

## Influence of the Quality of Metal Sheet Edges After Strip Slitting Processes in Integrated Lines on the Quality of Laser Welds

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### ABSTRACT

This paper concerns issues related to the processes of sheet metal slitting and laser welding in technological lines. It includes a discussion of the industry needs and requirements for semi-finished products in the form of thin metal sheets. Furthermore, the basic technical solutions used in automatic strip slitting equipment and selected process parameters based on a specific material are described. The presented results were obtained on the basis of practical verification of the assumptions using newly designed devices implemented into production. The research material consisted of samples taken from S235JR sheet after strip slitting on an integrated slitting line and samples taken from a finished sideboard profile after laser welding. The welding process had been carried out using a CO<sub>2</sub> laser, TruLaser Cell 1100, with a power of 4 kW. Areas of a laser-welded joint were analysed for varied condition of the sheet edges at the production speed of 4 m/min. Microscopic weld examination for the sheet edges without strains or burrs revealed a deep penetration at the level of 2355 µm, allowing to obtain a joint with a length of 1607 µm, a small heat-affected zone, and the correct structure. The paper shows possible problems and causes of their occurrence in industrial conditions.

**Keywords:** strip slitting, sheet metal processing, slitting lines, laser welding.

### INTRODUCTION

The development of technology and advancement in the automation of processing entail the need to use feedstock supplied on a mass scale. At present, most of the production in the automotive, construction, energy, agrifood, household appliance and related industries is based on feedstock in the form of cold-rolled sheet in coils. Regardless of the industry, a wide range of materials are used: from sheets of non-ferrous metal alloys to classic structural and high-strength steels to advanced multi-layer sheets. An increase in the strength parameters of modern materials, wear resistance or susceptibility to machining, plastic forming or joining processes, each time requires a thorough scientific analysis of the phenomena we are dealing with. The lack of scientific basis when solving technological problems often

renders it time-consuming and costly [1–8]. Despite the wide variety and good availability of materials, steel remains at the forefront in terms of application. For example, in rail vehicles, steel still accounts for more than 65% of their structure weight. The replacement of LSS (Low Strength Steels) with HSS (High Strength Steels) and UHSS (Ultra High Strength Steels) is a natural step in view of development and the need to reduce weight. However, it should be remembered that the increase in strength properties, e.g. yield strength from 210 MPa for LSS to 210–550 MPa for HSS and even up to 1200 MPa for UHSS, forces serious changes in the construction of machines and tools used for their processing while maintaining adequate efficiency [9]. The speed of modern sheet metal slitting lines reaches 600 m/min. Advanced drive and control technologies allow for a significant acceleration of the

process [10–13]. However, the quality of products processed at such high speeds is a separate issue. Besides its surfaces, the quality of a metal sheet also involves its side edges created in the slitting process. The cutting edge is not merely a line defining the strip width but also a set of more advanced phenomena and effects which influence subsequent technological stages. Areas of plastic strain or material breakage as well as cutting burrs are only some of the issues that give rise to analyses determining the appropriate design and construction of cutting units [14–17].

### MARKET NEEDS AND REQUIREMENTS

The basic requirements regarding the chemical composition, properties, dimensional tolerances, etc. of cold-rolled sheets are specified in the standards EN 10130, EN 10131 [18, 19], etc. The standards define the basic requirements for the feedstock intended for further processing. However, in most cases, customers set additional requirements related to their specific needs conditioned by the intended use of the product, operating conditions, and the processing technology applied. The ability to satisfy customer needs is closely linked to the production capacity and the amount of material delivered. Increasing the slitting line speed entails the need to analyse the possibilities of cutting specific materials with completely new processing parameters. The standard geometric parameters for the arrangement of slitter knives (Fig. 1) in the new systems should be treated as an approximate starting point.

### CUTTING PROCESS DEFECTS

The diversity of cut materials and the significant increase in cutting speed may result in the occurrence of process defects. The scope of defects formed on the edge of a slit sheet may include a set of phenomena of excessive plastic strain in the areas of direct contact with the edge of the knife and in the adjacent areas (Fig. 2A) [23, 24]. Other types of defects that may occur are micro-cracks in the material. These are often unnoticeable upon the initial optical analysis. However, the effects of micro-cracks may affect further sheet metal processing and damage to finished pieces at the actual operation stage. Examples of cracks formed in the cutting area and located in the deeper layers of the material are shown in Figure 2b.

The market demand for metal sheets and strips with a minimum number of cutting edge defects has been growing along with the increasingly more common use of laser joining technology [26–31]. Thus, coil slitting companies are nowadays frequently faced with the requirement that the edge of the cut sheet be free of strain and burrs.

In view of the continuous reduction of production costs, the preparation of sheet edges for laser welding becomes an undesirable process. A strip of sheet metal after slitting is currently treated as a semi-finished product ready for further processing without unnecessary and costly treatments. An example of such solutions is the production of loading platform sideboards by the Polish company Pronar (Fig. 3a–b). Input material in the form of a precisely slit strip, adapted to the geometry of the sideboard, is the direct feedstock for roll forming with a combined laser welding system.

