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Stamping of Thick Sheets After Welding Process

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This paper focuses on the analysis of post-weld forming of 8 mm thick sheet metal, with particular reference to the influence of the weld zone, heat affected zone, and residual stresses on the course of the forming process and deformation characteristics. Experimental tests were carried out on steel specimens joined by active gas shielded welding. After the welds were made, the specimens were subjected to stamping tests. Observations revealed significant differences in the strain distribution in the weld regions compared to the parent material, which manifested itself as increased stress concentration and a tendency to initiate microcracks, especially in the heat affected zone. Variable hardness gradients and tensile stresses acting perpendicular to the weld line proved to be particularly significant. Successful post-weld pressing of thick plates requires not only optimisation of the parameters (forces, punch radius, process speed) of the forming process but also appropriate preparation of the weld itself — by controlling the heat affected zone structure, applying stress-relieving heat treatment, or preemptively removing the layer with microcracks in the future pressing area. Particularly for thicknesses above 6–8 mm, local differences in mechanical properties become crucial for maintaining material continuity and avoiding cracks. This article highlights the importance of an integrated approach to the design of post-weld sheet metal stamping technology, in which not only the geometry of the tool but also the previous stages of blank preparation, the quality of the welded joint and the structural characteristics of the material in the transition zones play an important role.

topics: tailor welded blanks (TWB), laser cutting, metal inert gas (MIG) welding, heat-affected zone (HAZ)

1. Introduction

Ensuring high productivity and quality of the deep drawing process for steel products with complex geometries is one of the key challenges of modern production engineering. In industrial practice, so-called tailor welded blanks (TWB) have seen growing application, as they enable sheets of different thicknesses and/or steel grades to be joined prior to the forming process. This solution allows a reduction in product weight and a rational distribution of strength within the component structure. However, literature [1, 2, 5–8] indicates that the introduction of the weld into the intensive deformation region can significantly reduce the formability, especially in the case of high-strength/complex-phase high-strength steels (HS/CP HSS). To date, research on the TWB stamping has mainly focused on thin sheets (< 2 mm). The research gap includes thicknesses ≥ 6 mm, relevant to heavy machinery and infrastructure steel construction sectors. The aim of this paper is to fill this gap by experimentally evaluating the influence of preparatory processes (laser cutting + metal inert gas (MIG) welding) on the stamping of S355MC sheets with a thickness of $g = 8$ mm. In order to correctly analyse the results of the stamping process of S355MC steel heavy plates after welding, first material tests for this steel were carried out, such as static tensile test, determination of the plastic anisotropy coefficient, measurement of the hardness of the matrix and the heat affected zone, metallographic tests, and roughness measurement.

Specimens that met specific standards or were made in accordance with the way of making the sheets for stamping were used for the tests.

TABLE I

Chemical composition of S355MC steel [%].

