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Comparison of Manual and Robotic MAG Welding-Related Costs and Efficiency in Terms of Quality and Social Factors

Abstract: The article is concerned with the implementation of robotic welding processes taking into consideration economic, quality-related and social factors. The robotisation of welding processes has been an ongoing process in the global market for many years, yet social and economic factors, particularly in Poland, continue to be responsible for a relatively small number of robotic welding implementations. The study presents the comparative analysis related to welding costs and efficiency.

Introduction

Polish entrepreneurs are becoming increasingly aware as regards the need for higher production efficiency and competitiveness of their own companies. As a result, many are investing more and more in robotisation-based solutions. According to various analyses, the major reason for robotisation is the necessity of increasing production capacity and business competitiveness as well as the need for improving quality and eliminating human presence in hazardous areas. Most companies which have decided to implement robotic solutions have enjoyed expected production, saving and market-related benefits [4, 6, 11].

Industrial companies which have already invested in the robotisation of production have seen an increase in production volume and a decrease in product manufacturing unit costs. A report by the Institute for Market Economics states that the robotisation of production increases the international competitiveness and sales volume. An additional advantage resulting from robotisation is the increased technological advancement of production processes. Figure 1 presents advantages following the installation of robots in production facilities [4, 6, 11].
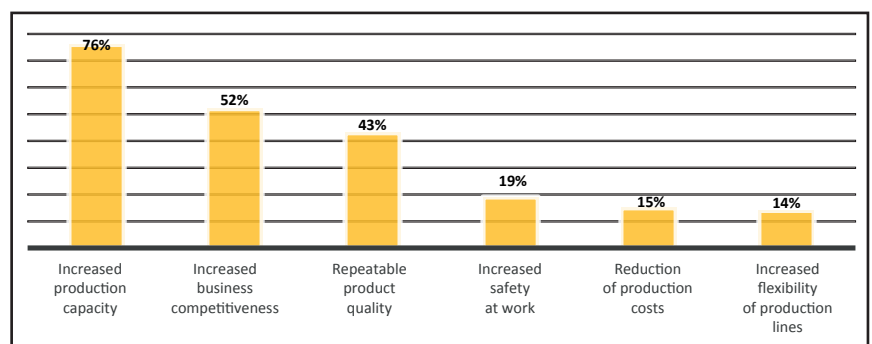

Fig. 1. Advantages related to robotisation [4]

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Despite numerous advantages resulting from the robotisation of welding processes, the very first implementation of robotised systems should be performed very carefully to avoid many potential traps and typical mistakes which could result in efficiency-related problems and increased running costs. The performance of the comparative analysis of welding efficiency and costs, including an investment in a robotic welding station, marks the first step to effective implementation [5, 12, 14].

Objective of publication

This publications aims to compare traditional, i.e. manual, and robotic welding methods in terms of economic, quality-related and social factors.

Product and process characteristics

An element used in comparative tests of manual and robotic welding methods was composed of one 2.5 mm thick embossed part made in steel S355MC. The joining of the element required the making of two fillet welds. Welding consumables used in the welding process were the following:

– electrode wire according to Pn-en iso 14341-A-G4Si1, Böhler, 550 kg,
– shielding gas according to Pn-en iso 14175-M20-ArC-8 (92% Ar, 8% CO_2) [13].

Operations performed using the robotic welding station were the following [13]:

1. The staff fixed workpieces in positioners on the right.
2. After the fixing, the robot moved to the cleaning device and stopped at the initial position waiting for the pressing of the pushbutton START. The pressing of the pushbutton START initiated the welding of the elements on the right.
3. During welding performed on the right side the staff removed joined elements on the left side, subjected the elements to visual tests (rejecting defective ones) and fixed one-element die stampings on the left. After the

verification of the fixing and the welding on the right side, the robot moved to the second station. The operator pressed the pushbutton START and the robot started to make welds on the elements.
4. The entire process was cyclical.