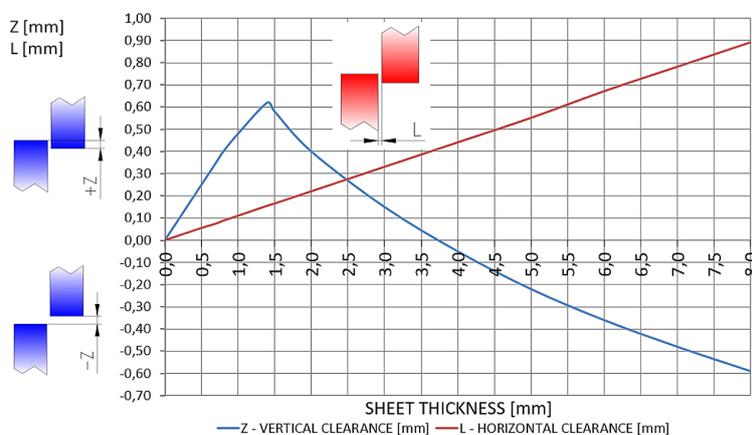
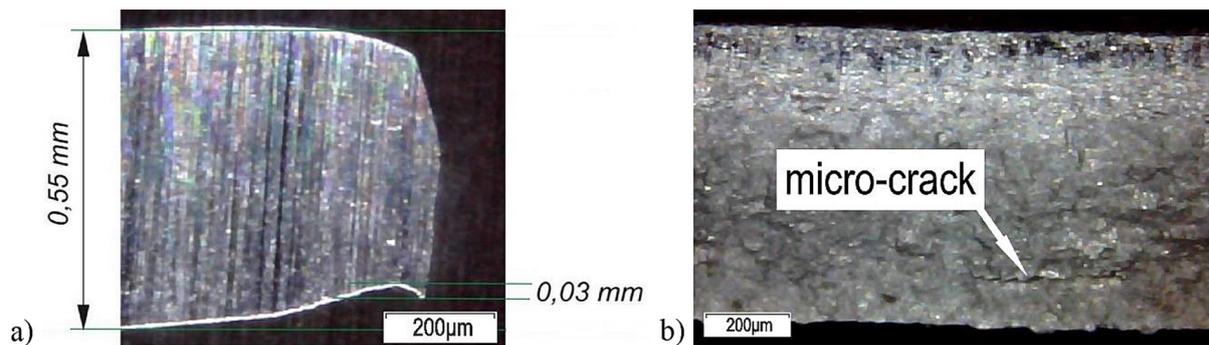


Fig. 1. Standard geometric parameters for the arrangement of knives in classic slitting shears [20–22]



**Fig. 2.** Cutting process defects, (a) excessive plastic strain of the sheet edge in the cutting area, (b) micro-cracks in the deeper parts of the material, formed after the strip slitting process [25]

Steel sheets are not the only focus of consumers' interest; zinc alloy sheets are also now produced with high attention to the cutting edge. A large increase in interest on the part of the construction market, in particular regarding the possibility of using this material for façade systems, has made it necessary to adapt the companies' machine parks to higher speeds and to ensure high quality of the input product [33–35]. Figure 4 shows a modern production line for zinc alloy sheets with an integrated longitudinal and transverse cutting system, implemented at the company ZM Silesia S.A. in Katowice. For both of these plants, the production lines were designed and manufactured by the Polish innovation & design company Inmet.

## MODERN DESIGN SOLUTIONS FOR SLITTING LINES

Slitting lines can be divided into two groups according to their purpose:

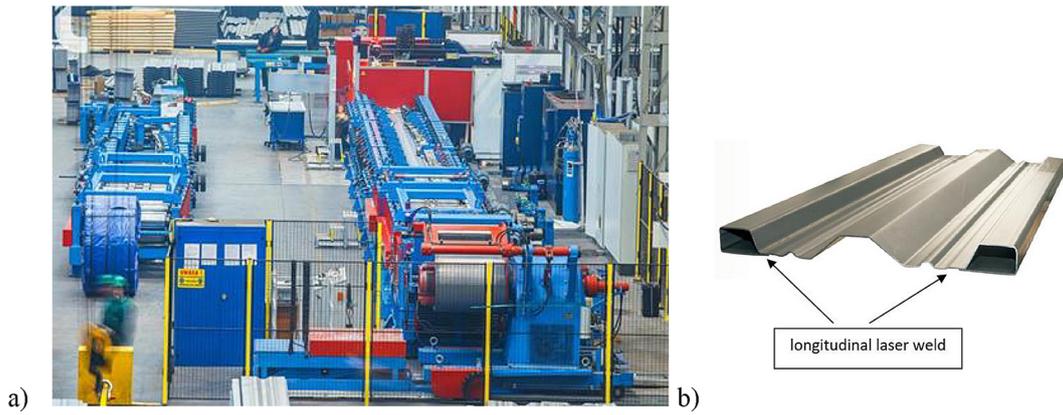
- independent lines,
- integrated lines.