C	Mn	Si	P	S	Ti	Al	Nb	V
0.12	1.50	0.03	0.025	0.02	0.15	0.015	0.09	0.20

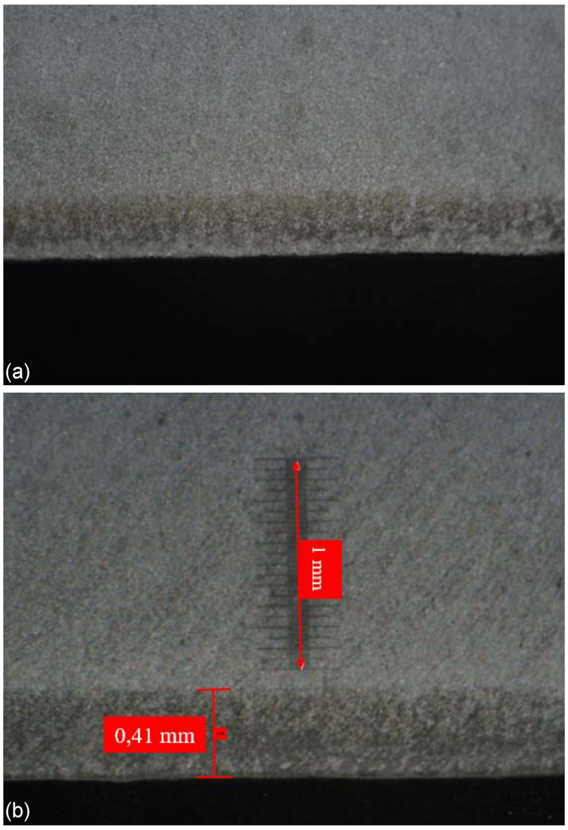

Fig. 1. Macroscopic image of (a) the heat-affected zone, (b) the width of the heat-affected zone.

TABLE II

Catalogue properties of S355MC ($g \geq 6$ mm). Here, A — elongation, R_e — yield strength, R_m — ultimate strength.

	Parameters		
	$R_{e\ min}$ [MPa]	R_m [MPa]	A_{80} [%]
In accordance with EN 10149-2	355	430 560	≥ 17

2. Methods and materials

2.1. Material properties and preliminary examination of S355MC steel

S355MC steel plate is a hot-rolled structural steel plate designed for cold forming and welding. Tests were carried out on S355MC metallurgical products that comply with the EN 10149-2 standard. The chemical composition is shown in Table I, and selected properties, as declared by the manufacturer, are presented in Table II.

Static tensile test was carried out according to EN ISO 6892-1. Specimens were prepared from S355MC steel according to the guidelines. Tests were carried out on a TesT GmbH tensile testing machine (model 113.100 kN.L, KJ/NW/A1104). Table III shows the results of the tensile test.

TABLE III

Results obtained from the static tensile test.

Parameter	Mean value
Tensile force F [N]	75264
Cross-sectional area narrowing Z [%]	61.7
Upper yield strength R_{eh} [MPa]	356.3
Tensile strength m [MPa]	470.4
Percent elongation after rupture A_5 [%]	30.7

TABLE IV

Process parameters for cutting S355 steel with a thickness of 8 mm.

Parameter	Specification
Laser power	5 kW
Working gas type	oxygen
Gas pressure	0.5 bar
Cutting feed rate	2.6 m/min
Nozzle diameter	1.2 mm
Focal length of lens	7.9”
Cutting gap	0.7 mm

The blanks, which were subjected to welding and then stamping, were cut using laser cutting technology. Consequently, a heat-affected zone (HAZ) occurred at the periphery of the sheets. Due to the presence of the HAZ, a microscopic examination was also carried out in accordance with EN ISO 6520-1 to determine the extent of this zone. The result of the examination is shown in Fig. 1a, b.

The heat-affected zone is located in an area ≈ 0.41 mm wide from the edge of the sheet to the centre of the material.

The action of the laser beam hardens the steel, so the samples were subjected to hardness test. Hardness measurements were carried out using the Vickers method according to EN ISO 6507 1. A Vickers HPO 250 hardness tester (VEB Leipzig, KJ/NW/U2822) with a diamond indenter was used. The hardness tested ranged from 158 HV in the matrix to 170 HV in the HAZ.

2.2. Preparation of semi-finished products

The preparation sequence comprised four main stages: laser cutting (Fig. 2), edge bevelling, MIG welding, and facing to align the disc surfaces. A brief description of these processes is given below.

Fig. 2. Semi-finished products after laser cutting operation.

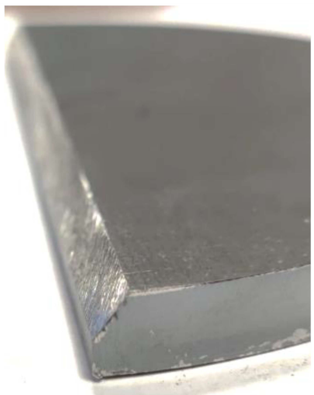

Fig. 3. Edge beveling.