Analysis of costs and efficiency

Applied formulas

The analysis of the efficiency and costs of welding processes involved the use of worktime measurements (time study) according to the technical worktime standard, information contained in the documentation of the Welding Procedure Specification and information provided by business representatives about worktime management. The calculations were performed using the following dependences [7, 8, 10, 15]:

– weld weight

$$G = V \cdot \gamma \ [kg] \tag{1}$$

where V – weld volume [cm³/m], γ – specific gravity [kg/dm³]

– cost of the wire

$$K_D = G \cdot C_D \ [PLN/kg] \tag{2}$$

where G – weld weight, C_D – price of the wire [PLN/kg]

– cost of the gas

$$K_G = G \cdot C_G \cdot E \ [PLN/kg] \tag{3}$$

where G – weld weight, C_G – price of the gas [PLN/kg], E – 0.6-1.0 coefficient for the MIG/MAG method

– labour cost

$$K_R = 1.2 S_h \cdot T_N \ [PLN/h] \tag{4}$$

where S_h – welder's remuneration with all allowances, T_N – total welding time

– cost of electric power

$$K_{El} = (power \ P \cdot C_{el}) + (power \ Q \cdot C_{el}) \ [PLN/kWh] \tag{5}$$

where C_{el} – price of electric energy, power P – active power, power Q – passive power

– direct welding costs

$$K_B = K_D + K_G + K_R \; [PLN] \qquad (6),$$

– arc burning time coefficient

$$W_j = \frac{t_g}{T_N} \cdot 100\% \qquad (7)$$

where t_g – principal welding time, T_N – total welding time

– robotic station utilisation degree

$$W_R = \frac{n \cdot t_n}{T_E} \cdot 100\% \qquad (8)$$

where n – number of products per year, t_n – unit welding time [h], T_E – effective robot operation time per year [h].

Profitability of robotic implementations in welding processes

The analysis included the development of a formula enabling the verification of economic profitability of robotic implementations in welding processes. Presented below is the methodology applied when developing the above-named formula. The initial element was the cost of manufacturing 1 element (cost per piece). Obviously, robotic production costs should be lower than those of manual fabrication. The foregoing can be expressed using the following dependence [13]:

$$\frac{(m + n_1 + p_1)}{q} > \frac{(m + n_2 + p_2)}{q} \Big| \cdot q$$

$$m + n_1 + p_1 > m + n_2 + p_2$$

$$m + n_1 + p_1 - m - n_2 - p_2 > 0 \qquad (9)$$

$$(n_1 + p_1) - (n_2 + p_2) > 0$$

n_1 – consumption of energy during manual welding [PLN/kWh],
p_1 – welder's remuneration including all allowances [PLN],
n_2 – consumption of energy during robotic welding [PLN/kWh],
p_2 – operator's remuneration including all allowances [PLN],
q – number of pieces,
m – cost of welding consumables/filler metals [PLN].

If $(n_1 + p_1) - (n_2 + p_2) > 0$, the implementation of robotisation is profitable. In such a case, the return on investment confronted with manual welding can be calculated using the following
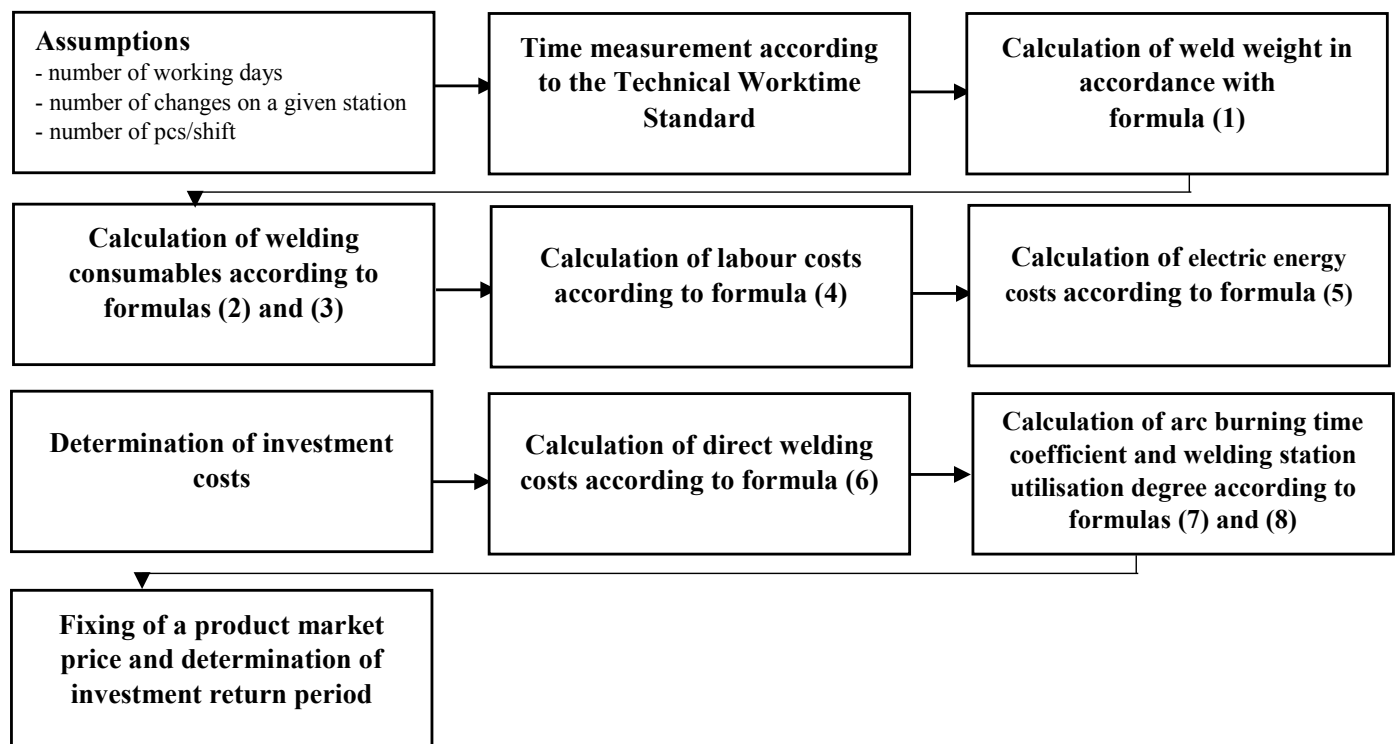

