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QUALITY MANAGEMENT METHODS FOR THE EVALUATION OF MANUFACTURING HIGH-STRENGTH STEEL JOINTS

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Purpose: Novelty of the paper is to present the economic aspect of steel braze welding for transportation application. Classic welding process of HSS steel is treated as more difficult and expensive process than braze welding. The aim of the article is to present steps 5 and 6 of 8D analysis, which are used to develop the braze welding process for S 690 QL steel that is less expensive process than welding.
Design/methodology/approach: Quality management methods (8D method, 5 WHY) were used to identify nonconformities, determine their causes and reduce production costs. To improve the quality of the production process and eliminate the causes of existing material incompatibility, it was found that a new process of material bonding should be used. Various filler materials were used. Main parameters of the braze welding process were tested and then the quality of the obtained joint was checked.
Findings: Quality management methods indicated that a viable solution to the problem required the development of a new process and the use of other electrode wire materials. In step 6 of the 8D analysis, the proper filler materials and parameters of the process were proposed.
Research limitations/implications: It is possible to realize the process without expensive preheating. The most favorable process parameters have been discovered.
Practical implications: The proposed process innovation will result in savings of production, and the presented solution will contribute to the improvement of the joint manufacturing process.
Social implications: Braze welding process allows for energy savings.
Originality/value: It is to propose a new solution in automotive and rail transport. The article is especially addressed to the elements of the various means of transport.
Keywords: process improvement, quality management methods, production savings, transport, braze welding.
Category of paper: Research paper.

1. Introduction

One of the reported problems with the production of connectors by means of transport is the high cost of the manufacturing process compared to the safe operation time of the weld. To solve the problem effectively, it was necessary to determine the causes of the problem, propose a way to reduce the cost, and implement corrective actions. 8D method is a team-based problem-solving approach/process of 8 critical steps with a focus on actions to contain, correct and prevent recurrence of the problem (Lubas Wahyudi, Wulandari, 2020). The authors of the article used a modified 8D method to solve the problem, but the article presents only the 6 steps.

First step is establishing a team consisting of material science, means of transport and quality management experts. The team have a good knowledge of the product (joints) and processes (welding), and it has adequate capability to introduce proper solutions to the identified problem.

In the second step, the team described the problem in detail. The cost drivers were identified (material purchase costs, equipment use, personnel costs, etc.) and it was concluded that the greatest savings could be achieved through material and technological changes. The current manufacturing process generates almost 75% of the final product costs, which, according to Pareto-Lorenz analysis, is the main problem. It was assumed that shortening the process (and thus reducing staff time, machine use time, etc.) should translate into lower costs. During the brainstorming session, some proposals were rejected, such as reducing staff numbers, which, according to the authors, could result in employee overload and ultimately lower product quality. It was also analyzed whether there were any errors in the process, generating unnecessary costs and affecting the service life of the final material. Such causes include, for example, improper storage of materials, errors in instructions. It has been stated that to truly eliminate a problem, it is needed to identify its true cause. This is not an easy step, so it is important to work as a team and look at the problem from different perspectives. At this stage of the project, quality tools such as Ishikawa analysis and the 5 Why method were used (Wirawan, Minto, 2021). An example of the 5 WHY analysis is presented in Fig. 1.