Independent slitting lines are self-contained sets of devices that allow for decoiling, leveling, longitudinal or transverse cutting, coiling or storage using stacking systems. An example of an independent slitting line is shown in Figure 5. Frequently, lines of this type operate in service centres whose primary task is to provide a wide customer base with feedstock selected in terms of dimensions and grade.

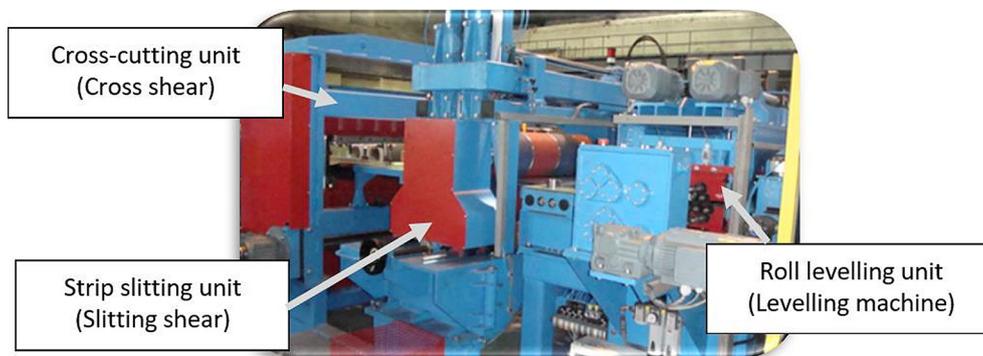
Integrated lines are complete production systems in which the slitting module is an integral part of the entire production line. The slitting unit

in these systems must ensure the appropriate quality of feedstock for the subsequent stages of strip processing in a continuous process. An example of an integrated slitting line is shown in Figure 6. The longitudinal cutting modules in these solutions tend to have a smaller range of adjustments and applications due to the specific scope of the product range manufactured. The transverse cutting module often works in a flying shear system.

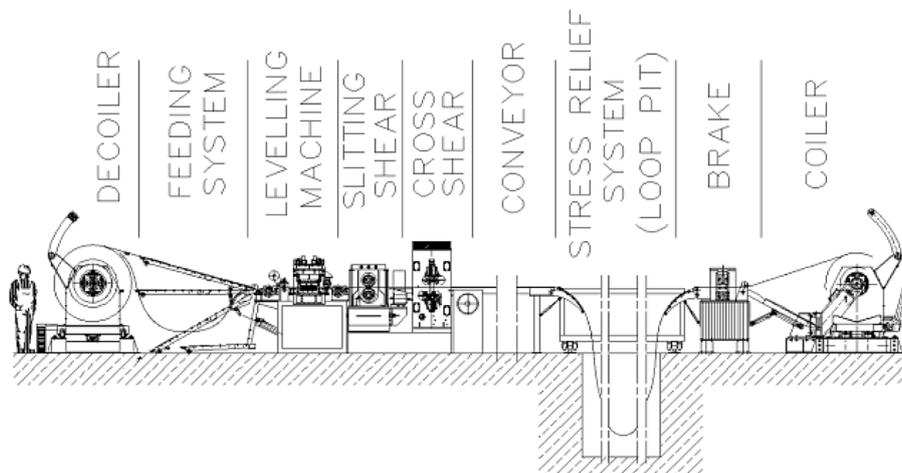
Regardless of the type of analysed technical solutions, the time of setting the cutting system (i.e. adjusting the position of the slitter knives and slots) determines the downtime of the entire production system. Extending the downtime always entails a financial loss. Optimisation in this regard is achieved through the use of modern solutions for shear working systems and computer support. Furthermore, processes related to strip slitting, such as evacuation of waste material, should not be overlooked. Since the waste is a fragment of the cut strip, it has the same properties as the cut material. In the case of sheets with increased strength properties, waste storage and evacuation are likely to cause large problems. Figure 7 shows a slitting shear together with a waste winding system and a sample screenshot from the program supporting the setting of a slitting shear by the company Dienes. The use of supporting programs helps to ensure the correctness of the process, repeatability of the cutting quality, faster assembly of tools in the correct order, and reduction of the risk of assembly and setting errors. Considering the successive stages of slit sheet strip processing, laser welding seems to be the most demanding process in terms of the quality of the sheet edge as well as deviations in the straightness and longitudinal corrugation of the strip.



**Fig. 3.** (a) An integrated line for slitting, profiling and laser welding of steel sideboards by Inmet in a Pronar production hall, (b) A sideboard by Pronar made of a steel strip cut longitudinally, profiled and laser-welded in one technological process [32]



**Fig. 4.** A fragment of an integrated line for slitting zinc alloy sheets by Inmet in a Silesia production hall [36, 37]



**Fig. 5.** An example of an independent slitting line [36, 37]

## TEST STAND

The influence of the quality of the sheet strip edge on the quality of laser welds was tested in industrial conditions. The test samples were welds created in the production process of the area of closed profiles of trailer sideboards of trucks and agricultural vehicles. The production took place

on an integrated production line equipped with e.g. profiling and laser welding systems. Laser welding was carried out using the construction of a research profile guiding and positioning station by Inmet and a laser unit by Trumpf. Type of CO<sub>2</sub> laser used: TruLaser Cell 1100 with a power of 4 kW. The design of the welding unit including the basic functional modules is shown in Figure 8.

