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Deep-Penetration Welding as a Method for Saving Materials and Increasing the Load-Carrying Capacity of Welded Structures

Abstract: The study presents possible savings resulting from the use of deep-penetration welding processes in the fabrication of welded structures. The study-related tests revealed 80% savings of filler metals and the 50% reduction of welding distortions without compromising the maximum load-carrying capacity of welded joints. The tests involved steel grades S355J2, S460NL, S700MC, S690QL and 450HBW (Hardox) having thicknesses restricted within the range of 8 mm to 20 mm as well as filler metal grades G4Si1 and G69.

Keywords: fillet weld, butt weld, deep-penetration welding process, welding capacity, welding distortions

DOI: *10.17729/ebis.2020.5/2*

Introduction

Welded structures are composed of elements joined using (primarily) two types of welds, i.e. butt welds and fillet welds. The above-named welds differ in several ways. The most important differences between the two weld types are enumerated in Table 1 [1]. The most important feature responsible for the popularity of fillet welds is their ease of making. Fillet welds do not require the employment of highly skilled welders or bevelling the edges of elements to be welded. In turn, the use of butt welds necessitates the bevelling of plates, pipes or other elements, significantly increasing fabrication costs (longer time required for order completion, use of additional equipment, increased base material processing-related waste) and, consequently, discouraging designers from using butt welds in welded structures.

However, in terms of the quality of finished and loaded structures, fillet welds are less favourable than butt welds. The former do not reach the thickness (thus strength) of elements to be joined and are responsible for notches increasing stresses in weld roots (avoidable in butt welds. Modern welded structures are designed using the ultimate limit state method [2], translating into the effort of key nodes and structural elements at a level close to their yield point. The accumulation of stresses may lead to the exceeding of the aforesaid yield point and trigger changes in the static system of forces followed by the initiation and the development of cracks proceeding from the weld root side to the weld face side [3]. The lack of penetration in the weld root may become the most vulnerable area of the entire structure, particularly if the latter is

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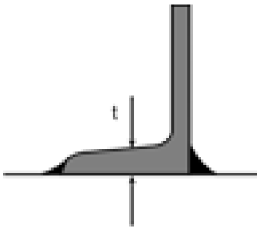
exposed to variable stresses derived from external loads. The above-named structural solutions constitute the majority of presently fabricated welded structures and are present in bridges, cranes, mining machinery, civil engineering structures (both floating and off-shore) as well as in power engineering equipment exposed to elevated or high temperature and high pressure. It is important that such structures should be characterised by safety, stability and reliability, i.e. features which are more difficult to achieve using fillet welds only. It should be noted that the design engineer designing a given structure and assuming the presence of fillet welds

Table 1. Features of butt and fillet welds [1]

Butt welds	**Fillet welds**
Butt welds nearly always have the same thickness as that of elements to be joined, or of the thinner of them (except for butt welds with incomplete penetration permitted by Eurocode 3).	Properly designed and made fillet welds never have the same thickness as that of elements to be joined; they are usually restricted within the limits presented below (above 3 mm): • $t_{sp}>0.2\ t_{max}$, • $t_{sp}\leq 0.7\ t_{min}$ in relation to one-sided welds, • $t_{sp}\leq 0.5\ t_{min}$ in relation to one-sided welds. As regards the welding of hot-rolled sections, the above-named values amount to 0.6 t and 0.8 t respectively:
	
Above a certain thickness, related to a given welding method, materials to be joined must be bevelled.	Fillet welds to not require welded elements to be bevelled.
Butt welds should be characterised by the flat or slightly convex face.	The convex weld face is always unfavourable, both in terms of strength and costs. The most favourable face of the fillet weld is concave; the flat face is acceptable
Butt welds do not increase the volume of structures.	Fillet welds increase the volume of structures.
Butt welds are intended for transmitting primary loads.	Fillet welds are used in elements exposed to lower and not exposed to vibratory loads.
The cross-section of butt welds is defined by the thickness of elements. It is possible to reduce the cross-section of butt welds by using arc methods characterised by high power density.	Fillet welds can be enlarged "on the inside" - on condition that this face has been documented. It is possible to increase the thickness of fillet welds using deep-penetration welding methods [1].
The ease of performing NDTs and the possible obtainment of weld roots characterised by high mechanical parameters (except for butt welds with incomplete penetration).	Both in terms of one and two-sided welds the possibility of checking the presence and the quality of penetration is limited. As a result, the weld root may contain notches and crack initiators.
The length of the weld is always the same as that of materials to be joined.	The effective length of the weld is not strictly related to the length of elements to be joined. It is possible to use intermittent runs. The length of single segments of fillet welds is restricted within the range of 6 a_{sp} to 150 a_{sp} (a_{sp} – effective thickness of the weld), yet it cannot amount to less than 30 mm. Above 150 a_{sp} or 1.7 m, welds are characterised by lower effective strength.

