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The Reduction of Stresses and Strains in High-Quality Welded Structures through the Application of Innovative Welding Methods

Abstract: The study discussed in the article aimed to compare the high-performance robotic MAG TANDEM process with the partly mechanised MAG STANDARD process. Experimental tests involved comparisons concerning the heat effect of the dual-electrode MAG TANDEM process with that accompanying the single-electrode MAG STANDARD process. The tests also included comparisons of linear welding energy (heat input) and its effect on stresses and strains generated during the fabrication of welded structures.

Keywords: MAG TANDEM process, MAG STANDARD process, welded structures

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Introduction

One of the most promising variants of robotic gas-shielded metal arc welding methods is the MAG TANDEM process. MAG TANDEM welding involves the application of a system consisting of two welding power sources which power two independent electric arcs and melt both the base material and the filler metal in one weld pool. The advantages of the above-named process are the following:

1. melting efficiency exceeding 20 kg/h [1],
2. possibility of obtaining butt and fillet welds characterised by high-quality weld faces, using high welding rates of up to 4 m/min [2],
3. application of a tracking system in the form of a current arc sensor; welding rates being of up to 1.5 m/min [3],
4. high arc burning stability in the dual-electrode (two-wire) system, reducing welding spatter in comparison with that accompanying the MAG STANDARD process [4].

Available research publications lack information concerning the quality of joints made using the MAG TANDEM method, particularly in relation to actual values of welding stresses and strains. The assessment of stresses existing in welded structures discussed in the article is based on the Barkhausen method. Progress in tests concerning physical properties of parameters combined with developmental progression of electronics (in terms of the fast processing and visualisation of data) have enabled the application of the Barkhausen effect (taking place in ferromagnetic materials) in non-invasive measurements of stresses in any area/spot of welded structures made of ferromagnetic materials [5]. Carbon and low-alloy structural steels belong to a group of materials characterised by high and accurate Barkhausen method-based measurability of stresses in welded joints [6]. The Barkhausen effect consists in the stepped change of ferromagnetic material (grains) magnetisation triggered by the variable magnetic field. The blocking of grain movements depends on, among other things, stresses present in a magnetised material. The above-named "resistance" (magnetisation ease) can be measured as the valued of voltage induced in a detection coil (the so-called Barkhausen noise) and visualised based on characteristics (determined only once) of a material subjected to measurement and manifested by the level of stress in any area/spot of the welded structure (including welded joints). The above-presented method

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combines the advantage of test non-invasiveness with testing accuracy and rate.

The advantages enumerated above are responsible for the rapidly growing popularity of the MAG TANDEM method, making it particularly useful in tests of welded structures. The intensity and directions of stresses in base materials used in the fabrication of welded structures as well as stresses generated during the processing of materials (particularly during welding processes) determine ultimate stresses and plasticity of finished structures. Obviously, stresses significantly affect the quality and operational safety of welded structures.

Heat input assessment

During experimental tests involving the use of the MAG TANDEM and MAG STANDARD methods, temperature measurements were performed on the joint surface opposite in relation to the surface directly affected by welding arc. Such an approach was dictated by the fact that the near-weld area of a material subjected to welding was characterised by the fastest cooling rate (dependent, among other things, on linear energy) and that the above-named area was free from disturbances triggered by arc radiation. To prevent temperature measurements from affecting the course of thermal processes in the weld axis it was necessary to apply a non-contact method involving the use of an infrared camera, whose advantage was its independence of thermal processes [7]. The comparison of heat inputs was based on the measurement of heat propagation in a workpiece and the adoption of the same heat efficiency coefficient for the MAG TANDEM and MAG STANDARD processes. The primary condition concerning the performance of tests was the assumption according to which a heat input was proportional to the amount of heat emitted from the material as a result of radiation. On the basis of the above-named condition it was possible to assume that the radiated power of the object heated by welding arc was proportional to arc effective energy (taking into account losses connected with spatter and emission of heat from arc into the environment). Because of the fact that energy losses were taken into account using the coefficient of the thermal efficiency of the process, the occurrence of differences (if any) concerning a heat input to the material in relation to the same apparent arc power of both processes resulted from different heat input methods, i.e. by a dual-arc heat source and a single electrode.