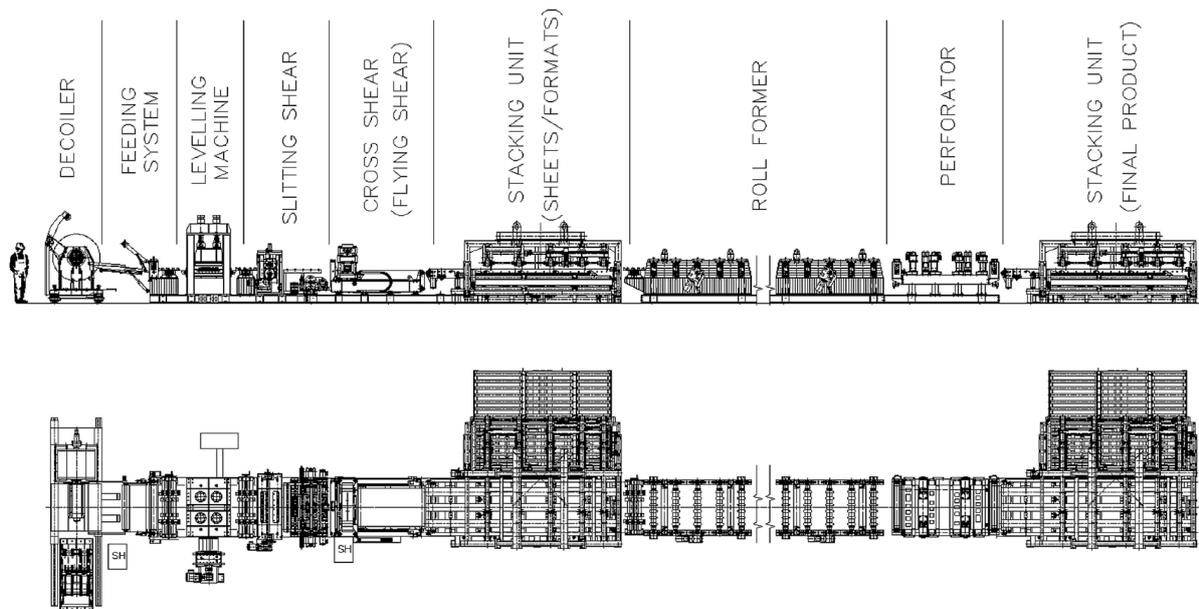


Fig. 6. An example of an integrated slitting line with a production line [36, 37]

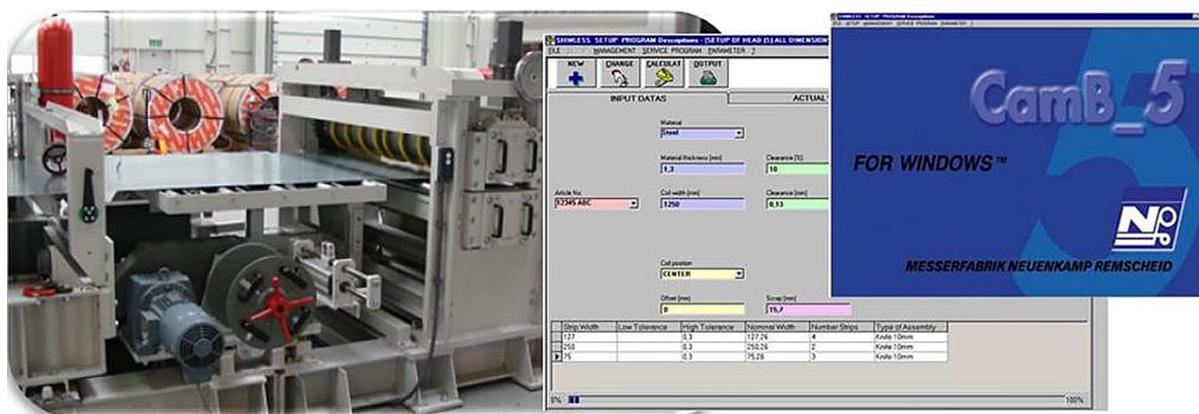


Fig. 7. Slitting shear with a waste winding system by the company Inmet and sample windows of the program supporting the control of the cutting process by the company Dienes [36–38]