should take into consideration difficulties connected with the verification of the quality of welds and the possibility of not detecting critical imperfections gravely affecting the safety of the further operation of the entire structure. Therefore, now that materials to be joined can be subjected to deeper penetration, this possibility should be utilised (both during the design and the fabrication of structures) in technologically advanced arc or hybrid welding methods to transform fillet welds into butt or butt-fillet welds. Such a process is favoured by the mechanisation, automation and robotisation of preparatory and overall welding works. As a result, without incurring additional costs and complicating fabrication operations, it is now possible to transform fillet welds into butt or butt-fillet welds and, to a significant extent, dispense with preliminary bevelling and the employment of highly skilled welders. Savings resulting from the reduced application of filler metals, welds characterised by high quality as well as the easier, faster and automated verification of quality will become common. The quality of welds depends primarily on the adjustment and the maintaining of previously assumed welding process parameters. After combining robots with peripherals, welding manipulators/positioners and the welding arc power supply units, welding processes can be performed in flat (PA) or horizontal (PB) positions. The possibility of avoiding other restricted positions enables the application of higher current-voltage parameters leading to the deeper penetration of welds and higher process efficiency. As a result, without bevelling, it is possible to join thick elements not only in butt but also in angle joint, T-joint and cruciform configurations. Slight excess weld metal or the controlled excessive penetration of the filler metal on the weld root side are minimal if compared with the volume of material-consuming fillet welds. Butt welds or butt-fillet welds obtained in the above-presented manner are characterised by strength higher not only than that of fillet welds but also than the strength of the base materials in the joint area. In addition, the aforesaid fabrication method effectively prevents the oversizing of welds in structures, usually adopted in relation to maximum permissible thicknesses (0.7 t_{min} in relation to one-sided or 0.5 t_{min} in relation to two-sided fillet welds). The new possibilities result primarily from the use of various MAG and hybrid (laser-MAG or plasma-MAG) welding methods. Welds are largely made in the same manner but, instead of fillet welds, butt or butt-fillet welds are obtained. The gap between perpendicularly matched elements is filled, thus eliminating internal notch-induced

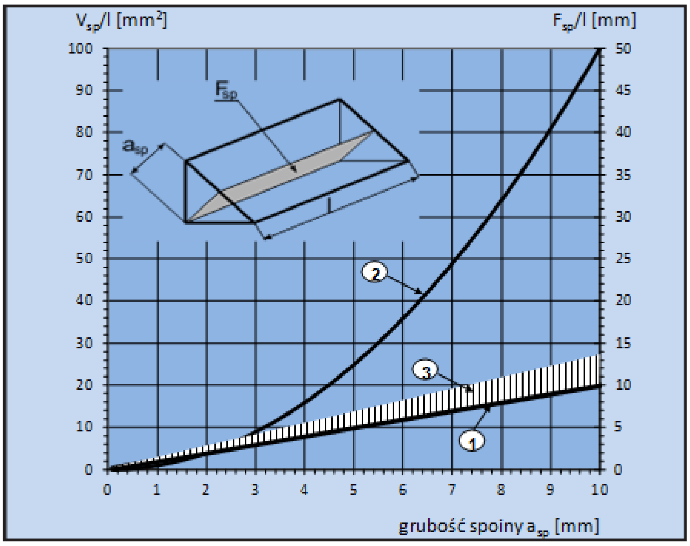


Fig. 2. Differentiated increase in the strength (1) and the volume (2) of the symmetric flat-faced fillet weld; (3) – area of possible increase in strength obtained through deeper penetration allowed by PN-EN 1993-1-8:2006 Eurocode 3