Assumptions - number of working days - number of changes on a given station - number of pcs/shift	Time measurement according to the Technical Worktime Standard	Calculation of weld weight in accordance with formula (1)
Calculation of welding consumables according to formulas (2) and (3)	**Calculation of labour costs according to formula (4)**	**Calculation of electric energy costs according to formula (5)**
Determination of investment costs	**Calculation of direct welding costs according to formula (6)**	**Calculation of arc burning time coefficient and welding station utilisation degree according to formulas (7) and (8)**
Fixing of a product market price and determination of investment return period		

Fig. 2. Diagram presenting the welding cost calculation methodology

formula [13]:

$$\frac{i}{(x-y)}+1=L_n \qquad (10)$$

i – cost of investment [PLN],
x – gross profit after 2 years – robotic welding [PLN],
y – gross profit after 2 years – manual welding [PLN],
L_n– number of years.

Methodology of the comparative analysis

The comparative analysis included several stages. Figure 2 presents the diagram presenting the methodology applied when calculating welding costs to determine process efficiency [13].

Analysis

MAG robotic welding

Calculation of MAG robotic welding costs in relation to steel elements
- Assumptions:
  - three-shift work, 250 working days;
  - 532 pcs/shift = 2128 pcs/day = 532000 pcs/ year;
- Calculations:
  - t_g = 5.3 h/shift = 15.9 h/day = 3975 h/year;
  - t_0 = 1.3 h/shift = 4 h/day = 1000 h/year;
  - t_p = 1.4 h/shift = 4.1 h/day = 1025 h/year;
  - T_N = 8 h/shift = 24 h/day = 6000 h/year;
- Weld weight:
  - V_1 = (½ · 2.25 · 2.25) · 25=63.28 mm³;
  - V_2 = (½ · 2.25 · 2.25) · 52,5=132.89 mm³;
  - $V=V_1+V_2$ = 196.171 mm³=0.000000196171 m³;
  - ρ = 7800 kg/m³
  - $G = V \cdot \gamma$=0.000000196171 · 7800=0.0015 kg;
- Cost of wire:
  - K_D = 0.0015 kg · 7 PLN=0.0105 PLN/piece = 5586 PLN/year;
- Cost of gas:
  - K_G = 0.0015 kg · 0.6 · 5.7 PLN=0.00513 PLN/ piece = 2729.16 PLN/year;

- Cost of labour:
  - K_R = 1.2 · 66.5 PLN/h · 8h=638.4 PLN/shift = 1915.2 PLN/day = 478800 PLN/year;
- Cost of electric energy:
  - Power P = 342.3 Wh = 0.342 kWh;
  - Power Q = 91.86 Varh = 0.0919 kVarh;
  - K_{EL} = (0.342 kWh · 0.38 PLN) + (0.0919 kVarh · 0.38 PLN) = 0.16 PLN/piece = 85120 PLN/year;
- Cost of equipment:
  C_u = 420 000 PLN;
- Direct costs:
  - K_B = 5586 PLN + 2729.16 PLN + 478800 PLN + 85120 PLN = 572 235.16 PLN/year;

In the first year the company invested 420 000 PLN in the robotisation of the welding station, therefore the total cost incurred during the production of 532000 pieces amounted to:
$K_{Br} = C_u + K_B$ = 572235.16 + 420000 PLN = 992235.16 PLN;
- Arc burning coefficient:

$$W_j = \frac{t_g}{T_N} \cdot 100\% = \frac{3975}{6000} \cdot 100\% = 66\%$$

- Robotic station utilisation degree:

$$W_R = \frac{532000 \cdot 0{,}007}{6000} \cdot 100\% = 62\%$$

The market price of one piece (product) amounted to 8.30 PLN. After producing 532000 pieces, sales revenues amounted to

532000 × 8.30 = 4415600 PLN.

