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Thick-Walled Materials Weldability Assessment Based on Test SEP 1390

Abstract: The article presents issues related to weldability assessment concerning thick-walled materials used in the making of steel welded structures. The article describes weldability assessment tests in accordance with the guidelines of test SEP 1390, recommended for thick-walled structural materials exposed to dynamic loads. The objective of the tests involved the assessment of the usefulness of test SEP 1390 when evaluating the weldability of thick-walled structural materials used for welded structures.

Keywords: weldability, properties of structural materials, bend test, cracks assessment, destructive tests

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Introduction

Global economic growth initiates numerous investments in civil engineering, power engineering, metallurgy, shipbuilding or raw materials excavation and processing. Usually, investments in these industries entail the making of large-sized and thick-walled structures having structural nodes requiring various thick-walled welded joints demanding appropriate technologies and conditions guaranteeing the obtainment of necessary properties. One of the primary properties of materials used in structures and products is weldability, particularly important in relation to materials requiring thermal processing involving thick-walled elements. The notion of variously defined weldability is directly connected with the usability of materials when making welded joints in specific conditions and using specific technologies in order to obtain stable joints of required quality and operational characteristics. Weldability includes many factors directly affecting the final result of welded joints and connected with appropriate design, technological implementations and proper metallurgical processes. Practical applications require the determination of weldability-related material features using analytical methods (computational formulas), simulations (simulators of welding thermal cycles) and other technological tests. Analytical methods are popular (including the determination of carbon equivalent (CE)) because of relatively low costs and due to the quick obtainment of required results, unlike very expensive and time consuming simulation-based tests. Technological tests are often used for verifying analytical methods and in order to confirm quality assumptions required by related standards and guidelines. Recommended technological tests are often connected with

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material cracking or crack susceptibility and include Tekken or CTS tests as well as tensile tests in the z-axis focused on steel susceptibility to lamellar cracking [1,2,3]. Test SEP 1390, recommended by the German Institute of Steel and Iron (ABV), is used when assessing the weldability of structural material having a thickness equal to or exceeding 30 mm and characterised by plasticity restricted within the range of 235 to 355 MPa [4, 5, 6]. This test was previously known and described in research publications as the Kommerell test [2, 5].

This study presents weldability tests and their assessment based on SEP 1390 guidelines, involving thick-walled elements made of structural steel S355J2+N used in welded structures. The test results should provide a variety of valuable information necessary when taking decisions related to selecting appropriate thick-walled materials to be used in welded structures.

Characteristics of Weldability Test SEP 1390

Test SEP 1390 is focused on the weldability of materials having a minimum yield point restricted within the range of 235 MPa to 355 MPa and a thickness equal to or exceeding 30 mm [4, 5]. The weldability tests consist in bending a specimen sampled from an appropriately prepared material. The bend test assesses the possibility of blocking a crack induced in a special overlay weld of a specimen subjected to a bend test. The shape of the specimen sampled for the tests is presented in Figure 1. The dimensions of specimens in relation to the thickness of a material being tested are presented in Table 1.

When welding thicker materials, it is necessary to remove the excess material to a thickness of 50 mm, leaving one post-roll unprocessed surface. The satisfaction of this condition is necessary because of limitations concerning loads of up to 1000 kN on standard testing machines. The scheme of a weldability test performed in a bend test involving a properly prepared specimen is presented in Figure 2. Important dimensions concerning the specimens are presented in Table 2.

Table 1. Dimensions of the specimens in relation to the thickness of tested material [4]

Material thickness g [mm]	Specimen length L_p [mm]	Specimen width B_p [mm]	Overlay weld length L_n min [mm]	Groove radius R [mm]
$30 \le g \le 35$	410	200	175	4
$35 < g \le 40$	440	200	190	4
$40 < g \le 45$	470	200	220	4
$45 < g \le 50$	500	200	220	4
$g > 50$	500	200	220	4