(i) Laser cutting (TruLaser 3060 Fiber, TruDisk 6001) — parameters are listed in Table IV. The first stage was to cut the blanks from 8 mm thick sheet metal. These parts were laser-cut using a Trumpf TruLaser 3060 Fiber machine equipped with a TruDisk 6001 solid-state laser. The laser radiation emitted by the TruDisk 6001 has a wavelength of ≈ 1.03 μm, which allows more efficient energy absorption by the workpiece than in the case of a CO_2 laser.

(ii) Bevelled edge — 30° milling, gap $\sim$ 1.5 mm. (This process was followed by bevelling of the edges of the plates.) Bevelling is carried out in order to facilitate the welding process and to obtain an adequate fusion of the material. The resulting weld is then correct in terms of geometry and quality. Bevelling is performed as shown in Fig. 3 to produce a "Y"-shaped weld.

(iii) MIG welding — parameters are listed in Table V. The next operation was to join the edges of the two plates using a butt weld in a MIG welding process. An ESAB Warrior 500i CC/CV welding machine was used. Semi-finished products in the form of a disc were obtained.

TABLE V

Welding process parameters.

Parameter	Specification
Current intensity	210 A
Arc voltage	22.5 V
Shielding gas	82% Ar + 18% CO_2
Shielding gas flow	18 l/min
Electrode wire	0.1% C, 0.9% Si, 1.5% Mn
Diameter of electrode wire	1.2 mm

TABLE VI

Values of trimming allowances for flange alignment [3].

Drawpiece height h [mm]	Trim allowance h' [mm]
6	1.2
12	1.6
20	2
25	2.5
38	3
50	3.5
65	4
75	4.5
90	5
100	6
125	7
over 125	5% h

(iv) Facing — alignment of disc surfaces (depth ≤ 0.2 mm). Facing operations were carried out to obtain flat surface of the blanks. The discs were prepared for the stamping process.

3. Stamping process design

The theoretical diameter of the blank was determined from equation

$$D_{\text{theor.}} = \sqrt{d^2 + 4\,d\left(h + h'\right)}, \qquad (1)$$

where: $D_{\text{theor.}}$ [mm] — theoretical diameter of the blank, d [mm] — average diameter of the blank, h [mm] — height of the blank, h' [mm] — trim allowance.

Formula 1 applies to a cylindrical drawpiece without a flange (Fig. 4).

When determining the theoretical diameter of the blank, the material allowance h' for trimming should be taken into account for subsequent flange alignment. The allowance values depend on the height of the stamping and are shown in Table VI.

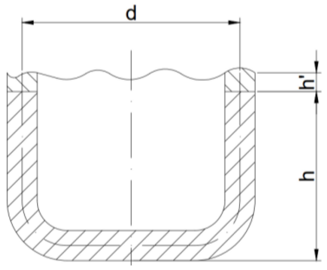

Fig. 4. Diagram of the drawpiece without a flange (own development).

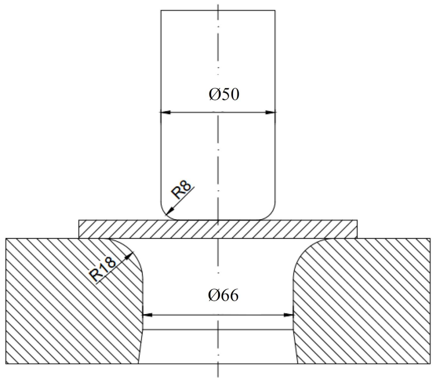

Fig. 5. Dimensions of the stamping die.

For a drawpiece with the expected dimensions $h = 45$ mm and $d = 50$ mm, the material allowance of 3.5 mm was chosen. The diameter of the output disc was calculated. Theoretical diameter of the blank was $D_{\text{theor.}} = \sqrt{58^2 + 4{\times}58{\times}\,(45 + 3.5)} = \sqrt{14616} \approx 120.9$ mm. The blank diameter $D = 121$ mm was assumed for the tests.