Test specimens were subjected to shot blasting in order to obtain the rough uniform surface characterised by high emissivity (amounting in the case under discussion to approximately 0.7) [8]. The above-presented preparation helped reduce the measurement error connected with the non-homogenous surface condition and, consequently, the random value of the coefficient of emissivity. The analysis of recorded data enabled the obtainment of information concerning the actual temperature of the surface of the object subjected to observation.

Measurement station

The measurement of temperature distribution in the joint subjected to analysis involved the use of a V20PR2-5 infrared camera (Fig. 1). Before the test, the camera was subjected to temperature calibration by introducing the dependence of coefficient of emissivity ε in the function of the temperature of the element subjected to the test. The emissivity of the surface was calibrated by comparing infrared radiation-related data with results obtained using a K-type thermocouple.

The tests made it possible to identify temperature changes during the heating and cooling of the base material surface, located on the opposite side of the joint in relation to the surface affected

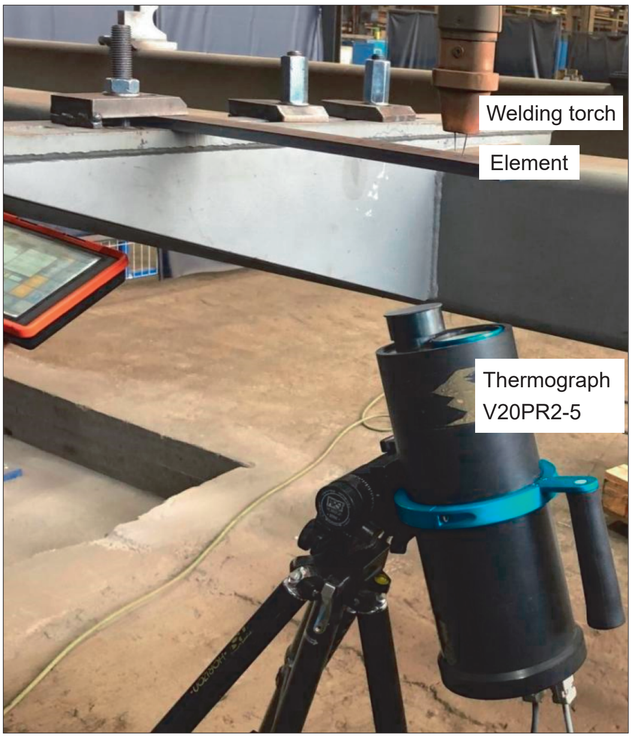

Fig. 1. Non-contact measurement of temperature during the MAG STANDARD and MAG TANDEM processes

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by the heat source. The recording of temperature was accompanied by measurements of current, arc voltage, filler metal wire travel rate and welding rate. The subsequent stage involved the comparison of temperature curves of both processes by measuring the field under the heating and cooling curves within the same time interval (Fig. 2–4). The tests were performed maintaining comparable linear welding energy in the MAG STANDARD and MAG TANDEM processes (in relation to the similar consumption of the filler metal per 1meter of the weld length).

Table 1 presents welding parameters applied during the MAG STANDARD and MAG TANDEM processes and infrared tests. The welding processes parameters were designated as follows:

U_{d1}, U_{d2}, I_{d1}, I_{d2} – welding voltage and welding current flowing through the leading and following filler metal wire respectively,

V_{e1}, V_{e2} – travel rate of the leading and following filler metal wire respectively.

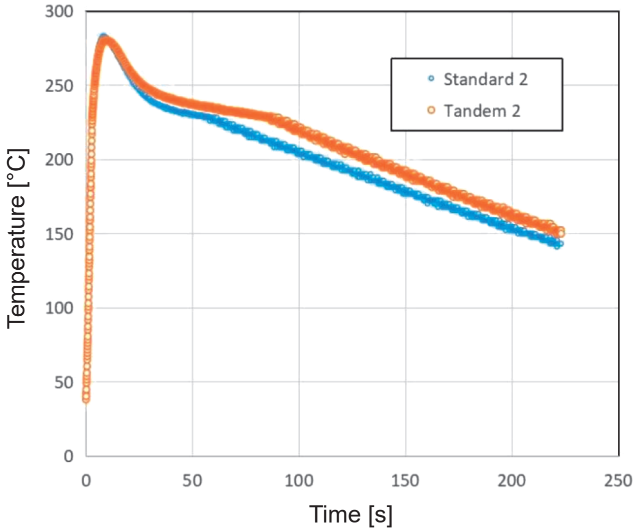

Fig. 3. Heating and cooling curves in relation to the MAG STANDARD (V_s = 0.5 m·min^{-1}; E_l = 10.84 kJ·cm^{-1}) and MAG TANDEM processes (V_s = 0.82 m·min^{-1}; E_l = 11.1 kJ·cm^{-1})