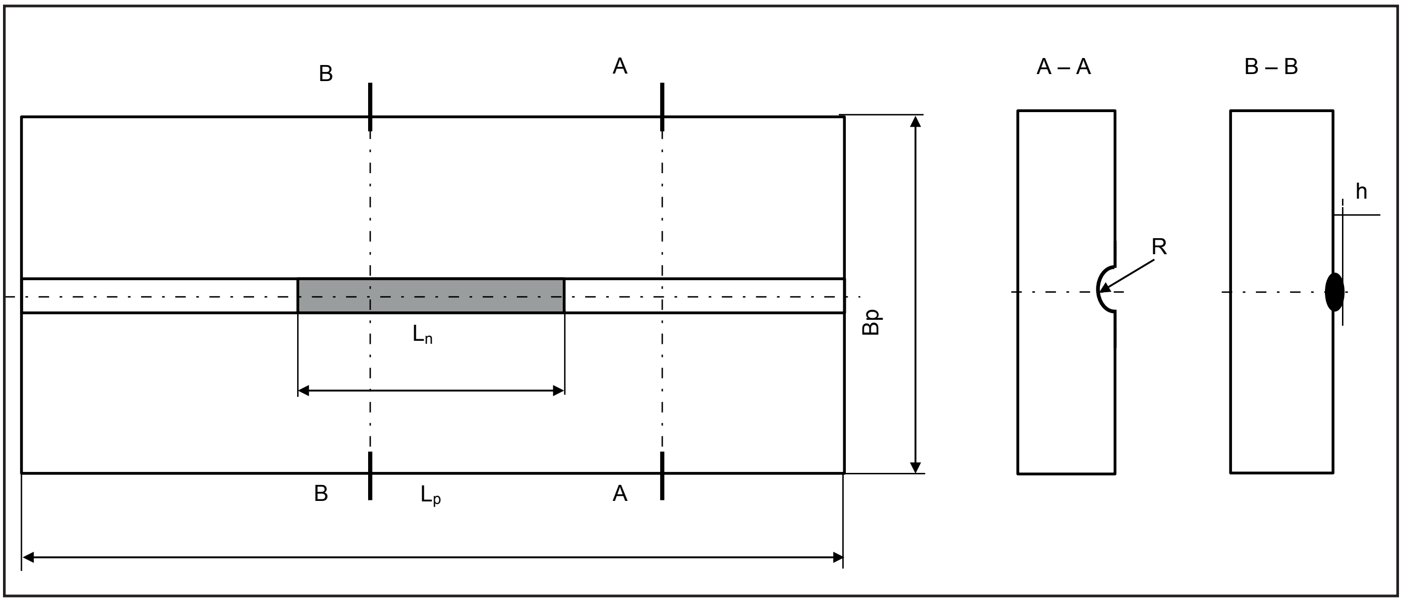

Fig. 1. Scheme of the specimen subjected to test SEP 1390; 1- material, 2 – overlay weld [4]

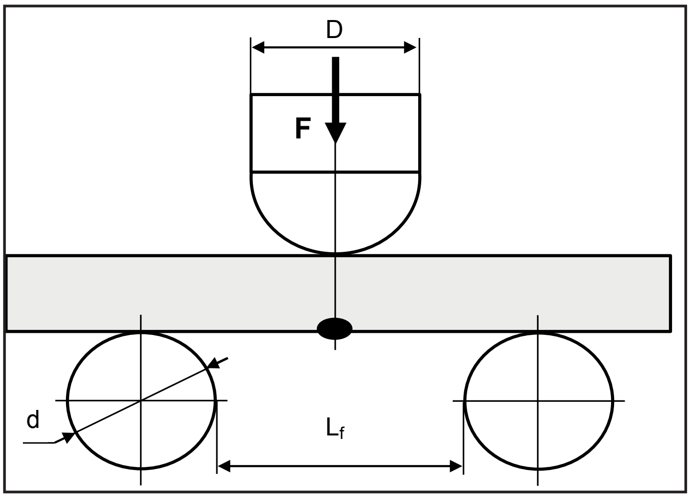

Fig. 2. Weldability tests performed in the bend test [4]

Table 2. Dimensions of the scheme involving the bend tests of the specimens [4]

Thickness g [mm]	Mandrel diameter D [mm]	Distance between supports L_f [mm]	Support diameter d [mm]
$30 \leq g \leq 35$	105	190	
$35 < g \leq 40$	120	220	
$40 < g \leq 45$	135	250	≥ 50
$45 < g \leq 50$	150	280	
$g > 50$	150	280	

The bend tests were performed using a testing machine having a significantly large load range, preferably up to 1000 kN, using appropriate fixtures according to the test scheme presented in Figure 2.

