is 224 HV. (see Fig. 1, a) and the average effective hardness of the HAZ is 216 HV (see Fig. 3, b). The calculation error is +3.6%. Therefore, the calculated and actual results of the metal hardness measurements of the high-temperature HAZ of E36 welds are fairly well harmonized and confirm the adequacy of the model (Eq. 1). It is not possible to determine the strength characteristics of the high-temperature sections of OT of welded compounds in practice due to their small length. However, by using known dependencies, they can be estimated with reasonable confidence. This assessment is well in line with the requirements of the international standard ISO 18265, which establishes the tensile strength relationship between Vickers, Brinell and Rockwell [15]. In this context, knowing the actual hardness indicators, it is possible to approximate the properties of the different welded compound sites. Experiment has shown that satisfactory error is also achieved. For example, the minimum hardness value of the base metal E36 for welded welding energy of 2.5 kJ/mm is 170 HV (see Fig. 3, a), which corresponds to a strength limit of ~545 MPa. Actual value of 500 MPa (cf. table 1). In this case, the theoretical error does not exceed +9%. For welding strokes of 4.2 kJ/mm, the minimum hardness of the base metal is 170 HV (see Fig. 3, b), which corresponds to a strength of ~545 MPa. Actual value 510 MPa (Table 1). In this case, the determination of the hardness limit of a metal does not exceed +7%.

By reasoning in this way it is possible to determine the strength of the metal of the high-temperature section of HAZ in terms of its hardness. For example, the mean hardness of the high-temperature HAZ. for welding energy of 2.5 kJ/mm is 210 HV (see Fig. 3, a), which corresponds to the strength limit of 675 MPa and is well in line with the design value of 770 MPa (see Fig. 1, b). The error is +12 per cent. For welding stroke energy of 4.2 kJ/mm, the mean hardness of the metal of the high-temperature segment of the ABS was 216 HV (see Fig. 3, b), which corresponds to the strength limit of 695 MPa and is well in line with the design value of 700 MPa (see Fig. 1, b). The error is less than 1%, which confirms the adequacy of the mathematical model (Eq. 2) with this degree of correlation.

Thus, knowing the exact chemical composition of steel, it is possible, using the given dependencies, Perform a primary assessment of the strength of the metal of the high-temperature sections of steel, depending on the cooling conditions of the weld joint during welding, with a sufficiently high degree of accuracy for practical purposes.

The plasticity of a metal HAZ and especially its impact viscosity depends not only on macro-indicators such as chemical composition, method of manufacture and thickness of the roller, cooling conditions during welding, structural state of the metal, Tenderloin directions, cut shape and test temperature conditions for the samples. Structural and chemical micro heterogeneity of the metal, quantity and morphology of non-metallic inclusions, purity of the grain boundary, concentration of dissolved gases and other multiple factors are also decisive, which are not included in the known regression models estimates of the impact viscosity (impact) of the metal of the high-temperature HAZ sites. This significantly reduces the reliability of the calculations. Correlation coefficients generally do not exceed 0.75 [3; 18; 19]. In this context, most authors simulate the impact strength of high-temperature HAZ areas for samples with a circular cut at room temperature. However, it is the evaluation of impact viscosity values for samples with a V-cut at negative temperatures that is of practical importance [3; 21].

The distribution of average impact work in the different zones of test welds is shown in Fig. 4 (a, b).

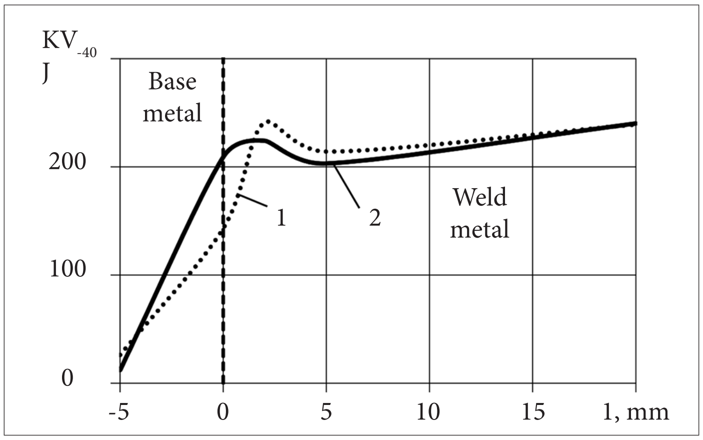


***Figure 4**. Average impact in different welded joint areas (T-orientation): a)HI=2.5 kJ/mm; b) HI=4.2 kJ/mm*

The analysis of the results showed that the minimum impact values in all cases exceeded the regulated value for E36 KVT_{-40} 24 J steel. However, there is significant anisotropy of properties in different welded areas. In addition, the range of actual impact values within the range of up to 25% in the high-temperature HAZ location of interest is variable, which makes accurate prediction problematic and once again confirms the low stability of the performance of the metal impact HAZ for the thickness of E36 steel (T-orientation). The greatest variation, however, is found at metal sites 2-5 mm from the molding line, probably due to the formation of the most unstable structure in this area with the maximum negative influence of the gases dissolved in the metal [4].