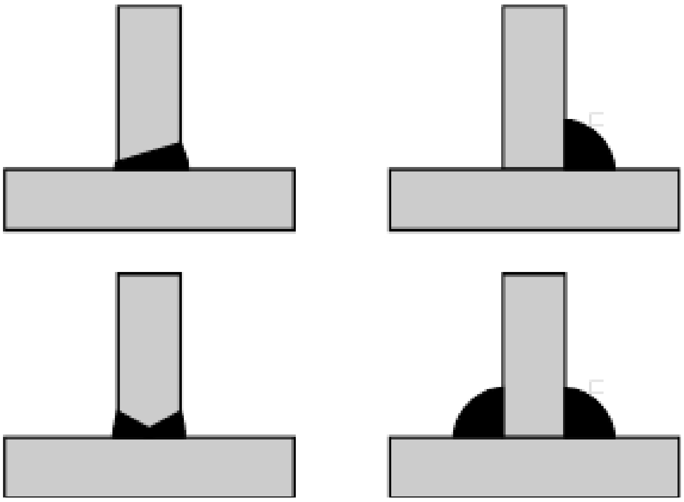


Fig. 1. Equivalent section of butt welds and fillet welds in the T-joint

accumulation of stresses. Another, less obvious, yet immensely important aspect related to the elimination of fillet welds from welded structures was the structural reduction of the size of welding distortions by moving weld gravity centres towards neutral axes of sheets/plates to be joined. Moving the weld gravity centre towards the aforesaid axes and the reduction of their elements protruding outside the outline of sheets/plates favours the elimination of welding distortions. Therefore, design engineers and welding technologists are tasked with replacing the type, shape and location of welds in welded joints.

The assumptions presented in Figure 2 revealed that the volume of the fillet weld increased significantly faster than its strength, whereas the load-carrying capacity of the butt weld was proportional to the thickness of elements being joined.

Experimental tests

Within project POIR.01.01.-00-0779/18 implemented in conjunction with the Zugil S.A. company from Wieluń, the Institute of Technologies and Automation of the Częstochowa University of Technology performed tests aimed to determine whether it was possible to reduce the consumption of filler metals and of welding distortions in T-joints and cruciform joints previously made using the standard MAG welding process and to obtain the maximum load-carrying capacity of the aforesaid joints (rupture in the base material or within the base material strength range). The tests involved five steel grades, i.e. S355J2, S460NL, S700MC, S690QL and 450HBW (Hardox), used in the Zugil S.A. company. The tests included the making and rupturing of T-joints and cruciform joints (Fig. 3) having thicknesses of 8+8 (8+8+8), 12+12 (12+12+12) and 20+20 (20+20+20) respectively. The filler metals used in the tests were electrode wire grades G4Si1 and G69. The deep-penetration welding process was performed using a Qirox robotic welding system (Cloos) [4], a Quineo Puls 601 Pro arc power supply unit and the Rapid Weld process. To identify the mechanism and values of rupture forces, the deep-penetrated T-joints were subjected to non-standardised Author-designed rupture tests performed as presented in Figure 4.

The results of the tests are presented in Figures 5–9. The mean values concerning the consumption of the filler metals (formula 1) were presented assuming the full load-carrying capacity of the joints made using the above-named