Preparation of Test Specimens

Specimens should be sampled from a material to be tested in accordance with the range specified in the guidelines of tests SEP 1390, concerning the type and thickness of a material to be tested. Specimens should be cut out and subjected to mechanical treatment to reach appropriate dimensions; external edges of specimens should be rounded. Specimens used in tests of thicker materials should be subjected to on-side treatment, i.e. the removal of excess material to a thickness of 50 mm, leaving one post-roll unprocessed surface. A groove for overlay welding, having the radius R4, should be made by subjecting the unprocessed surface to mechanical treatment in accordance with the scheme (Fig. 1).

An overlay weld should be made on the specimen in accordance with the scheme presented in Figure 1, using MMA welding and a thick-covered rutile electrode having a core dimeter of 5 mm. The overlay weld should be of the appropriate length (L_n) specified in Table 1, depending on the thickness of material and the height of excess weld metal (h) amounting to approximately 1 mm. The overlay weld should be made using a continuous run, without stopping.

The specimens for material weldability test SEP 1390 were made in accordance with the previously presented guidelines, using 30, 40 and 60 mm thick sheets made of steel S355J2+N. The material used in the tests satisfied yield point and thickness-related requirements. The most important data characterising the steel in view of the experiment are presented in Table 2.

The specimens for the tests involving the same thickness, designated as 1/40 and 2/40 were sampled from various material batches. The value of carbon equivalent for the steel used in the tests was determined in accordance with recommendations specified by the International Institute of Welding (IIW) using the following dependence:

$$Ce = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

The above named value should amount to 0.47% for material thicknesses restricted within the range of 40 mm to 150 mm. If the material thickness-related conditions concerning the

Table 2. Characteristic data of steel S3553J2N [7,8]

Specimen designation	Material thickness T [mm]	Yield point Re [MPa]	Tensile strength Rm [MPa]	Carbon content C [%]	Carbon equivalent Ce
1/30	30	356	558	0.16	0.41
1/40	40	355	556	0.16	0.42
2/40	40	363	545	0.17	0.42
1/60	60	358	512	0.18	0.44

boundary values of carbon content and carbon equivalent, i.e.

$C \leq 0.20\%$ and $Ce \leq 0.45\%$ and $g \leq 25\ mm$

or

$C \leq 0.20\%$ and $Ce \leq 0.41\%$ and $25 < g \leq 37\ mm$

are satisfied, it can be assumed that special precautions during welding are not required. It is necessary to follow recommendations formulated by IIW in relation to steel having strength R_m = 490-690 MPa and the use of low-hydrogen welding process. Materials of greater thicknesses, i.e. above 40 mm, meet the conditions named above if carbon equivalent has a value of $Ce \leq 0.40\%$. If the above named conditions are not satisfied and if there are factors connected with a significant material thickness, e.g. joint restrain degree, the risk of the formation of hard structures and, as a result, of cold cracks is significant.

The materials used in the tests can be classified, according to the above named criteria, as meeting the requirements in relation to a thickness of 30 mm, as being close to satisfying the above named criteria as regards both specimens having a thickness of 40 mm and as not satisfying the criteria as regards the material having a thickness of 65 mm. Technological tests SEP 1390 involving these materials should enable the verification of weldability-related assessment determined analytically.

Appropriately prepared specimens made of all the materials used in the tests were used for making MMA welded overlay welds. The overlay welds were made using OK FEMAX 33.80 thick-covered electrodes having a core diameter of 5 mm and meeting the guidelines specified for test SEP 1390 [9]. The above named electrodes are recommended when welding thick elements and provide weld deposit characterised by a low carbon content and mechanical properties appropriate for the steel used in the tests. Figure 3 presents the specimen without and with the overlay weld.