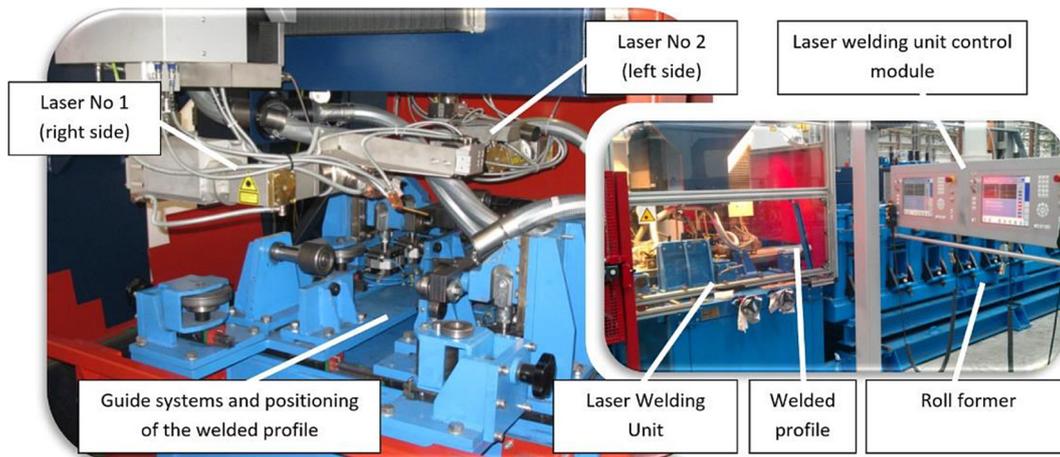
The welding module was equipped with a system for automatic positioning of the laser beam in relation to the sheet edges.

## MATERIAL AND METHODS

The research material were samples cut directly from the sheet metal strip and test profiles of the products made on the integrated production line. The tests were carried out for 2-mm-thick S235JR steel sheets (Table 1), after prior leveling, strip slitting, shaping in a profiling unit, and laser welding. The observation covered the edges of sheets after strip slitting in the conditions of corrected settings of the slitting unit and their influence on the correctness of laser welds. An

analysis of the microstructure of the joint area was carried out for the correct weld.

Due to the difficulties resulting from sampling from the technological line, for the corrected settings of the strip slitting unit, a 1000 mm long test section of the strip was determined each time. Samples for the analysis of metal sheet edges after the strip slitting process were initially cut with a grinding disc at a distance of 200 mm from the end of the test section, then cut with a laboratory saw, and included in resin. The samples for testing and observation of the welded joint were taken from the finished profile at a distance of 200 mm from the beginning of the test section. This solution made it possible to collect samples immediately after the material had left the strip slitting unit and the laser welding module. In order for



**Fig. 8.** System for the laser welding of the sideboards of trucks and agricultural vehicles built in the integrated production line by Inmet – test site [36]

the structure of the joint to be revealed, the samples were ground using sandpaper with gradated grit, polished, and etched. Macroscopic and microscopic metallographic examinations were performed in accordance with EN ISO 17639 [40]. The diagram of sampling from the test section is shown in Fig. 9. In order to obtain cut edge defects in the form of strain and burr required for the analysis, slit knife clearance adjustments were made manually.

## RESULTS AND DISCUSSION

The examination of the microstructure of the correct laser weld on the tested material was carried out on samples etched with the Nital reagent using the Axiovet 200MAT microscope with the Image Express and GstarCAD software. The

analysis covered selected areas of the weld (A) and heat-affected zones (B) (Fig. 10–12).

In order to verify the influence of the quality of the sheet edges on the quality of the laser weld, an analysis of the joint area was carried out based on photographs. The analysed samples were divided and ranked depending on the condition of the edges, the possibility of pressing the elements in the joining process, and the accuracy of the laser beam (dependent on the positions of the joined elements). Tables 2 to 4 show the observed test results.

The model laser weld presented in Figure 10 is characterised by correct and deep propagation of the laser beam. The penetration depth reaches 2355  $\mu\text{m}$ . With the applied positioning of the joined elements and the welding angle of 26°, the width of the weld together with the HAZ is within the range of 1200  $\mu\text{m}$ , allowing to create

**Table 1.** Selected properties and chemical composition of S235JR steel according to EN 10025–2 [39]

Standard	EN 10025–2				
Material	S235JR (1.0038)				
Chemical composition [%]			Mechanical properties		
C	$\leq 40$ mm	$\leq 0,17$	Thickness:	$R_e$ [MPa]	$R_m$ [MPa]
	$> 40$ mm	$\leq 0,20$	$< 16$ mm	$> 235$	350–510
Mn	$\leq 1.40$		16–40 mm	$> 225$	350–510
P	$\leq 0.035$			A longitudinally [%]	A transversely [%]
S	$\leq 0.035$		$< 1.0$	$> 17$	$> 15$
N	$\leq 0.012$		1.0–1.5	$> 18$	$> 16$
Cu	$\leq 0.55$		1.5–2.0	$> 19$	$> 17$
			2.0–2.5	$> 20$	$> 18$
				KV [J]	
			$< 150$	$> 27$	