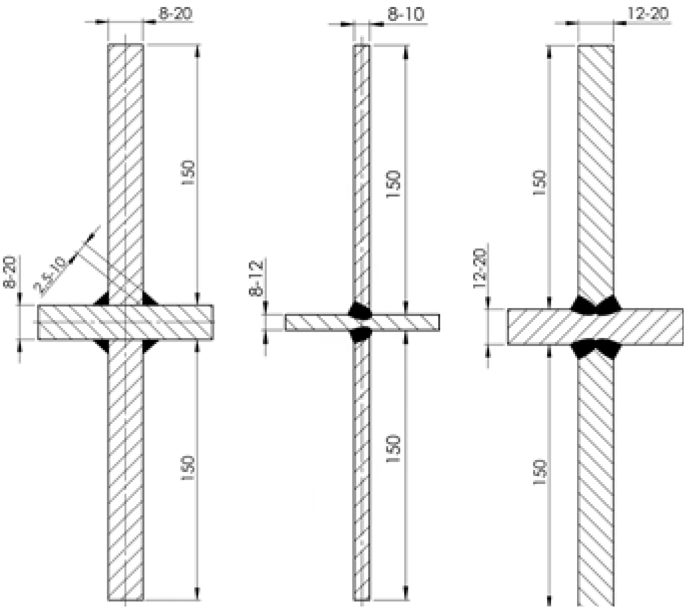


Fig. 3. Cruciform joints with a) fillet welds made using the standard process, b) one-sided butt welds and c) two-sided deep-penetration welds

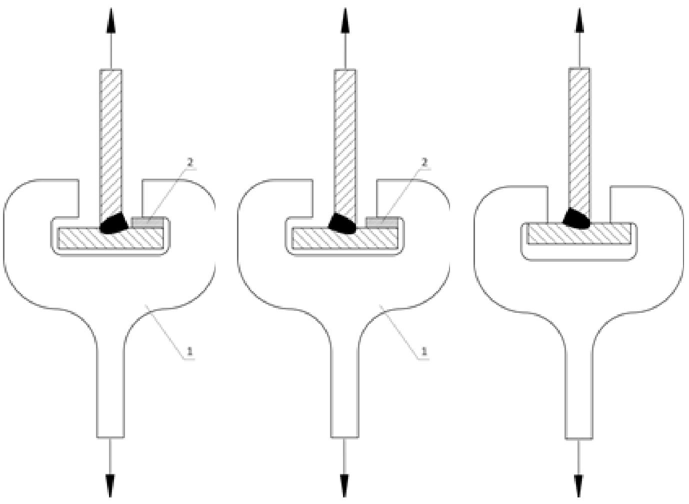


Fig. 4. Schematic diagram presenting the rupture tests of the T-joints made using the deep-penetration process: a) with the simultaneous tension of the weld face, b) with the simultaneous tension of the weld root and c) with the symmetric tension of the weld face and root

base materials and filler metals. It should be noted that the results obtained in the tests are similar to theoretical assumptions presented n Figure 2.

$$S_{MD} = \frac{\pi d_e^2}{4} \cdot \frac{V_e}{V_s} \cdot k \qquad [\mathrm{mm}^2] \qquad (17)$$

where

d_e – diameter of the electrode wire [mm],
V_e – filler metal wire feeding rate [m/min],
V_s – welding rate [m/min],
k – number of welds (of the same dimensions) in the joint.

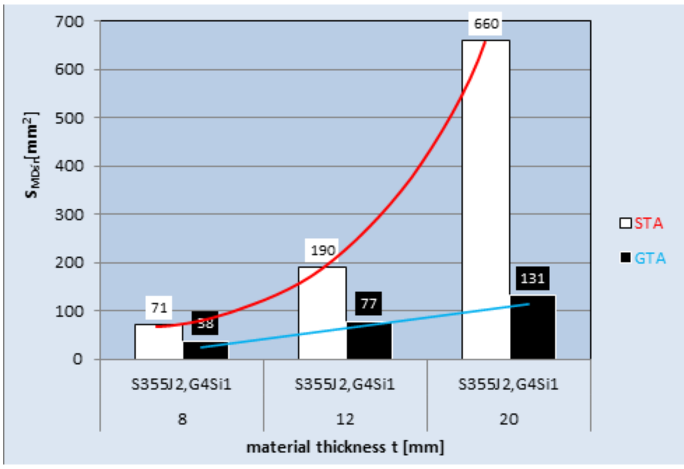


Fig. 5. Mean consumption of the filler metal S_{MD} in the joints made using the standard process (STA) and the deep-penetration process (DP); joints having the strength of the base material BM (S355J2/G4Si1); filler metal savings restricted within the range of 46% (in relation to t=8 mm) to 80% (in relation to t=20 mm)