The actual stamping coefficient was then determined using [4]

$$m = \frac{d}{D}, \tag{2}$$

where: m — actual stamping coefficient, D [mm] — diameter of the blank (disc). The actual stamping coefficient was $m = \frac{58}{121} \approx 0.48$.

During the pressing process, corrugation of the side wall of the stamping can occur. In order to prevent this phenomenon, a presser is used. Its use depends mainly on the ratio of the material thickness g to the blank diameter D. Thus, if the following inequality is satisfied

$$\frac{g}{D} \times 100 < 1.5, \tag{3}$$

where g is the thickness of the sheet (blank), the use a pressing tool is required. On the other hand, when

$$\frac{g}{D} \times 100 < 2, \tag{4}$$

then the presser is not used. If the ratio of the material thickness g to the blank diameter D, multiplied by 100, is between 1.5 and 2, then the type of a material and the degree of deformation are the main factors determining the use of a presser. To confirm or exclude the need for a presser during stamping, we calculated the ratio of the material thickness g to the die diameter D. It is equal to $\frac{8}{121} \times 100 \approx 6.61 > 2$. It was noted that the inequality (4) was satisfied, and so the need for a presser in the pressing process was therefore ruled out.

The maximum stamping force was then calculated based on [3]

$$F_{\max} = 1.4\pi\, g\, R_m \big(D - d\big), \tag{5}$$

where: $F_{\max}$ — maximum stamping force, R_m — tensile strength of the material.

After substituting the relevant values into (5), the maximum value of the discharge force was obtained, $F_{\max}{=}1.4\pi \times 8 \times 470.4 \times \big(121{-}58\big) = 1042.74$ kN.

TABLE VII

Parameters of the PYE 250 hydraulic press (own development).

Parameter	Value
Nominal pressure	2500 kN
Maximum slider speed for upward movement	63 mm/s
Maximum slide speed during downward movement	20 mm/s
Maximum slide return force	800 kN
Maximum stroke of the press slide	500 mm
Nominal pressure in the hydraulic system	20 MPa
Work table dimensions	700 × 900 mm

TABLE VIII

Averages of measurements of 20 drawpieces.

Parameter	Average value
Inner diameter [mm]	49.30
Outer diameter [mm]	66.04
Height [mm]	47.95

3.1. Stamping process

Stamping trials were carried out on a PYE 250 hydraulic press with the parameters shown in Table VII.

The previously prepared discs were placed in a stamping die consisting of a 50 mm diameter punch and a 66 mm diameter die. The rounding radius of the punch was 8 mm and the trailing radius of the die was 18 mm. The dimensions of the stamping die are shown in Fig. 5.

The stamping was then carried out without the use of a presser.

Fig. 6. Stamping die (own development).

Fig. 7. Defective drawpiece.

Fig. 8. Drawpiece with the detached bottom.

Fig. 9. Defective drawpieces with broken welds.

TABLE IX

Dimensions of drawpieces.

Parameter	Maximum value	Minimal value
Inner diameter [mm]	49.30	49.21
Outer diameter [mm]	66.04	65.78
Height [mm]	47.95	48.04

The trials resulted in normal stamping and drawpieces with defects. Figure 6 shows an example of a drawpiece in which the stamping process was carried out correctly.

The dimensions of 20 drawpieces were measured, and the results are given in Table VIII.

The trials also resulted in stamping with defects that failed the stamping process. Figure 7 shows an example of a drawpiece in which the bottom was torn during stamping.

Figure 8 shows a drawpiece in which peripheral cracking also occurred in the bottom zone, resulting in detachment.

The drawpieces in Fig. 9 are also not compliant. Cracking of the weld material occurred during the stamping process.

3.2. Analysis of the results of technological tests

The preparation of blanks for stamping involved producing the blanks using laser cutting technology. Thanks to the high precision of this technology, the use of a state-of-the-art solid-state laser, and the appropriate selection of the laser operating parameters, the blanks achieved high dimensional accuracy.