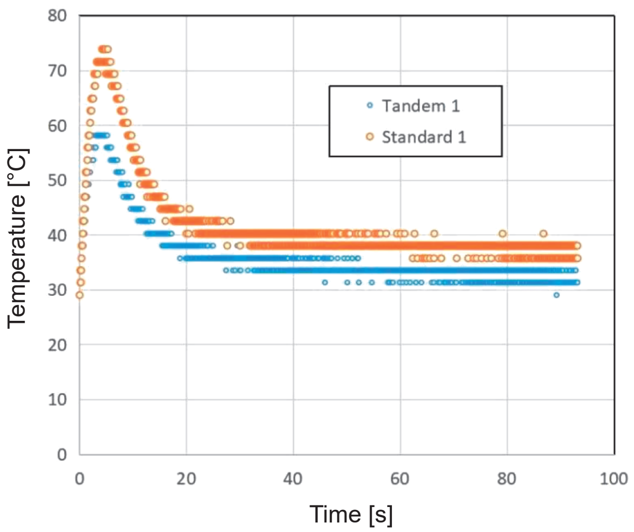

Fig. 2. Heating and cooling curves in relation to the MAG STANDARD (V_s = 1.15 m·min^{-1}; E_l = 4.27 kJ·cm^{-1}) and MAG TANDEM processes (V_s = 2.30 m·min^{-1}; E_l = 3.92 kJ·cm^{-1})

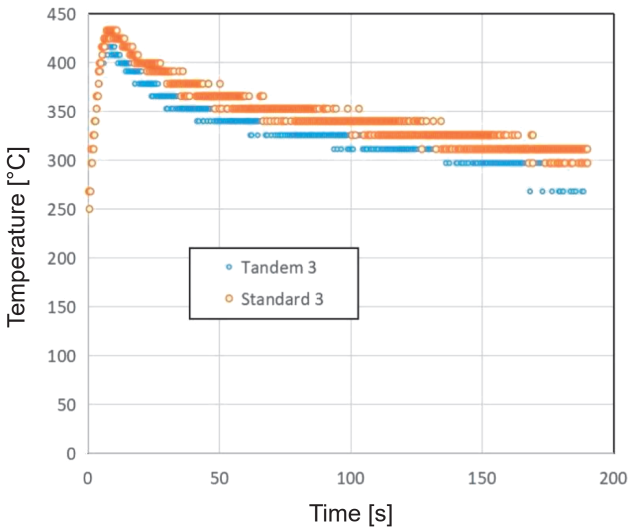

Fig. 4. Heating and cooling curves in relation to the MAG STANDARD (V_s = 0.34 m·min^{-1}; E_l = 15.77 kJ·cm^{-1}) and MAG TANDEM processes (V_s = 0.6 m·min^{-1}; E_l = 14.96 kJ·cm^{-1})

Table 1. Welding parameters used in the MAG STANDARD and MAG TANDEM processes

Welding method	Welding current		Welding voltage		Filler metal wire feed rate		Welding rate	Linear energy
	I_{d1}	I_{d2}	U_{d1}	U_{d2}	V_{e1}	V_{e2}	V_s	E_l
	[A]	[A]	[V]	[V]	[m·min^{-1}]	[m·min^{-1}]	[m·min^{-1}]	[kJ·cm^{-1}]
TANDEM 1	289	245	26.9	29.6	14	11	2.3	3.92
STANDARD 1	288	-	28.4	-	12.5	-	1.15	4.27
TANDEM 2	286	246	27.5	29.7	14	11	0.82	11.10
STANDARD 2	299	-	30.2	-	13	-	0.5	10.84
TANDEM 3	281	245	27.6	29.4	14	11	0.6	14.96
STANDARD 3	291	-	30.7	-	13	-	0.34	15.77

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Temperature changes at points located in the axis perpendicular to the weld (during the MAG TANDEM and MAG STANDARD processes) are presented in Figures 2–4. The comparison of the heating and cooling curves (Figures 2–4) revealed that different heat inputs (i.e. by single welding arc in the MAG STANDARD process and by the heat source featuring two arcs in the weld pool in the MAG TANDEM process) changed heating intensity affecting the base material (in terms of similar welding parameters (linear welding energy)). A higher heating rate during the MAG TANDEM process approximately doubled the welding rate without changing linear welding energy (similar to that of the MAG STANDARD process).