The estimated impact strength of high-temperature HAZ metal for sharp-cut samples and test temperature -40°C is KV_{-40}=32 J, for weld weld energy of 2.5 kJ/mm and KV_{-40}=38 J, for weld energy of 4.2 kJ/mm (see Fig. 1, a) which differs significantly from the real figures (see Fig. 4). In this context, the regression model for the calculation of the metal impact viscosity of the high temperature sections of the HAZ (Formula 4) by chemical composition, taking into account the cooling conditions of the weld, Does not provide a satisfactory correlation between design and actual data and cannot be recommended for practical application for the evaluation of properties of metal HAZ welded compounds of high-thickness steel of category E36 (T-orientation).

Thus, in practical terms, existing mathematical models for the evaluation of mechanical performance (R_m, R_{eH} and HV) to optimize weld compound properties and reduce related material costs HAZ metals can be used in the development of welding processes for E36-grade thick-steel steel structures. The operation of the impact (KVT_{-40}) is mandatory.

CONCLUSIONS

1. Analytical methods for calculating the mechanical characteristics of high-temperature HAZ sites (R_m, R_{eH} and HV) for chemical composition, taking into account the cooling rate after welding, Provide a level of confidence sufficient for practical application and can be

recommended for the primary evaluation of the properties of welded compounds of high-thickness steel plates of category E36 (T-orientation).

2. The minimum values of impact work in all cases exceed the regulated indicator for steel of category E36 – $KVT_{-40} \geq 24$ J. There is a significant anisotropy of properties in different zones of welded joints. In the high-temperature section of the HAZ, in both cases, the range of actual values of the impact work has a deviation of up to 25%, which makes accurate prediction problematic and once again confirms the low stability of the impact work of the HAZ metal for thick rolled steel of E36 category (T-orientation). At the same time, the greatest spread of values is typical for metal sections at a distance of 2-5 mm from the fusion line, which is probably due to the formation of the most unstable structure in this area with the maximum negative effect of gases dissolved in the metal.

3. Impact work (KV_{-40}) of high-temperature sections of the HAZ is not subject to analytical assessment, with the degree of accuracy required for industrial practice. For further application of the analytical evaluation, it is necessary to conduct studies of the effects of gases on the impact work. And also to make the necessary corrections of the coefficients in the analytical formulas.

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Комплексна оцінка зварюваності сталі підвищеної пружності

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Анотація. Сучасне виробництво сільськогосподарської техніки та обладнання, корпусів суден, стаціонарних нафтових бурових платформ, вітроенергетичних установок та інших металоконструкцій широко використовує листову сталь підвищеної міцності. Основним виробничим процесом є зварювання, якість якого залежить від багатьох факторів, у тому числі від здатності сталі протистояти зварюванню. Відомо, що властивості зони термічного впливу значною мірою залежать від фазових перетворень, характер яких визначається інтенсивністю та розвитком дифузійних процесів перерозподілу вуглецю та легуючих елементів під впливом зварювального термоциклу. Тому необхідно оцінити зварюваність сталі певного хімічного складу, щоб вибрати оптимальний спосіб і технологічні параметри режиму зварювання для виготовлення конкретної металоконструкції. З метою зниження матеріальних витрат можна використовувати аналітичні методи розрахунку, які були розроблені в Інституті електрозварювання ім. Е.О. Патона. Вони базуються на аналізі літератури та вивченні близько 150 діаграм термокінетичного розпаду аустеніту. Математичні моделі дозволяють з достатньою точністю прогнозувати фазовий склад і механічні властивості високотемпературної зони термічного впливу в залежності від хімічного складу і часу охолодження металу, нагрітого до максимальної температури 1350 °С., в діапазоні температур 850–500°С. Однак такі випробування є досить дорогими і не дозволяють оптимізувати властивості зварного шва при зміні режиму зварювання, зварювальних матеріалів та інших основних технологічних факторів. У зв'язку з цим ставилося завдання оцінити надійність запропонованої методики при дослідженні зварюваності суднобудівної сталі підвищеної міцності категорії Е36, для найслабшого Т (поперечного) – орієнтації листа товщиною 50 мм. Високі показники категорії сталі досягаються обмеженим збільшенням вмісту алюмінію або інших елементів (Nb, V, Ті), що забезпечує розмір аустенітного зерна не більше п'ятого бала. Дослідження показали, що аналітичні методи розрахунку механічних характеристик високотемпературних ділянок ЗТВ за хімічним складом з урахуванням швидкості охолодження після зварювання забезпечують достатній для практичного застосування рівень достовірності та можуть бути рекомендовані для первинної оцінки властивостей зварних з'єднань, листів великої товщини зі сталі категорії Е36 (Т-подібна орієнтація). Ударна робота (KV-40) високотемпературних зон термічного впливу не підлягає аналітичній оцінці з необхідним для виробничої практики ступенем точності

Ключові слова: сталь категорії Е36, оцінка зварюваності, аналітичні методи розрахунку в зварюванні, комплексні механічні випробування, механічні властивості, ударна в'язкість, твердість сталі