The next step was to join the two plates using a welding process. By bevelling the edges of the plates, full weld penetration was achieved. The chosen welding parameters made it possible to carry out the process without metal spatter and to obtain a weld with the correct shape.

The stamping process proceeded well for the stamping shown in Fig. 6. There was no damage to the products. The height of the drawpieces was below the expected value with allowance, as shown in Table IX.

It was observed that this does not adversely affect the products, as the resulting allowance is sufficient to trim the edges and to make them even. However, in order to obtain drawpieces with a larger allowance of material, the diameters of the blanks must be increased. The surface of the products in the weld area showed no defects. Drawpieces with defects were also obtained during testing. When stamping the drawpieces shown in Figs. 7 and 8, peripheral cracking of the wall in the bottom zone occurred, followed by detachment. This may be due to the use of a punch with too small a rounding radius. In contrast, the stampings in Fig. 9 show a defect in the form of material cracking at the weld area. This may be due to defects in the weld.

4. Discussion

Comparing the results with the literature, it was found that a hardness difference of up to 20 HV is not critical for S355MC steel, even at a thickness of $g = 8$ mm, provided that it is supported by a punch radius of $Rs \geq 10$ mm. It is worth noting that $Rs = 8$ mm was used in the present tests, which contributed to local bottom overloading. Finite element analysis (FEA; ABAQUS 2024, model Hill48) showed that increasing Rs to 12 mm reduces the maximum modification factor of the principal stress by $\sim$ 15%. In addition, weld microdefects (pores ≤ 100 μm, lack of fusion) have been shown to be more critical than the increased hardness of heat-affected zone (HAZ). Suggestions for industrial practice include radiographic inspection of welds and the use of wires with reduced Si content ($< 0.5\%$), which reduces the risk of spot embrittlement. The aim of this study was to determine the effect of a technological sequence — including laser cutting, edge bevelling and MIG welding — on the course and results of the deep drawing process for thick-walled sheets of S355MC structural steel ($g = 8$ mm). The study combined full material characterisation (static tensile test, Vickers hardness, roughness, macroscopic and microscopic analysis of HAZ) with technological tests conducted on a hydraulic press with a pressure of 2500 kN. Both drawpieces meeting the requirements ($m \approx 0.48$) and products with defects (bottom cracks, cracks in the weld) were obtained, which enables the identification of the critical factors determining defect formation. The results indicate that a local increase in hardness in the HAZ ($\approx$ 163 HV, with a width of 0.4–0.5 mm and $\Delta HV = 17$) does not limit formability, provided that optimal tool geometry ($Rs \geq 10$ mm) and the absence of weld defects are ensured. This work provides new data on the stamping of tailor welded blanks in higher-strength steels, especially for thicknesses above 6 mm, which are rarely reported in the literature. Predicting the structural properties of sheet metal components is important to ensure reliability in engineering applications. There is ongoing work on plastic processing. It has been shown that crush strengthening introduces local material properties that directly depend on the degree of deformation occurring during fabrication.

5. Prospects for future research

A thermoplastic damage model that accounts for the HAZ hardness gradient is planned, as well as cup drawing tests when the sheets are heated to 300°C (semi-hot forming). In addition, the implementation of adaptive press controllers (AI Lite) to compensate for uneven drawing is being considered.

6. Conclusions

Laser cutting + MIG welding technology enables the manufacture of S355MC blanks with $Ra \approx 1.2$ μm and $\Delta HV \leq 17$, providing a formability of $m \approx 0.48$.

A punch radius of less than 10 mm significantly increases the risk of bottom cracking; the recommended value is 12 mm.

Fusion defects in the weld are the major factor in crack initiation; 100% non-destructive testing (NDT) inspection of welds is necessary.

Further reduction of HAZ hardness ($<$ 10 HV) requires pulsed fibre laser and hybrid MIG laser welding.

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