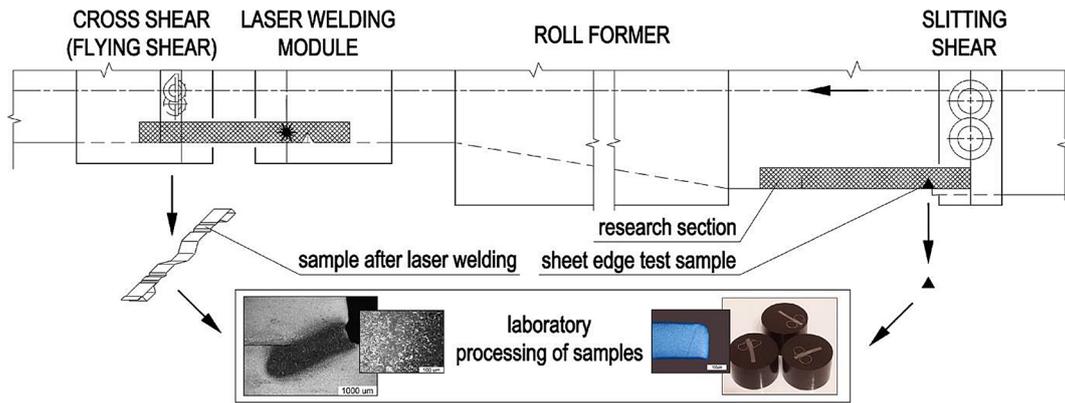


Fig. 9. Diagram of the sampling process in the production line

an actual joint with a length of 1607  $\mu\text{m}$ . It should be noted that a small HAZ within the range of 210–240  $\mu\text{m}$  is characteristic of laser welds. The small size of the laser weld and the HAZ compared to other welding methods have a significant impact on the structure of the material in the joint area. Observation of the ‘A’ area (Fig. 10, Fig. 11b, Fig. 12b) allows for the HAZ to be analysed. This area is characterised by a ferritic and ferritic-pearlitic structure in the immediate vicinity of the weld and a slight grain size increase. The ‘B’ area (Fig. 10) shows the structure of the weld itself in its end part. Observation of the ‘B’ zone (Fig. 11a, Fig. 12a) shows the presence of a mixed structure characteristic of laser welds, with a radial arrangement in the direction of the HAZ. In addition, the presence of fine martensite can be observed in the weld. The formation of martensitic structures is favoured by a concentrated thermal laser beam and very good cooling conditions through heat transmission to the adjacent sheet areas, as well as the presence of protective gas.

The quality of the weld itself is determined by the appropriate quality of the sheet metal

edges, taking into account the strain of the surfaces resulting from the physics of the cutting process and the strain resulting from the arrangement of slitter knives. Table 2 shows the optimum working conditions for the welding unit. A correct weld is the result of edge strain arising from the conditions of the cutting process (parameter  $a, b < 2^\circ$ ) and the lack of deformation or cutting burrs, with good positioning and pressure of the elements. Strain in the form of deflection (parameter  $c$ ) exceeding  $3^\circ$  and the occurrence of cutting burrs (Table 3–4) introduce disturbances in the laser welding process. The lack of adhesion, by spreading the edges, the possibility of bending and rolling the burr, favours the creation of empty spaces in the planned weld area. In such cases, despite the well-parametrised laser beam, it is possible to detect weld displacement, internal bubble formation, change in weld shape, etc.

It should be mentioned that guiding and positioning systems, due to their design and lack of a drive, feature limited capabilities. The task of these systems is not to straighten the strip and eliminate faults in the feedstock, but the