Fig. 3. Specimen before surfacing and with the overly weld

Bend Test

The bend test should be performed using a testing machine provided with appropriate fixtures in accordance with the scheme presented in Figure 2. The specimen should be placed on support rollers, with the overlay weld facing down. The bending mandrel of an appropriately selected diameter, i.e. following the scheme (Fig. 2) and data presented in Table 2, should be placed in line with the axes of the bottom supports, on the other side, so that the pressure exerted by the machine could cause the symmetric bending of the specimen, extending the overlay weld. The bend test should be performed under a constant load. During the test, the area subjected to tension and the bending angle of the specimen should be monitored. The test should be interrupted after reaching a bend angle of at least 60° or after the fracture of the specimen.

The specimen before the test, fixed in the bending device being part of a Heckert EU 100T testing machine, is presented in Figure 4.

By observing crack formation and propagation in the extension zone, it was possible to initially assess the correctness of the bend test (see Fig. 5). The observation was performed using a mirror placed under the specimen subjected to bending.

Fig. 4. Specimen in the bending device placed in the testing machine

Fig. 5. Initial stage of crack formation induced in the overlay weld of the specimen subjected to bending

Bend Test Assessment

After the bend test, the specimen was subjected to assessment including the visual inspection of the surface of the specimen with the overlay weld and measurement of crack lengths in relation to the overlay weld axis. In order to obtain better resolution when assessing the size of a crack, it is recommended to perform penetrant tests on the surface.

The test result should be regarded as positive if at least one crack is formed in the overlay weld. The crack should go beyond the HAZ of the overlay weld and be blocked in the base material of the specimen; the maximum length of the crack should not exceed 80 mm. If the length of the crack exceeds 80 mm, the test result should be classified as negative. In turn, if the bend test is not accompanied by the formation of any crack or if a crack formed does not go beyond the HAZ, reaching the base material, the result of such a test should be treated as invalid and the test should be repeated.

If the test of a given material finished negatively, the material should be excluded or two new specimens should be sampled from the same control group and be subjected to the test again. The result of the repeated test will be regarded as positive if both specimens have met related requirements.

The specimens after the bend tests, visual tests and penetrant tests are presented in Figures 6, 7 and 8 respectively. Figure 6 presents the 30 mm thick specimen, whereas Figures 7 and 8 present the specimens having a thickness of 40 mm. The penetrant tests made it possible to precisely determine the sizes of the cracks formed during the bend tests.

Figure 6 presents four cracks formed in specimen no. 1/30, made of 30 mm thick steel S355J2+N and subjected to bending up to an angle of 600. The maximum length of the crack passing from the weld axis through the HAZ to being blocked in the plate material amounted to 17 mm. The length of one of the remaining cracks was at the border of satisfying the requirements, whereas the other cracks did not meet the related requirements. However, ultimately, the required weldability criterion specified for this material in test SEP 1390 was satisfied.

Figure 7 presents five cracks formed in specimen no. 1/40, made of 40 mm thick steel S355J2+N and subjected to bending up to an angle of 600. The maximum length of the crack passing from the weld axis through the HAZ to being blocked in the plate material amounted to 63 mm. The lengths of two of the remaining cracks satisfied the requirements, whereas the other cracks did not meet the related requirements. However, the required weldability criterion specified for this material in test SEP 1390 was satisfied.

Figure 8 also presents five cracks formed in specimen no. 2/40, made of 40 mm thick steel S355J2+N and subjected to bending up to an angle of 600. The maximum length of the crack passing from the weld axis through the HAZ to being blocked in the plate material amounted to 76 mm. The lengths of two of the remaining cracks satisfied the requirements, whereas the other cracks did not meet the related requirements. However, the required weldability criterion specified for this material in test SEP 1390 was satisfied.