In the first year, after taking into consideration the investment costs, the profit amounted to:

4415600 – 992 235.16 = 3 423 364.84 PLN.

In the second year, the company only incurred direct costs, without additional investment costs. As a result, the profit amounted to:

4 415 600 – 572 235.16 = 3 843 364.84 PLN.

The total profit for two years will amount to 7 266 729.68 PLN.

MAG manual welding

Because of the fact that in the company considered in the study the welding process was fully robotised, the MAG method-based manual welding was performed at Instytut Spawalnictwa.

Calculation of MAG manual welding costs in relation to steel elements

- Assumptions:
  - three-shift work, 250 working days;
  - 510 pcs/shift = 1530 pcs/day = 382 500 pcs/year;
- Calculations:
  t_g = 3.5 h/shift = 10.5 h/day = 2625 h/year;
  t_0 = 1.8 h/shift = 5.4 h/day = 1350 h/year;
  t_p = 2.7 h/shift = 8.1 h/day = 2025 h/year;
  T_N = 8 h/shift = 24 h/day = 6000 h/year;
- Weld weight:
  $V_1 = (1/2 \cdot 2.25 \cdot 2.25) \cdot 25 = 63.28$ mm³;
  $V_2 = (1/2 \cdot 2.25 \cdot 2.25) \cdot 52.5 = 132.89$ mm³;
  $V = V_1 + V_2 = 196.171$ mm³ = 0.000000196171 m³;
  ρ = 7800 kg/m³;
  $G = V \cdot \gamma = 0.000000196171 \cdot 7800 = 0.0015$ kg;
- Cost of wire:
  - K_D = 0.0015 kg $\cdot$ 7 PLN = 0.0105 PLN/piece = 4 016.25 PLN/year;
- Cost of gas:
  - K_G = 0.0015 kg $\cdot$ 0.6 $\cdot$ 5.7 PLN = 0.00513 PLN/piece = 1962.225 PLN/year;
- Cost of labour:
  - K_R = 1.2 $\cdot$ 30 PLN/h $\cdot$ 8h = 288 PLN/shift = 864 PLN/day = 216 000 PLN/year;
- Cost of electric energy:
  - Power P = 131.3 Wh = 0.1313 kWh;
  - Power Q = 74.3 Varh = 0.0742 kVarh;
  - K_{EL} = (0.1313 kWh $\cdot$ 0.38 PLN) + (0.0742 kVarh $\cdot$ 0.38 PLN) = (0.161 + 0.032) $\cdot$ 0.31 = 0.08 PLN/piece = 30600 PLN/year;
- Cost of equipment:
  - C_u = 35000 PLN;
- Direct costs:
  - K_B = 4016.25 + 1962.225 + 216 000 + 30600 = 252 578.475 PLN/year.

In the first year the company invested 35000 PLN in the welding power source, therefore the entire cost incurred during the production of 382 500 pieces amounted to:

$K_{Br} = C_u + K_B$ = 252 578.475 + 35000 PLN = 287 578.475 PLN.

The market price of one piece (product) amounted to 8.30 PLN. After producing 382 500 pieces, sales revenues amounted to 382 500 × 8.30 = = 3 174 750 PLN/year. In the first year, after taking into consideration the investment costs, the profit amounted to:

3 174 750 PLN – 287 578.475 PLN = = 2 887 171.525 PLN.

In the second year, the company only incurred direct costs, without additional investment costs. As a result, the profit amounted to

3 174 750 PLN – 252 578.475 PLN = = 2 922 171.525 PLN.

Table 1 presents the comparative analysis concerning costs related to the welding of the same number of products.

The profitability of robotic implementation (in relation to element no. 1) was calculated by substituting values n_1 = 30 600, n_2 = 61 200, p_1 = 216 000 and p_2 = 344 736 PLN to formula $(n_1 + p_1) - (n_2 + p_2)$. The calculations revealed that the implementation of robotisation was not profitable in relation to the same number of pieces as $(n_1 + p_1) - (n_2 + p_2) < 0$.