Analysis of stresses in the plate girder subjected to welding

The tests involved the making of two-sidedly welded double T-bars, i.e. made using the partly mechanised MAG STANDARD process (with the welding torch led manually) and the robotic MAG TANDEM process.

Subsequent tests involved Barkhausen method-based measurements of welding stresses and strains. Stresses were measured using a MagStress5c device (NNT) (Fig. 5), featuring calibration curves for structures subjected to measurements and made of steel S355J2.

Fig. 5. Fifth generation stress meter MagStress5C [9]

Stress measurements were performed along lines perpendicular to weld axes, using a resolution of between 10 mm and 20 mm. Stress measurement points were located in the weld, heat affected zone (HAZ) and in the base material. Figures 6 and 7 present the arrangement of measurement points and the element subjected to welding.

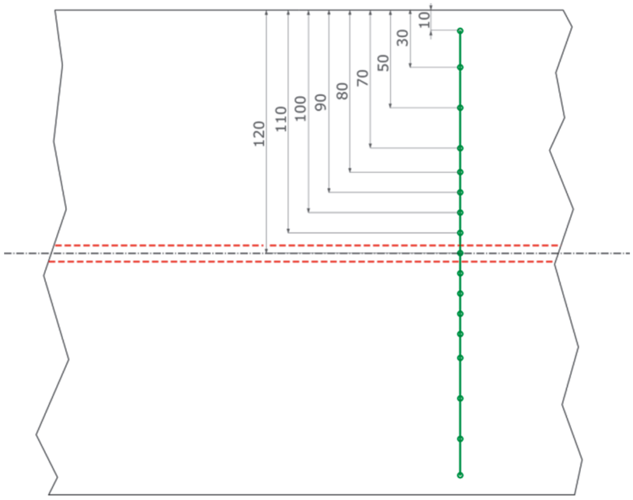

Fig. 6. Arrangement of measurement points on the double T-bar flange surface

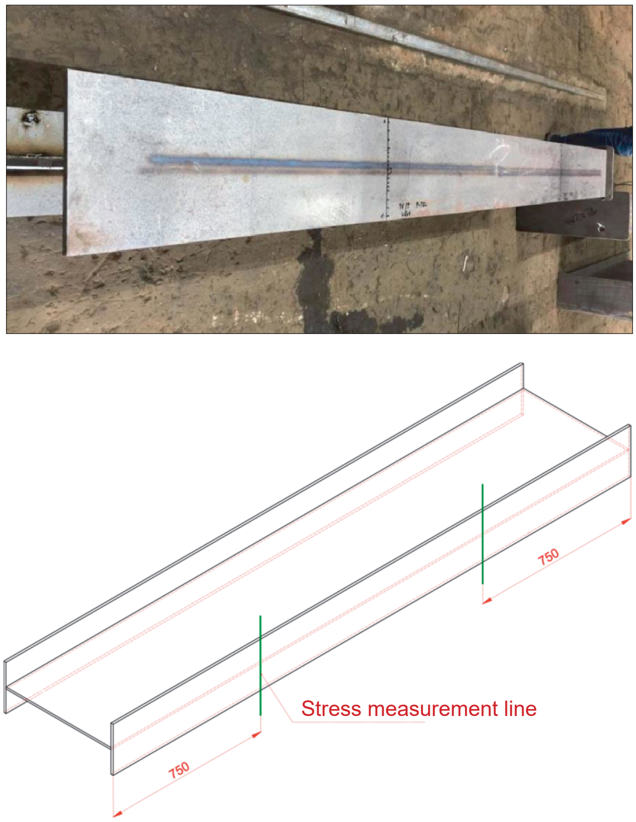

Fig. 7. Arrangement of measurement lines on the double T-bar flange surface

Stresses in MAG STANDARD and MAG TANDEM-welded double T-bar flanges

Measurements of MAG STANDARD-related stresses increased in the near-weld areas (including the weld and the HAZ) by between 400 MPa and 500 MPa if compared with those measured in the zones unaffected by heat generated during thermal cutting and welding processes (including the base material area outside the HAZ). Curves of stresses measured in the

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specimen subjected to MAG STANDARD welding are presented in Figure 8.