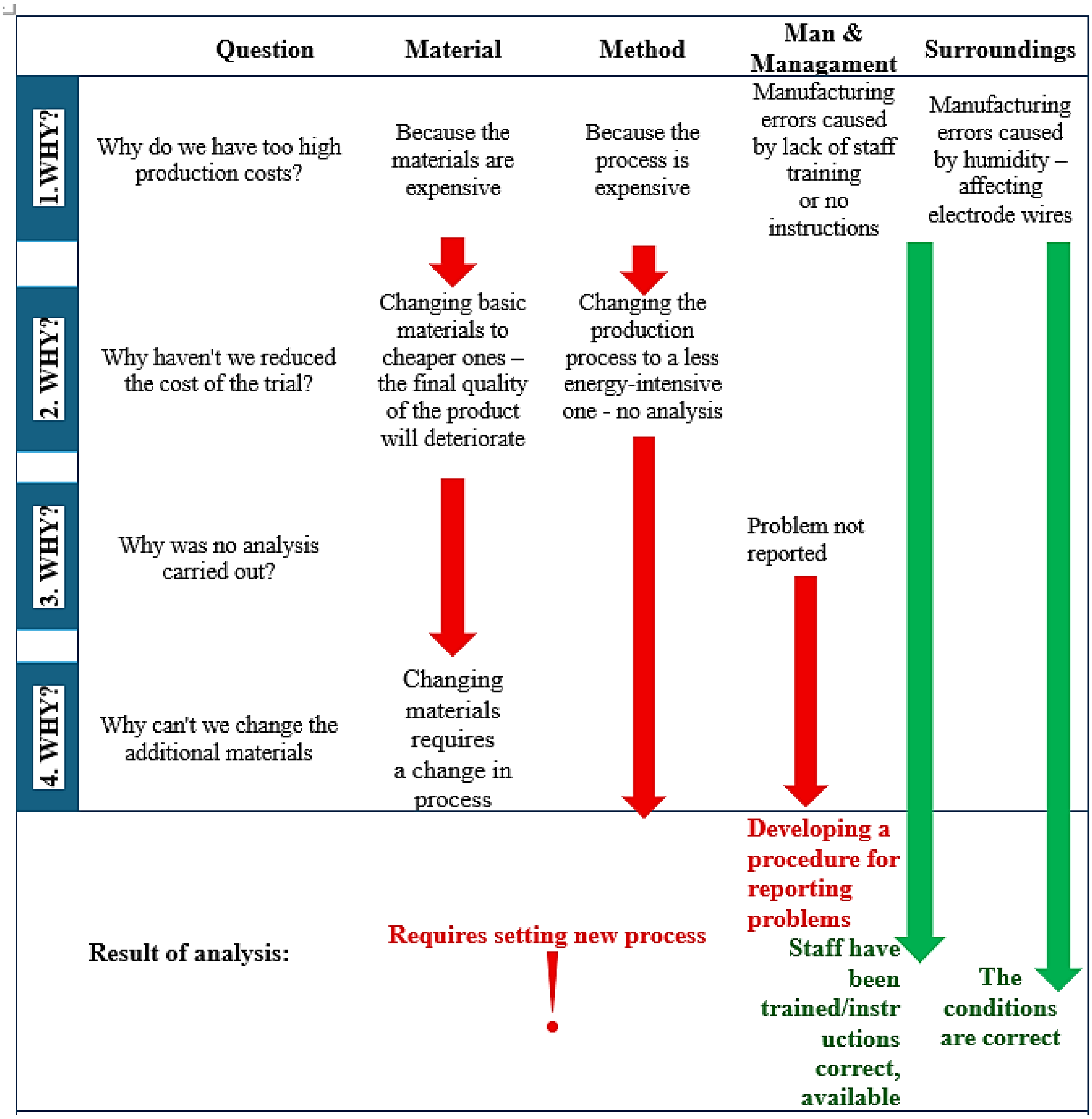

Figure1. Analysis 5 WHY.

The 5 Why analysis showed that a new process should be developed that uses other electrode wire materials and develop reporting procedures.

At these stages of the project (step 5-6), the authors of the paper developed a new process using different types of electrode wires. This part of the research as the main design achievement is widely described in the next chapters of the article. The solution required the application of extensive material expertise, knowledge of material testing methods, their selection and evaluation of the quality of joints obtained in the braze-welding process.

2. Step 5 and 6 of modified 8D analysis – braze welding process

Braze welding is mainly used in situations where it is important to obtain tightness and precision of the connection, and tensile strength is less important. Braze welding is mainly used in situations where it is important to obtain tightness and precision of the connection, and tensile strength is less important (Li, Hou, Tian, Hong, Nord, Rohde, 2022). This part of examination focuses on the welding of HSS steels, which are not easily welded for various reasons. One of the most important factors impairing weldability is the dominant martensitic structure of HSS steel, which promotes weld cracking (Punzel, Hugger, Dörringer, Dinkelbach, Bürger, 2020). Depending on the thickness of the material being welded, various process parameters are selected, such as welding speed, current intensity, arc voltage, and shielding gas flow rate. In conventional welding, costly preheating is often used. In principle, separate tests should be conducted for each thickness of HSS steel structure to determine the feasibility of achieving a safe joint and selecting the most appropriate parameters, which is quite tedious (Lee, Jeong, Lee, Fujii, Shin, Lee, 2023). Achieving high tensile strength is not essential for all joints, but universal connection of structural elements is. A significant number of these types of joints are used in the construction of transportation vehicles. This article analyzes the weldability of S690 QL steel, a representative of the HSS group of materials. The appropriate electrode wire was selected, and precise process parameters were established, which can be used for various sheets, as the sheets are not melted during the joining process. A literature review found no guidance on selecting electrode wires or process parameters. The classical welding process for HSS steels is much more widely understood (Mannucci, Tomashchuk, Vignal, Sallamand, Duband, 2018).