Calculations – summary
- The consumption of welding consumables was calculated in accordance with technological data (WPS) and time measurements performed in accordance with the technological worktime standard. In relation to 1 piece (product), regardless of the welding method, the consumption was the same and amounted to 0.016 PLN/piece.
- The consumption of electric energy by two stations was measured using specialist equipment developed by Instytut Spawalnictwa. The measurements revealed that the cost

Table 1. Comparative analysis of welding-related costs [13]

	MANUAL	ROBOTIC
Type of weld	fillet weld	fillet weld
Type of production	lot production, 3 shifts	lot production, 3 shifts
Number of pieces	382 500	382 500
Price per 1 piece	8.30 PLN	8.30 PLN
Number of pcs × price	3 174 750 PLN	3 174 750 PLN
Investment costs	35 000 PLN	420 000 PLN
Costs of welding consumables	wire: 4 016.25 PLN gas: 1 962.225 PLN	wire: 4 016.25 PLN gas: 1 962.225 PLN
Cost of electric energy	30 600 PLN	61 200 PLN
Labour costs	216 000 PLN	344 736 PLN
Direct costs in total	287 578.475 PLN	831 914.475 PLN
Cost of producing 1 piece (year 1)	0.75 PLN/piece	2.17 PLN/piece
Cost of producing 1 piece (year 2)	0.66 PLN/piece	1.08 PLN/piece
Gross profit (year 1)	2 887 171.525 PLN	2 342 835.525 PLN
Gross profit (year 2)	2 922 171.525 PLN	2 762 835.525 PLN

of electric energy during manual welding amounted to 0.08 PLN/piece, whereas the cost of energy during robotic welding amounted to 0.16 PLN/piece. As can be seen, higher energy consumption was generated during robotic welding.

– In relation to conclusion no. 1 and 2, the greatest savings when implementing robotisation were those of labour costs. Because of the fact that in the company subjected to the study manual welding was not performed, related tests were performed at Instytut Spawalnictwa. The comparative analysis included the average remuneration of a welder in the Silesian voivodeship (province), i.e. approximately 30 PLN/h. In the company subjected to the study the remuneration of operators was higher and amounted to 66.5 PLN/h.

– In relation to conclusion no. 3 and the calculated level of profitability, the implementation of a robotic welding station for one type of product proved unprofitable.

– As regards timing, the manual production of 382 500 pieces took 250 working days (3 shifts). The robotic production of the same number of pieces took 180 working days.

Because of the fact that the efficiency of a robotic station is significantly higher than that of manual welding, the analysis also included the effect of an increase in production capacity on the return of investment in relation to manual welding (Table 2). The obtained results revealed that the obtainment of required efficiency and the lowest production costs required the use of more manual welding stations. In view of the production organisation (lack of manual welding stations), process quality and product quality, the foregoing proved impossible to implement and unprofitable.

Quality

The quality of the products was analysed using visual tests (VT) and macroscopic metallographic tests. The visual tests were performed by the operator or the welder directly after the completion of the welding process. The macroscopic tests involved two 2 welds containing manually MAG welded joints and MAG welded joints made using the robotic technique. The analysis of product quality combined with the analysis of production organisation provided the basis for the assessment of the quality of manual and robotic MAG welding process [2].

Table 2. Comparative analysis of welding-related costs in view of increased efficiency [13]

	MANUAL	ROBOTIC
Type of weld	fillet weld	fillet weld
Type of production	lot production, 3 shifts	lot production, 3 shifts
Number of pieces	382 500	532 000
Price per 1 piece	8.30 PLN	8.30 PLN
Investment costs	35 000 PLN	420 000 PLN
Costs of welding consumables	Wire: 4 016.25 PLN Gas: 1 962.225 PLN	Wire: 5 586 PLN Gas: 2 729.16 PLN
Cost of electric energy	30 600 PLN	85 120 PLN
Labour costs	216 000 PLN	478 800 PLN
Direct costs in total	287 578.475 PLN	992 235.16 PLN
Gross profit (year 1)	2 887 171.525 PLN	3 423 364.84 PLN
Gross profit (year 2)	5 809 343.05 PLN	7 266 729.68 PLN
Time of return on investment	1 year	1 year
Higher profit in relation to manual welding	-	1 year