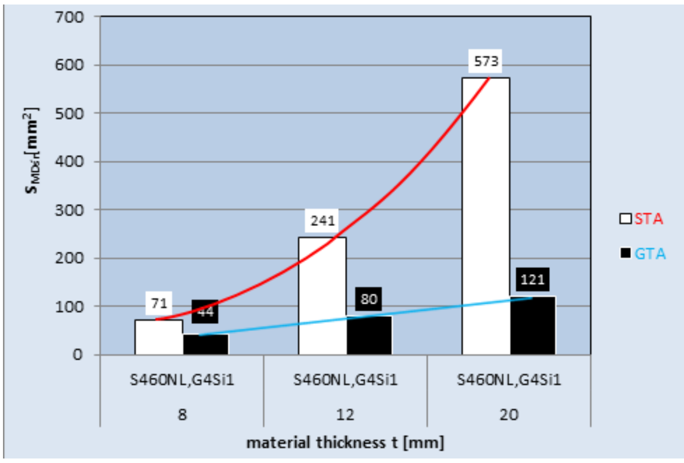


Fig. 6. Mean consumption of the filler metal S_{MD} in the joints made using the standard process and the deep-penetration process; joints of the maximum strength (S460NL/G4Si1); filler metal savings restricted within the range of 38% (in relation to t=8 mm) to 79% (in relation to t=20 mm)

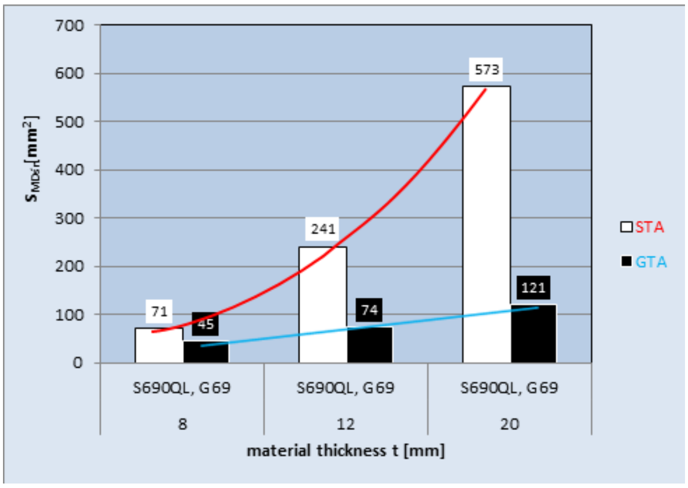


Fig. 7. Mean consumption of the filler metal S_{MD} in the joints made using the standard process and the deep-penetration process; joints of the maximum strength (S690QL/G69)

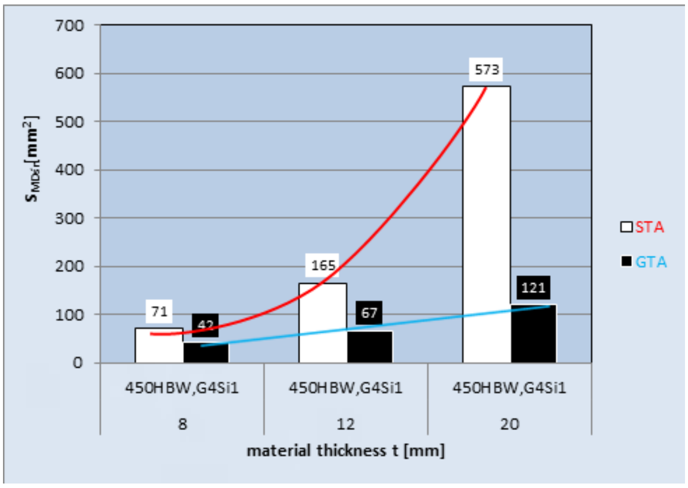


Fig. 8. Mean consumption of the filler metal S_{MD} in the joints made using the standard process and the deep-penetration process; joints of the maximum strength (450HBW/G4Si1); filler metal savings restricted within the range of 40% (in relation to t=8 mm) to 79% (in relation to t=20 mm)