Figure 9 presents the representative distribution of longitudinal stresses measured along the line perpendicular to the axes of the welds made using the robotic MAG TANDEM method. Figure 10 presents the macrostructure and parameters used in comparative tests.

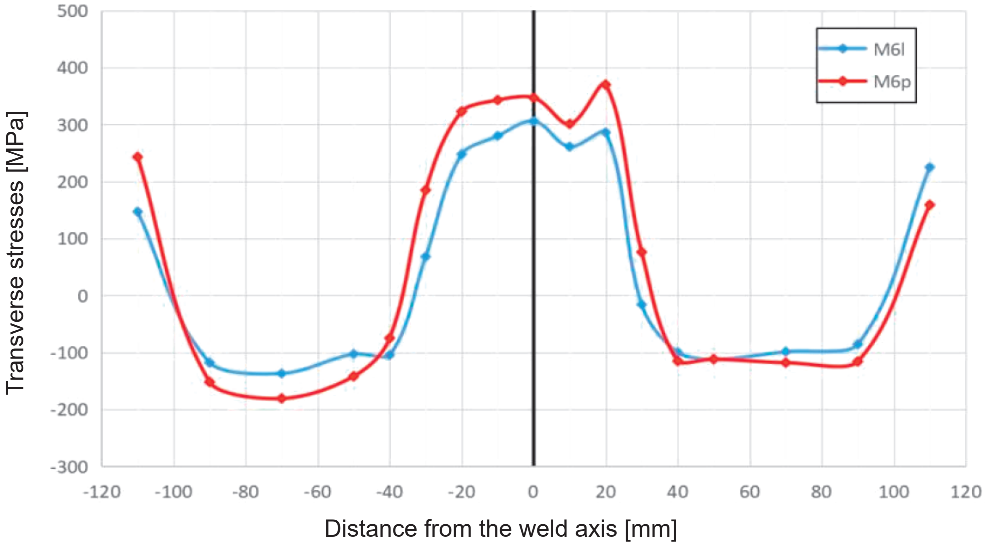

Fig. 8. Distributions of longitudinal stresses in the axis perpendicular to the web axis; stresses measured on the surface of the MAG STANDARD – welded demonstrator flanges

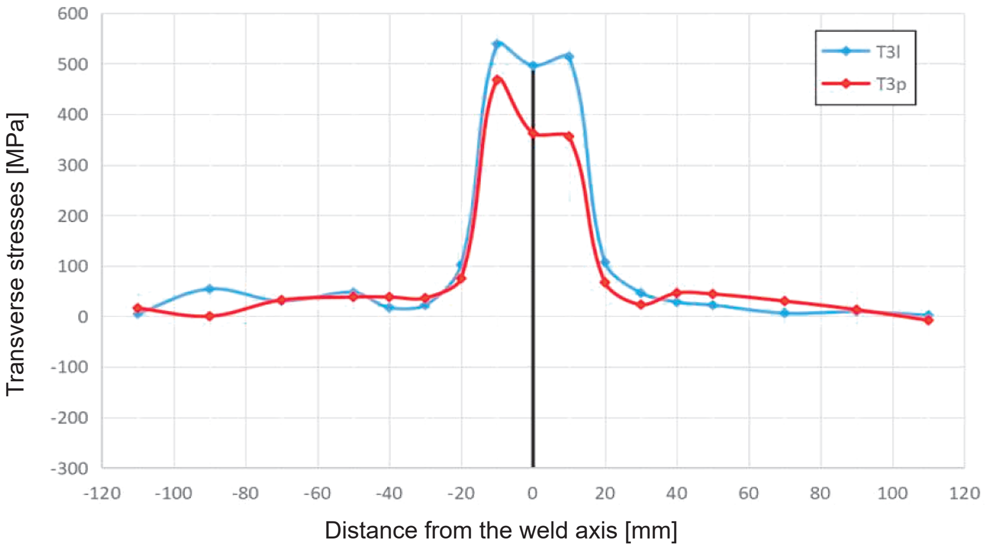

Fig. 9. Distributions of longitudinal stresses in the axis perpendicular to the web axis; stresses measured on the surface of the MAG TANDEM – welded demonstrator flanges