The product was subjected to direct non-destructive tests (VT) performed both generally and locally (Fig. 3). **Visual tests (VT)** were performed by the unaided eye, following the requirements of the PN-EN ISO 17637:2017 standard. Welding imperfections were assessed in accordance with PN-EN ISO 5817:2014 [2].
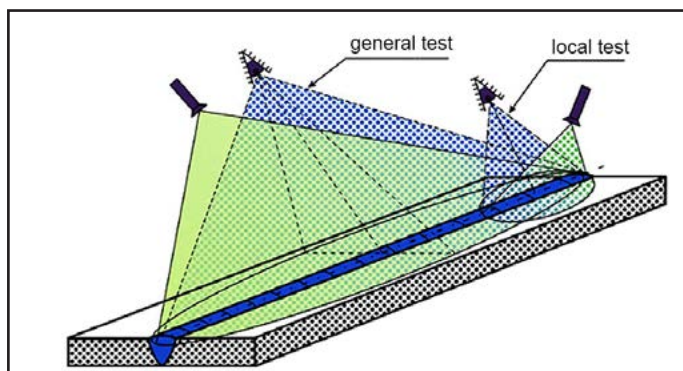
Fig. 3. General and local direct visual tests [2]

During the visual tests the optical path (Fig. 3) between the observer's eye (operator and welder) and the area subjected to examination remained unobscured. The above-named personnel were knowledgeable about related standards, regulations and technical requirements as well as enjoyed good vision checked every 12 months [2]. The visual tests were performed following the regulations of the PN-EN ISO 17637:2017 standard. Presented below are the detailed test conditions (Fig. 4) [2]:

– illuminance of the test joint surface amounted to 500 lx;
– use of an additional light source;
– distance between the observer's eye and the test surface amounted to 50 cm;
– angle of view (in relation to the test surface) was lower than 30°;
– good contrast and welding imperfection convexity effect were obtained;
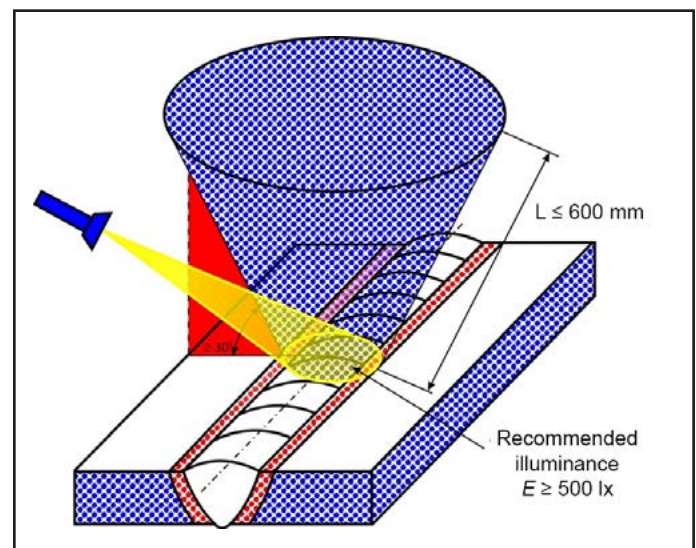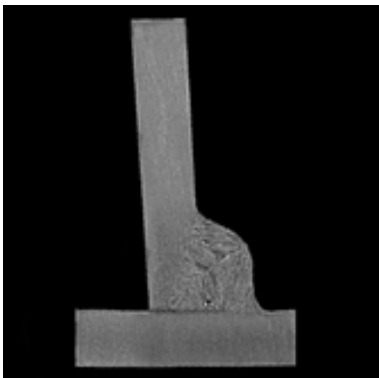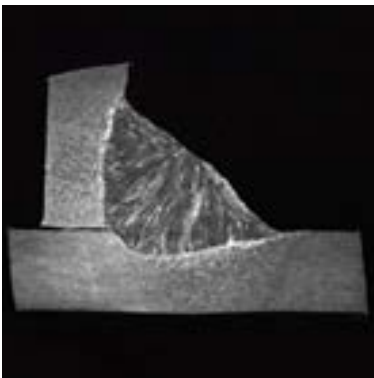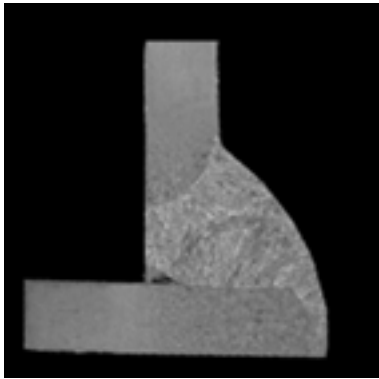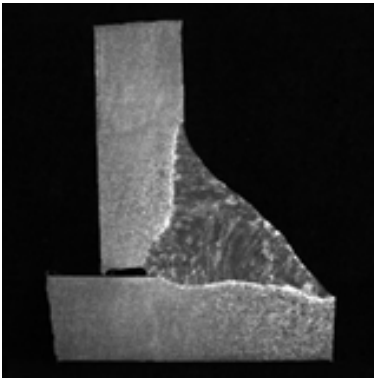– tests were performed using joints in the as-made state.