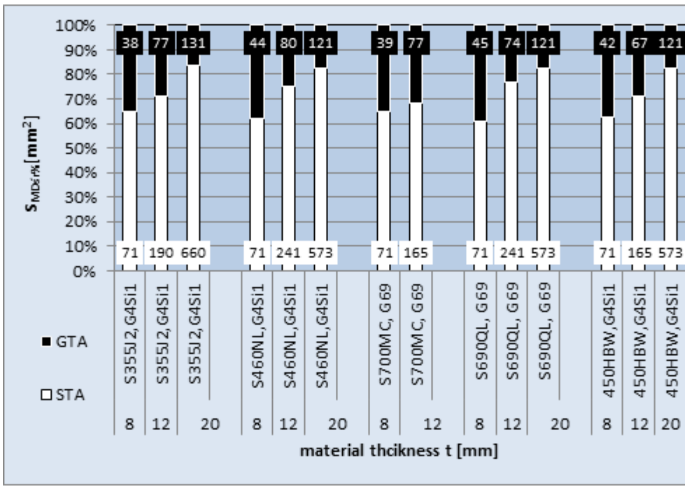


Fig. 9. Mean accumulated percentage consumption of the filler metal $S_{MDśr\%}$ in the joints made using the standard process and the deep-penetration process

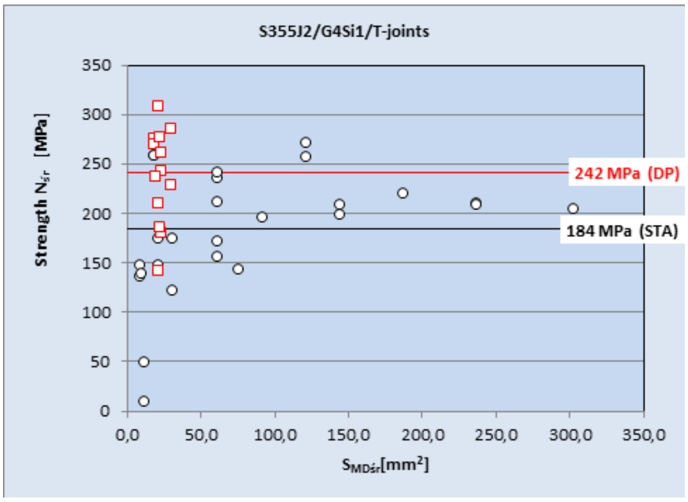


Fig. 10. Mean load-carrying capacity of the T-joints in the test involving the symmetric tension of the weld face and weld root (S355J2/G4Si1)

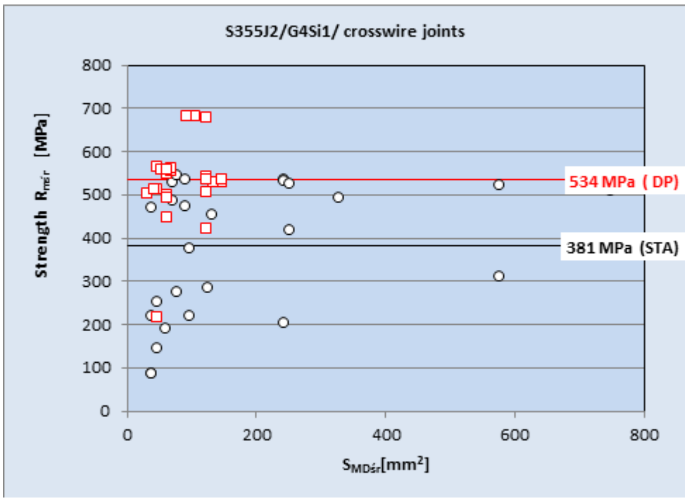


Fig. 11. Mean strength $R_{mśr}$ of the cruciform joints in the rupture test (S355J2/G4Si1)