Economic factors play an important role: brazing is generally much cheaper than conventional welding for a variety of reasons. The brazing process is economically more viable than conventional welding for many reasons The complete elimination of preheating is crucial. Furthermore, operating time is shorter, labor is reduced, and energy consumption is lower (Beck, Bantel, Boley, Bergmann, 2021). Brazing equipment is lighter and cheaper. Post-processing of the braze joint is usually unnecessary (Kumar, Arya, Palani, Madhukar, Sathiaraj, Patel, 2022). Material consumption is generally much lower (Sairam, Balaji, Menon, Manikandan, 2023). The authors also analyzed the braze welding process for environmental reasons, which is related to energy savings and lower material consumption.

2.1.Materials

For braze welding of S690 QL steel 3 various electrode wires were proposed. They were used as a shielding gas pure argon (without mixture with CO_2). The use of high purity argons is important to avoid braze welding incompatibilities. Helium is sometimes occasionally recommended to do shielding argon gas mixture. In the braze welding process, it was decided to realize process without preheating. The thickness of elements was 2 mm. Table 1 shows the mechanical properties of the S690 QL.

Table 1.
Tensile strength of tested material

Steel	YS MPa	UTS, MPa	A5, %
S690 QL	690	970	14

The table data shows that material has high tensile strength that depends on chemical composition (Table 2).

Table 2.
Chemical composition of S690 QL [6]

Steel	C	Si	Mn	P	S	Al	Cr	Cu	Mo	Nb	Ni	Ti	V	B
S690 QL	0.21	0.8	1.7	0.025	0.015	0.01	1.55	0.5	0.7	0.06	2.1	0.05	0.12	0.005

The table data shows that material has high amount of Ti, that has influence on mechanical properties of the material. Chemical composition of electrode wire is given in Table 3.

Table 3.
Chemical composition of wires for braze welding

Wires	Si, %	Mn, %	Fe, %	Zn, %	Ni, %	Cu, %
CuSi2	1.9	0.4	0.3	0.1	0.03	bal
CuSi3	2.9	1.2	0.5	0.1	0.05	bal
CuSi3Mn1	3.9	1.5	0.4	0.2	0.5	bal

Before starting to make joints, no chamfering was performed. The braze welding parameters were as follows:

- diameter of the electrode wire: 1 mm,
- arc voltage: 18 V,
- welding current was varied twice: 150 A, 170 A,
- welding speed was varied twice: 325 mm/min, 355 mm/min,
- shielding gas flow: 14 l/min
- the nature of the weld: single pass.

2.2.Methods

Brazed joints were created according to the instructions in the previous chapter. The quality of the joints was then checked using NDT (non-destructive testing) and DT (destructive testing) methods. Mainly, VT – visual test (using EN ISO-17638 standard) and TP –penetration test was carried out. Penetrant was a standard DBR, cleaner was BRE-S, developer was BEA. Time of penetration was 35 min. After NDT, some destructive tests were realized:

- tensile strength, PN-EN ISO 6892-1 from 2020,
- bending test, PN-EN ISO 5173.

2.3.Results and discussion

Braze welding joints were made using 3 various electrode wires (CuSi2, CuSi3 and CuSi3Mn1), with 2 various braze welding current (150 A, 170 A) and with 2 various welding speed (325 mm/min, 325 mm/min). Braze welding was realized without heat treatment. Following all the experiments, 12 different samples were made (Table 4).