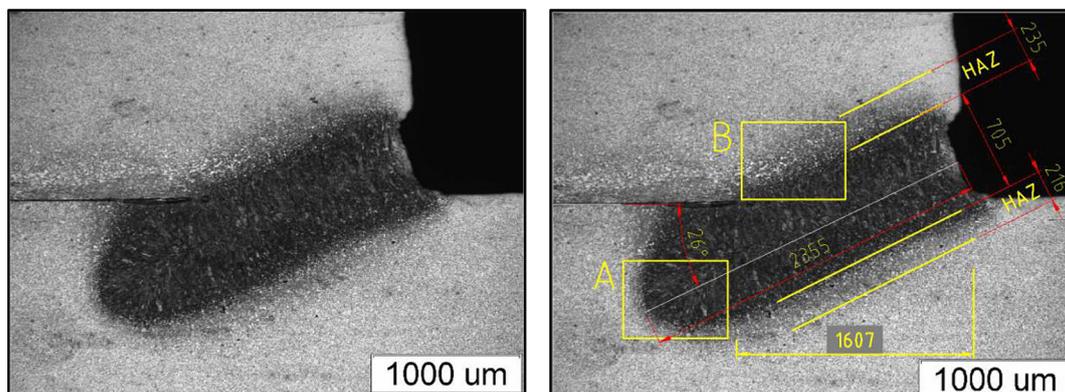


Fig. 10. The microstructure of the laser weld and the geometry of selected areas

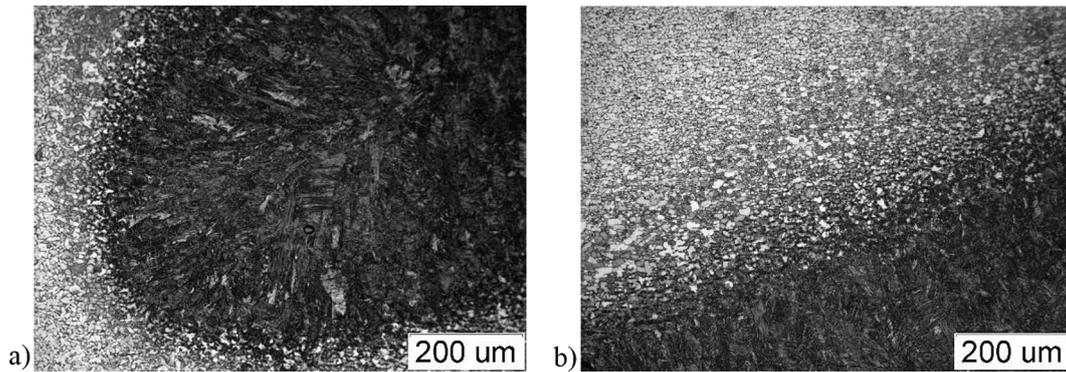


Fig. 11. The microstructure of the joint (area A) a) laser weld b) heat-affected zone (area B)

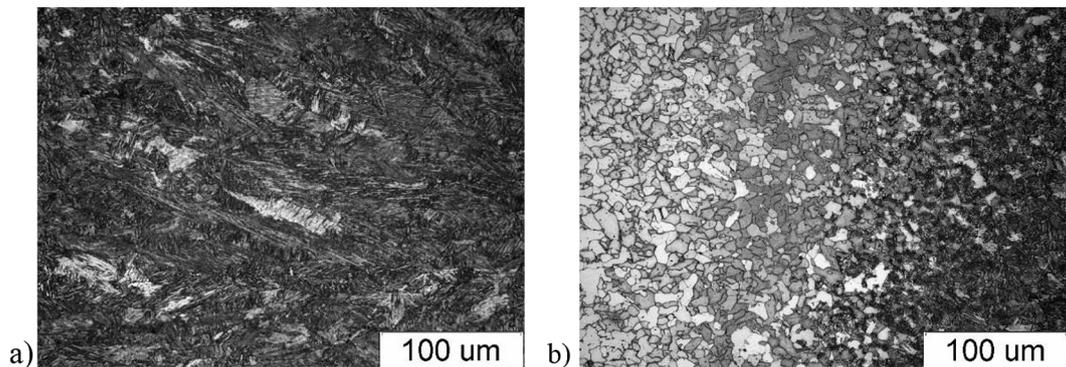


Fig. 12. The microstructure of the joint (area A) a) laser weld b) heat-affected zone (area B)

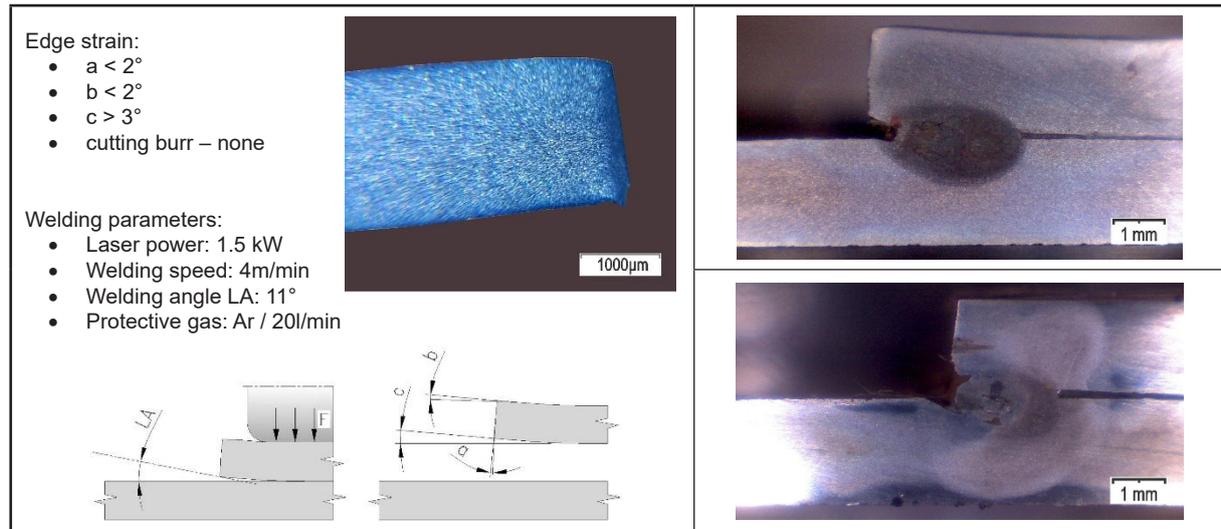
appropriate temporary positioning of the elements joined. When considering the characteristics and microstructure of a laser-welded joint area, it should be remembered that there are many components affecting its quality. Apart from the quality of the edges after the slitting process, other aspects that always should be taken into account include the proper positioning of the

workpiece, the laser beam, its power, protective gas pressure, welding speed, etc. Most of them are determined by the welding unit used as well as the integral software supporting the process. In this paper, only some of the many factors affecting the quality of the laser welding process have been outlined. In view of the fact that laser welding is becoming increasingly more popular in the