Fig. 4. Schematic VT conditions [2]

The assumption adopted in industrial practice states that the examination of a weld and a 10 mm wide zone (on each side of the weld) ensures the satisfaction of all requirements concerning all of the zones of a welded joint (i.e. the weld, the heat affected zone and the welded material adjacent to the HAZ). The tests enabled the identification of selected geometrical features of the test welds. However, the above-named dimensions should be treated tentatively as, in some cases, the HAZ could be much wider or the weld could contain welding imperfections. To establish quality-related facts it was necessary to perform macroscopic tests, the results of which are presented in Table 3.

Table 3. Comparison of the quality of the welds [13]

ELEMENT NO. 1 – fillet weld no. 1

Manual welding	Robotic welding
Imperfections	
Welding imperfections: – excessive convexity (fillet weld) according to PN-EN ISO 5817 (503) quality level C – short welding imperfection – improper edge of the weld according to PN-EN ISO 5817 (505) quality level D, – excessive asymmetry according to PN-EN ISO 5817 (512) quality level C,	Welding imperfections: Lack of imperfections according to PN-EN ISO 5817, quality level B

ELEMENT NO. 1 – fillet weld no. 2

Imperfections	
Welding imperfections: – lack of penetration – failure to satisfy the requirements of quality level D – inappropriate edge	Welding imperfections: Lack of imperfections according to PN-EN ISO 5817, quality level B

Factors affecting the implementation of robotisation

The comparative analysis concerned with welding efficiency, costs and quality enabled the identification of factors affecting the implementation of robotisation in welding processes. The identification of qualitative, economic and social factors also involved the author's individual experience and consulting experts at welding robotisation. The above-named factors are discussed in detail in the remainder of the article.

Method/Material

Inappropriate process organisation

The organisation of the process is affected, among other things, by **procedures, instructions, specifications etc.** Welding documentation is developed by specialists representing the top two competence levels, i.e. welding engineers or welding technologists. The above-named documentation contains a welding procedure specification (wps), a welding procedure qualification record (wpqr) along with an approved wps, instructions related to welding work checks (welding process check), reports concerning the assessments of welded joint quality and a welding log. The above-named documentation should be developed in the same manner, regardless of whether a welding process is manual or robotic.

Other factors affecting the process in terms of organisation include **standards and legal regulations**. When implementing standards, regardless of a welding technique (manual or robotic), it is necessary to comply with implemented quality systems and standards related to a given structure. In addition, production should follow valid legal regulations and the end product should not pose any risks to the health and safety of potential users. Complying with recommendations of quality management systems, standards and valid law regulations also positively affects costs.

Another factor is the so-called **_know-how_**, i.e. specific technical knowledge related to a given area. As regards welding, know-how stands for the ability to manufacture a product or structure. Both manual and robotic welding require the development of technologies, the adjustment of parameters and the design of a process in terms of organisation. Know-how also affects costs and quality both in manual and robotic welding [15].

Welding imperfections

The macroscopic metallographic tests revealed that welding imperfections were primarily present in manually MAG welded joints. In most cases, the welds made using robotic MAG welding or hybrid, i.e. laser + MAG, welding were characterised by higher quality than those made using manual welding. Welding imperfections undoubtedly affect the quality of end products and the quality improvement model therefore should be allowed for when developing the above-named model [2].

Raw materials/semi-finished products/substitutes

As regards raw materials, semi-finished products or substitutes, the most important factors affecting adversely the quality and costs of the process and those of the product are **improperly adjusted parameters related to a product or a wrong welding method, defective materials and materials improperly prepared for welding.** Defective materials can be provided by a distributor but also may result from improper storage or wrong pre-weld material preparation. The use of a defective material or improperly adjusted welding parameters can lead to the formation of welding imperfections, significantly reducing the quality of end products or even of the entire structure. Also in this case it is of no significance whether the welding process is manual or robotic. The improper use of a material can be also caused by the **improper marking system** and organisation-related problems.