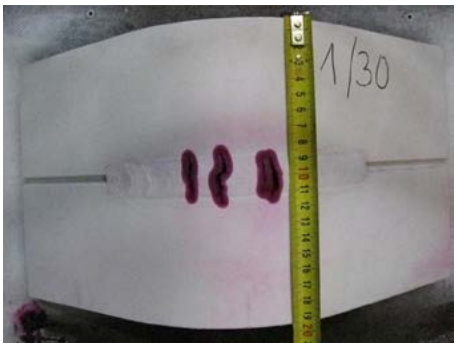

Fig. 6. Indications developed in the penetrant tests and involving the cracks formed after bending the 30 mm thick specimen

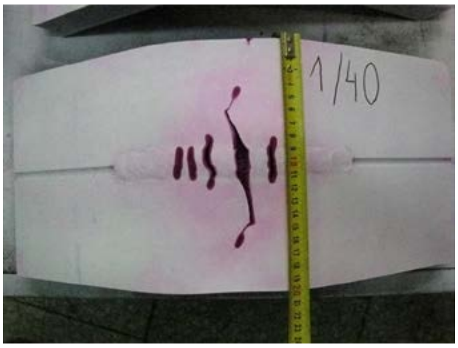

Fig. 7. Indications developed in the penetrant tests and involving the cracks formed after bending the 40 mm thick specimen

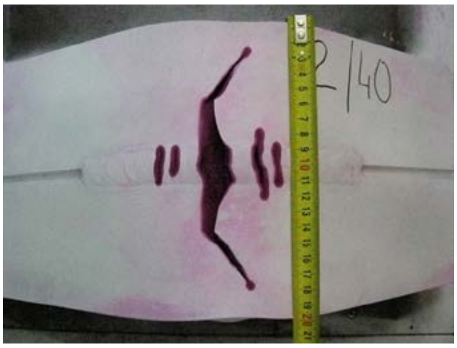

Fig. 8. Indications developed in the penetrant tests and involving the cracks formed after bending the second 40 mm thick specimen

In the last test, specimen no. 1/60, made of 60 mm thick steel S355J2+N fractured at a bend angle of 500. The fractured specimen is presented in Figure 9.

Until an angle of 500 the test proceeded normally with gradually increasing cracks, until a moment accompanied by a sudden explosion-like sound and the entire fracture of the specimen. Due to the negative result in test SEP 1390, the required weldability criterion of the material was not satisfied.

Fig. 9. Fractured specimen sampled from the 60 mm thick material

Summary

The tests demonstrated the usefulness of technological test SEP 1390 for weldability assessments concerning thick-walled materials made of steel S355J2+N and used in welded structures. The positive results obtained in the bend tests involving 30 mm and 40 mm thick elements confirmed good welding properties and the satisfaction of required weldability criteria. In turn, the test involving the 60 mm thick material produced a negative result. In the first specimen, the length of the maximum crack for the 30 mm thick material amounted to 17 mm, which demonstrated the very quick and effective blocking of the crack in the material and, at the same time, indicated very good welding properties of the material. In the second test, involving the 40 mm thick material, the length of the maximum crack was significantly longer and amounted to 63 mm, yet could still be regarded as relatively safe. In the third test, involving the same thickness but of material coming from another batch, the crack length amounted to 76 mm and was close to the boundary length of 80 mm. In turn, the test involving the 60 mm thick material produced a negative result. The specimen fractured before reaching the boundary bend angle of 600. The negative result concerning the 60 mm thick material disqualified the use of the material batch in welded structures. The results obtained in the technological tests involving all of the material thicknesses (30, 40 and 60 mm) fully coincided with the weldability assessment determined analytically. The verification of welding properties proved successful in the entire test range. Particularly interesting was the case concerning the weldability of the 40 mm thick materials where welding properties assessment results slightly exceeded boundary values, yet the technological tests were successful in spite of the fact that the crack dimensions were considerable - nearing the boundary values for the test. As a result, test Sep 1390 confirmed its usefulness when assessing the weldability of thick-walled materials, particularly those intended for critical structural elements exposed to dynamic loads.

The tests also revealed the significantly diversified frequency of crack generation in the overlay welds and the further propagation of the cracks in the material, justifying the hypothesis stating that factors affecting the diversified behaviour of cracks included the geometry and properties of the overlay weld made in the groove of the specimen subjected to bending.

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