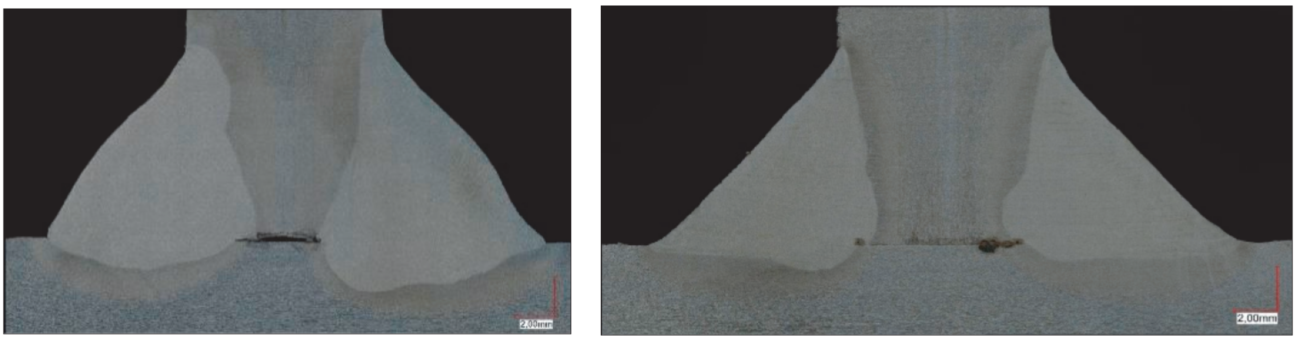

Fig. 10. Macrostructure of the MAG STANDARD (M6) and MAG TANDEM-welded joints (T2); welding parameters used in the TANDEM process: I_{d1} = 265-275 A, I_{d2} = 233-255 A, U_{d1} = 27.5-28.5 V, U_{d2} = 27.5–28.5 V; V_{e1} = 14 m·min^{-1}, V_{e2} = 11 m·min^{-1}; V_s = 0.6 m·min^{-1}; E_l = 1.15 kJ·mm^{-1}; welding parameters used in the MAG STANDARD process: I_s = 266–288 A; U_s = 30.2–30.9 V; V_e = 11 m·min^{-1}, V_s = 0.27 m·min^{-1} and E_l = 1.49 kJ·mm^{-}

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Similar to the partly mechanised welding process, the values of stresses were restricted within the range of 400 MPa to 500 MPa. However, stresses measured on the edges of flanges amounted to zero or were of favourable, i.e. compressive, nature and amounted to -100 MPa (which, among other things, resulted from the laser/plasma cutting of the plates). In addition, in terms of the MAG TANDEM process, the stress affected width in the web axis was lower by nearly twice. On average, as regards the MAG STANDARD methods, the width of the zone affected by intense welding stresses amounted to 80 mm, whereas in terms of the MAG TANDEM method, the above-named width was restricted within the range of 40mm to 60 mm (Fig. 8 and 9).

Deformations of double T-bar flanges welded using the MAG STANDARD and MAG TANDEM method

Measurements of strains in MAG STANDARD and MAG TANDEM-welded structures necessitated the making of 6 technological demonstrators in the form of welded plate girders. After the completion of the welding process, the welds were inspected and assessed using non-destructive methods, i.e. visual tests (VT) and magnetic particle tests (MT). Individual operations connected with the making of the demonstrators involved measurements of strains (angle strains, longitudinal sagging, transverse and longitudinal shortening and twisting) of the welded plate girders (by measuring relative locations of characteristic points of the geometry of the structure subjected to welding). The analysis of the structural strains revealed that, as regards angle strains, the most important displacements (in terms of quantity) were those at measurement points located on the flange surface (36 points for each demonstrator). Afterwards, it was necessary to compile relative values concerning the locations of the points after the tacking of the elements and after the making of all the welds and, next, to convert them into the values of angle strains of the flanges. Because of the fact that the result of strain concerning a given sample was quantifiable on the ordinal scale, it was possible to order values of strains in the decreasing sequence and, next, to attribute a successive number to each measurement (given angle α). Number 1 was attributed to the greatest strain, number 2 to the subsequent strain, etc. The results represented the sequence of ranks and were used for quantifiable comparisons not having normal distribution. The diagram presented in the aforesaid manner (Fig. 11) could be referred to the tolerances of welded structures presented in the PN-EN ISO 13920 standard (4 classes of tolerance, i.e. A, B, C and D, marked in the diagram as horizontal lines). The points located above the line of a given class of tolerance required thermomechanical straightening. The test results revealed that the application of the dual-electrode MAG welding process significantly reduced structural deformations and, as a result, costs of any additional straightening procedures aimed to maintain a given structure within a previously assumed execution class.