Table 4. Qualitative factors affecting the implementation of robotisation in welding processes; ("X" – effect, "0" – no effect, "X*" – positive effect in comparison with manual welding) [13]

No.	Factor	Effect on costs and quality in:		
		manual welding	robotic welding	hybrid welding
1.	METHOD/MATERIAL			
1.1.	**Wring process organisation**			
	Procedures	X	X	X
	Standards and laws	X	X	X
	Know-how	X	X	X
1.2.	**Welding imperfections**			
	Longitudinal crack	X	X*	X*
	Incomplete fusion	X	X*	X*
	Porosity	X	X*	X*
	Worm-hole	X	X*	X*
	Weld overlap	X	X*	X*
	Undercut	X	X*	X*
	Excess weld face penetration	X	X*	X*
	Improper weld thickness	X	X*	X*
	Lack of penetration	X	X*	X*
1.3.	**Raw materials, semi-finished products, substitutes**			
	Improperly adjusted parameters related to a product	X	X	X
	Defective material	X	X	X
	Wrong components	X	X	X
	Material improperly prepared for welding	X	X	X
	Wrong system of material marking	X	X	X
2.	HUMAN FACTOR			
	Lack of competence	X	O	O
	Lack of involvement	X	O	O
	Delays	X	O	O
	Low or lack of ethics	X	O	O
	Improperly adjusted "EQUIPMENT"	X	O	O
	Material losses	X	O	O
	Improperly performed welding process	X	O	O
3.	MANAGEMENT			
	Lack of control	X	X	X
4.	EQUIPMENT			
	Material losses	X	X	X
	Improper operation	X	X	X
	Power failures	X	X	X
	Wrong parameters	X	X	X

The above-named errors can be eliminated by the precise material coding system which should remain unchanged throughout the process. For instance, a simple designation method is the colour-marking of products (e.g. using paint) directly after their acceptance from the manufacturer [15].

Human factor

Welding personnel's **competence** is of great importance, particularly in terms of processes performed manually. Welder's manual skills, knowledge and experience substantially affect the quality and costs of structures. According to related analytical reports, the Polish market has been suffering from the lack of qualified welding personnel for several years. An additional problem is the **lack of worker's involvement.** In manually performed processes the above-named factor significantly affects the timeliness and quality of order processing. Overly low work ethic of welding personnel may result in the making of welded joints not satisfying quality-related requirements. In the worst case, the structure may not only be useless but put user's life and health at risk. Competence and involvement are also related to other factors including, among other things, **improperly adjusted equipment** and an **inappropriately performed welding process** [1, 3, 9].

Management

Welding coordination personnel are tasked with the control of work organisation. Welding processes should comply with related safety rules and regulations. In addition, welding coordination personnel should enforce the observance of procedures. The **lack of appropriate control** may lead to improperly performed welding processes, affecting quality, costs and efficiency [1].

Equipment

Primary factors adversely affecting equipment-related quality and costs include **improper operation, material losses and wrongly adjusted parameters**. An external factor negatively influencing the performance of a welding process is a **power failure**.

The comparative analysis focused on the quality, efficiency and costs related to welding processes performed using three different methods, i.e. manual MAG welding, robotic MAG welding and hybrid, i.e. laser + MAG, welding as well as the analysis of reference publications and talks with experts enabled the identification of factors affecting the implementation of robotisation in welding processes. The factors analysed in relation to quality, efficiency and costs are presented in Table 4.

Summary

The article presents the extensive analysis of efficiency and costs of manual and robotic MAG welding. The analysis involved the development of a formula enabling the identification of robotisation implementation profitability and the return-on-investment period contrasted with manual welding. The work included welding time measurements, i.e. process time study, the identification of material and energy consumption as well as the determination of total costs connected with the welding of an element. The greatest savings when implementing robotisation were those of labour costs. Because of the fact that in the case subjected to study the welder's remuneration rate was lower than that of the operator, the analysis of implementation profitability degree per 1 piece proved insufficient. In addition, in view of the fact that the efficiency of a robotic welding station is significantly higher than that of manual welding, the analysis involved the effect of an increase in production capacity on the return on investment confronted with manual welding. As can be seen above, the identification of robotic implementation profitability requires the analysis of numerous factors. The macroscopic metallographic tests revealed that welding imperfections were primarily present in welded joints made manually (MAG). In most cases, the welds made using robotic MAG welding were characterised by significantly fewer welding imperfections than those formed during manual welding. As a result, it could be concluded that properly prepared elements and the selection of an appropriate welding method favourably affect the quality of welded products.

The study also involved the identification of qualitative, economic and social aspects concerned with the implementation of robotisation in welding processes. The above-named factors confirmed that the use of welding robots has a significant and positive impact on product and process quality as well as on costs and work conditions.

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