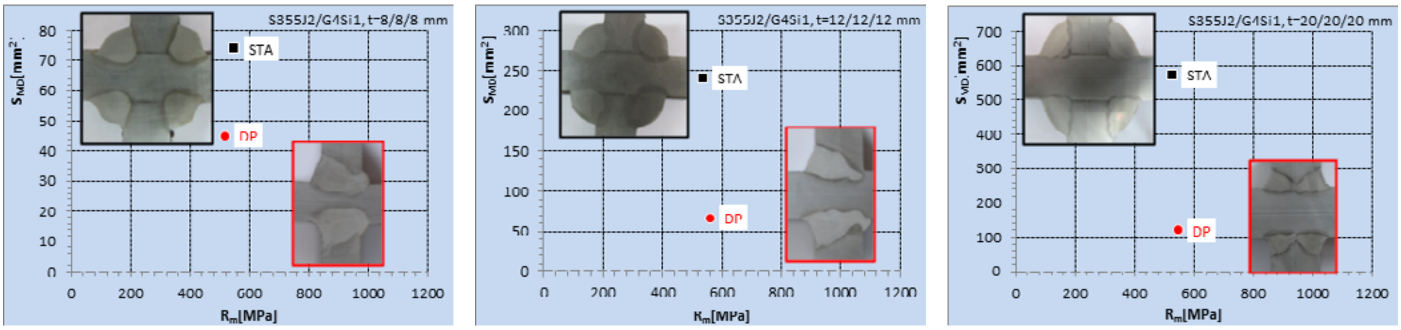


Fig. 12. Consumption of the filler metal S_{MD} in the two-sidedly welded joints made using the standard process (STA) and the deep-penetration process (DP); joints of the base material strength (S355J2/G4Si1); a) t=8/8/8 mm; b) t=12/12/12 mm and c) t=20/20/20 mm

The filler metal savings were restricted within the range of 36% (in relation to t=8 mm) to 79% (in relation to t=20 mm).

The tests involved the making of a total of 360 T-joints and cruciform joints having thicknesses restricted within the range of 8 mm to 20 mm. Material savings amounted to 35% in relation to the thinnest joints (8+8+8) and up to 80% in relation to the thickest joints (20+20+20). When assessing the load-carrying capacity of the T-joints (Fig. 10) and the cruciform joints (Fig. 11) it was possible to notice the significantly higher strength of the joints containing the welds made using deep-penetration process (DP) than that of the joints containing the welds made using the standard process (STA).

The reduced consumption of the filler metals, the decrease in the cross-sectional areas of the welds and the moving of their gravity centres towards the neutral axes of the elements being joined was accompanied by a decrease in angular distortions formed in the test joints after welding (Fig. 13). To a significant extent, the laboriousness of welded structures results from angular distortions as they necessitate the performance of post-weld, usually complex and time-consuming, straightening procedures.

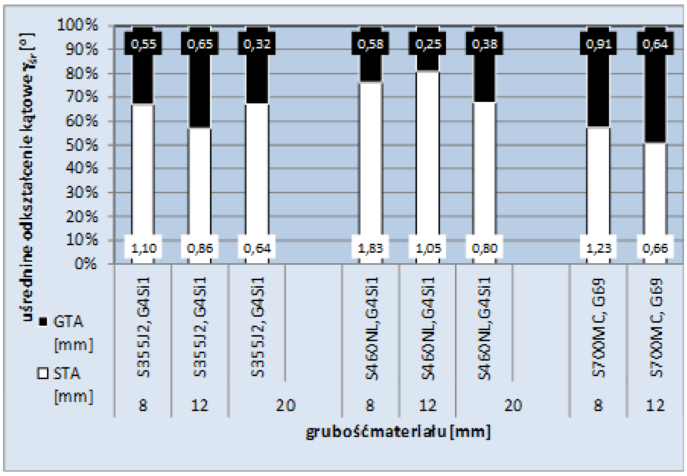


Fig. 13. Mean accumulated percentage angular distortion $\gamma_{śr}$ in the joints made using the standard process and the deep-penetration process

The use of deep-penetration welding methods makes it possible to meet several important structural and economic objectives. Joints are characterised by appropriate strength and their making requires low energy consumption. Welded structures do not undergo significant distortions and time needed for their fabrication can be significantly shortened. The above-named advantages increase along with decreasing weld volume.

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The research work was developed within project The Development of an Innovative Technology Enabling the Fabrication of Large-Sized (Crane) Structure Elements and Reducing Distortions of Welded Structures along with a Pilot Technological Line in the Zugil S.A company POIR.01.01.-00-0779/18.