Figure 12 presents the sum of the angle strains of the double T-bars made using the partly mechanised MAG STANDARD method and the robotic MAG TANDEM method. The data obtained in the tests revealed (Fig. 12) that the use of the MAG TANDEM process led to the 1.25-fold reduction of

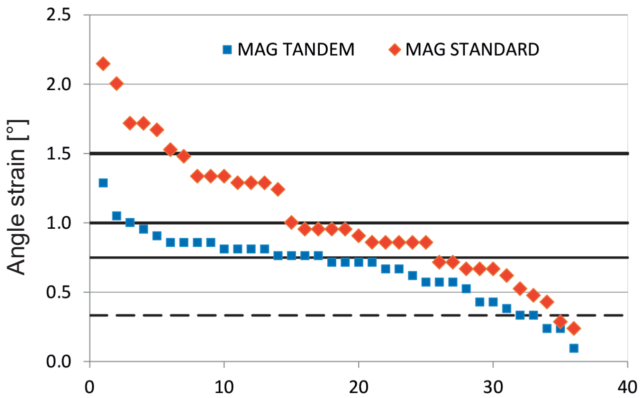

Fig. 11. Diagram presenting the arrangement of all the measurement points of the angle strains of the plate girders welded using the MAG STANDARD and MAG TANDEM methods

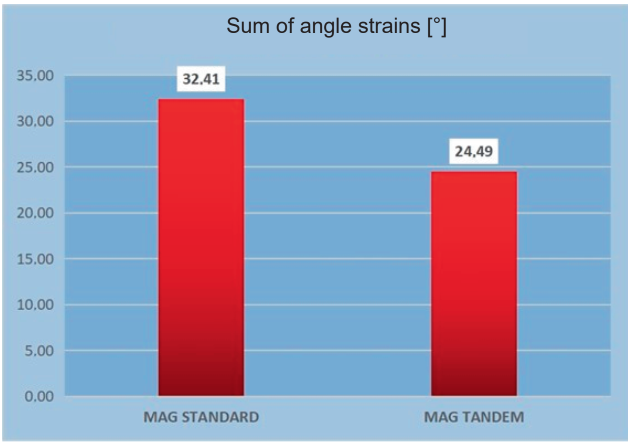

Fig. 12. Sum of unitary angle strains at the measurement points in the double T-bars welded using the MAG STANDARD and MAG TANDEM methods

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total angle strains in comparison with those present in the double T-bars made using the partly mechanised MAG STANDARD process.

Conclusions

The above-presented experimental tests revealed that the implementation of the MAG TANDEM process in production resulted in the approximately double reduction of a heat input to the joint without compromising welding efficiency (welding rate), which, in turn, led to the reduction of deformations in finished structures. Faster heating made it possible to increase welding rates which, in terms of the dual-electrode MAG TANDEM method, increased the efficiency of the welding process by twice. The Barkhausen effect-based stress measurements revealed that the heat input and the distribution of the filler metal melted by one or two heat sources significantly reduced welding stresses and, consequently, welding strains.

The application of the dual-electrode MAG TANDEM method increased welding process efficiency by twice while maintaining the comparable consumption of energy needed to power one and two arcs. As a result, both stresses and strains were less intense than those generated during the welding process involving the use of the MAG STANDARD method. The MAG TANDEM process fulfilled the previously assumed purpose of reducing welding strains, particularly during the welding of large-sized high-quality structures made using plates of medium and significant thicknesses.

The tests discussed in the article were performed within the project entitled *The Development of an Innovative Technology Enabling the Fabrication of Large-Sized Elements and Structures (Including Crane Structures) and Reducing Deformations of Welded Structures along with a Pilot Technological Line in the ZUGIL S.A. Company*. The project was financially supported within the confines of *Smart Growth Operational Programme* implemented by the Zugil S.A. company in Wieluń.

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