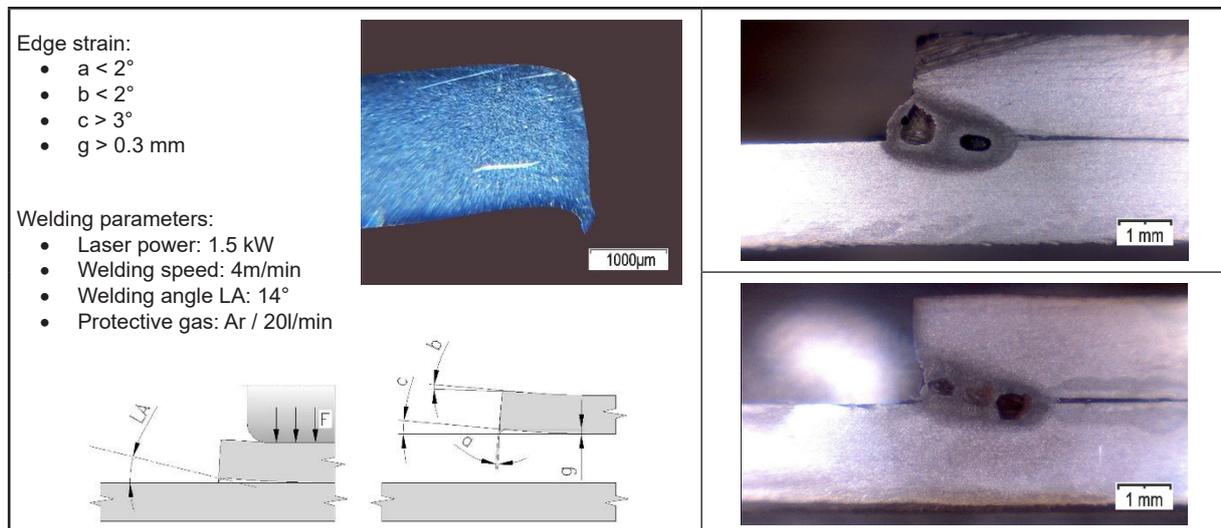
Table 2. Longitudinal laser welds for correctly prepared sheet cutting edges

<p>Edge strain:</p> <ul style="list-style-type: none"> <li>• <math>a &lt; 2^\circ</math></li> <li>• <math>b &lt; 2^\circ</math></li> <li>• cutting burr – none</li> </ul> <p>Welding parameters:</p> <ul style="list-style-type: none"> <li>• Laser power: 1.5 kW</li> <li>• Welding speed: 4m/min</li> <li>• Welding angle LA: <math>27^\circ</math></li> <li>• Protective gas: Ar / 20l/min</li> </ul>		

**Table 3.** Longitudinal laser welds with sheet cutting edge strain



**Table 4.** Longitudinal laser welds with sheet cutting edge strain and burring



industry and integrated production lines, the discussion herein serves merely as an introduction to a deeper analysis and research of the above-mentioned technological issues.

## CONCLUSIONS

Taking into account the results of the presented research and the observed relationships, the following conclusions can be drawn. The quality and correctness of laser welds depend on a number of factors. One of them is the quality of input material, in particular the quality of the edges after cutting with shears in the strip slitting process. This type of research involves significant difficulties, mainly due to the need to perform it

in a technological process. Edge deformation and excessive burring are one of the main factors that can disturb the correct course of the process and obtaining a continuous and durable weld.

For a laser welding speed of 4 m/min and power of 1.5 kW, for 2 mm thick S235JR sheets, for edges without strain or burrs, with a precise guidance and positioning system, it is possible to obtain welds that are correct in terms of structure as well as geometry. The fusion depth can reach 2355  $\mu\text{m}$ , which, in consequence, at the welding angle of  $26^\circ$ , allows for the actual joint length of 1607  $\mu\text{m}$ .

The analysed joint is characterised by a correct weld with a width not exceeding 1200  $\mu\text{m}$ , a narrow HAZ within the range of  $210 \div 240 \mu\text{m}$  with a ferritic and ferritic-pearlitic structure in the

immediate vicinity of the weld, as well as a small grain size increase.

Sheet edge defects after the strip slitting process, in particular edge strain exceeding  $3^\circ$ , in laser welding systems with an edge position control system, result in errors in the positioning of the laser beam. This can lead to displacement of the weld and the formation of undesirable gaps, conducive to corrosion of the joint at the stage of use of the finished product. A similar effect occurs when there is an additional defect in the form of excessive cutting burr. In addition, the combination of burring and strain of the sheet edges results in the formation of bubbles in the weld area.

Taking into account the presented research results and design experience, one may suggest that in order to eliminate the possibility of defects and problems occurring during laser welding in conditions of continuous production processes, special attention should be paid to the following aspects. A rigorous approach to the strip slitting process so as to minimise or completely eliminate the possibility of sheet edge defects at the outset. Accurate and precise guiding and positioning of the welded edges with a pressure system in the area of laser beam incidence. The use of a beam position control system that takes into account the possibility of sheet edge defects or allows for work with a constant welding angle.

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