Table 4.
Samples designations

Sample	Current, A	Electrode wire	Welding speed mm/min
U1	150	CuSi2	325
U2	150	CuSi3	325
U3	150	CuSi3Mn1	325
U4	170	CuSi2	325
U5	170	CuSi3	325
U6	170	CuSi3Mn1	325
U7	150	CuSi2	355
U8	150	CuSi3	355
U9	150	CuSi3Mn1	355
U10	170	CuSi2	355
U11	170	CuSi3	355
U12	170	CuSi3Mn1	355

Only 6 samples marked as U2, U5, U6, U8, U10, U11) were free from braze welding incompatibilities or defects (table columns are marked in green), but also 6 samples were treated as defective or unacceptable (table column marked in pink). Detailed observations and comments of the VT (visual test) and TP (penetration tests) results are presented in Table 5.

Table 5.
NDT results for tested braze welds

Sample	Observation
U1	Small cracking in braze weld
U2	Correct braze weld
U3	Correct braze weld
U4	Blisters and porosity
U5	Correct braze weld
U6	Correct braze weld
U7	Small cracking in braze weld
U8	Small cracking in HAZ
U9	Blisters and porosity
U10	Correct braze weld
U11	Correct braze weld
U12	Blisters and porosity

Generally, it was found that the choice of current and proper selecting of electrode wire is more important factor. The braze welding current should be at the level of 170 A. It was clearly noticed that the best electrode wire for brazing is CuSi3. Based on NDT, it can also be suggested that a faster braze welding speed might be more suitable for joining the S690QL steel. The next part of the investigation was to check the tensile strength of braze welds. Only those samples that had positive results in NDT tests were chosen to the account (U2, U5, U6, U8, U10, U11). Table 6 presents the tensile strength (UTS) of the braze weld.

Table 6.
Tensile strength of the dissimilar braze weld

Sample	Electrode wire	UTS [MPa]
U2	CuSi3	131
U5	CuSi3	141
U6	CuSi3Mn1	123
U8	CuSi3	141
U10	CuSi2	136
U11	CuSi3	152

The data from Table 6 allowed us to draw the conclusion that tensile strength of all tested joints was over 120 MPa. The analysis of Table 6 proves that the braze welds made with CuSi3 electrode wire have higher tensile strength. Next, a bending test was realized out to find the detachment angle. A bending test was carried out at ambient temperature. The results of bending test are demonstrated in Table 7.

Table 7.
Bending test of braze weld
Tensile strength of the dissimilar braze weld

Sample	Electrode wire	Detachment angle
U2	CuSi3	30
U5	CuSi3	35
U6	CuSi3Mn1	30
U8	CuSi3	35
U10	CuSi2	30
U11	CuSi3	40

The angle at which the joint deboned was the largest for sample U5, U8, U11. This confirms that the CuSi3 electrode wire is the most suitable for brazing S 690QL steel.

3. Summary

The article presents the possibilities of using quality management methods to identify the problem, determine its causes and develop a solution by experts. Application of the 8D method combined with brainstorming and the analysis of the 5 WHYs made it possible to identify areas that needed to be modified. The results of the analysis indicated the need to develop procedures for reporting problems, as well as to improve and modify the manufacturing process.

As a result of the work in this article, a new solution for the production process of welded joints for transport needs was created. This article presents the possibility of economic joining S 690QL steel without preheating. Preheating treats as expensive procedure due to the consumption of energy and propane preheating, gas for heating. The newly developed method allows for production savings. The properties of braze welding were tested using both non-destructive and detractive methods. The joints, despite the cheaper production method, are characterized by excellent properties. The possibility of obtaining brazed joints using three different copper-based electrode wires was carefully analyzed. Additionally, a decision was made to select different process parameters, which allowed us to produce 12 different samples for testing and joint quality assessment. Based on the braze welding study it was possible to assume that:

1. Braze welding of S 690QL steel leads to process savings in relation to joints made in the classical welding process.
2. Braze welding parameters (composition of electrode wires, braze welding current and speed) should be selected with great sensitivity.
3. The best mechanical properties of braze welds were obtained when the electrode wire CuSi3 was selected for the process.

In the next steps, reporting procedures should be developed, as indicated by the results of the 5 WHY method and the implementation and workplace procedures for the newly developed process.

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