Evaluation of the impact of electron beam welding parameters on the mechanical properties and microstructure of the resulting joint for 39CrMoV13 and M50NiL steel grades

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Abstract
The paper covers a study consisting on the implementation of the electron beam welding process of two steel grades: 39CrMoV13 and M50NiL. The welding process was carried out for two values of electron beam debunching, obtaining a joint having different widths. Then, for the samples, after each welding variant, heat treatment was carried out consisting of double tempering at 520 °C for 3 h, and single freezing at −84 °C for 3 h, combined with single tempering at 520 °C for 3 h. The impact of the parameters of the electron beam welding process and the subsequent heat treatment process on the mechanical properties and microstructure of the resulting joint was analysed. The conducted tests allowed to select the optimum welding technology combined with the heat treatment process for the tested steel grades ensuring that a weld is obtained in which the level of mechanical properties was close to the level of values obtained for the base material.

Keywords Electron beam welding · Heat treatment · Freezing · Tempering

1 Introduction

The process of electron beam welding (EBW) consists of the process of joining materials through a welding process using a concentrated electron beam that impacts the joined elements at a speed reaching 70% of the speed of light [1]. Such a highly concentrated energy source leads to the formation of a crater from the evaporated material, at the place of impact of the beam [2]. During the welding process, as the electron beam moves along the welding direction, the crater closes and two molten materials merge. The temperature of the electron beam welding process at the beam's point of impact can reach up to several tens of thousands of degrees Celsius, but these values are obtained only locally at the direct beam's point of impact [3]. The local heat concentration of the welding process prevents the entire volume of the material from heating, i.e. it eliminates the adverse effects that may be caused by deformation of the material as a result of high temperatures [4]. Conducting the welding process with the use of an electron beam makes it possible to obtain a relatively narrow weld, and thus a narrow heat-affected zone, which always adversely affects the mechanical properties of the joined materials [5].

The electron beam welding process is carried out under high vacuum conditions, to ensure its stability, as well as to intensify the process of degassing the weld. The speed of the electron beam welding process is much higher when compared to conventional welding methods, it can reach up to 100 mm/s [6].

The electron beam welding process is carried out using numerically controlled devices, with the possibility of their...
programming, which ensures high process repeatability, regardless of the operator’s experience. This method allows to save material due to the lack of the need to use an additional material as a binder.

The position of welding in the case of electron beam welding is discretionary and does not affect the properties of the weld as it happens in conventional welding processes, which extends the scope of using this method [7, 8].

The electron beam welding technology is widely used in the aviation, space, armament, electronics, medical, measurement devices and instrumentation, and electronics industries.

Until recently, the limitation in the use of this method was the dimensions of the vacuum chamber, however, this limitation is gradually being eliminated by the design and construction of welding machines equipped with very high capacity vacuum chambers. An example of such a device is a welding machine used by pro-beam GmbH & Co. KGaA in Germany, which has been equipped with a chamber enabling to weld components with dimensions of $6 \times 6 \times 14$ m and a weight of up to 100 tonnes (the capacity of the chamber is 700 m³).

The electron beam welding process makes it possible to join materials with different physical and chemical properties, which is usually impossible when conventional welding methods are used. This process makes it possible to join materials that until recently were considered difficult to weld due to the high thermal conductivity of these materials, e.g. aluminium or copper. It is also possible to weld active metals, i.e. beryllium, vanadium, as well as non-fusible metals, i.e. tungsten, tantalum, molybdenum and niobium.

The electron beam welding method should be used as an absolute welding method, if it is necessary to design a method of obtaining responsible elements characterised by a high level of fatigue strength [9].

Due to the limited width of the heat-affected zone that is generated in the electron beam welding process, this method can be used in elements that have previously been subjected to a heat treatment process, e.g. by hardening and tempering [10]. After the welding process for this type of elements, only stress-relieving annealing (for low-carbon steels) or tempering (for medium-carbon and alloy steels) is used, related to the levelling of thermal stresses and the reconstruction of the microstructure that was created in the welding process.

The article presents the results of the electron beam welding process for two steel grades, previously subjected to the heat treatment process, by means of hardening and tempering. The welding process was carried out for various parameters that led to obtaining different weld widths. After the welding process, the material was subjected to two types of heat treatment, a double tempering process, and single freezing combined with single tempering. The impact of the electron beam welding process and the subsequent heat treatment process on the mechanical properties and microstructure of the resulting joint was analysed.

## 2 Materials and methods

The electron beam welding process was carried out for two steel grades. The chemical compositions of the tested steels are presented in Table 1.

The process was carried out in industrial conditions, using a device belonging to the equipment of Pratt & Whitney in Kalisz, manufactured by STEIRGERWALD STRAHLTECHNIK GmbH (Fig. 1).

The shape and dimensions of the joined elements are shown in Fig. 2.

As a result of the welding process, a groove weld was obtained, the shape of weld is shown in Fig. 3.

| Grade       | C, %  | Mn, % | Si, % | Cr, % | Mo, % | V, % | Ni, % |
|-------------|-------|-------|-------|-------|-------|------|-------|
| 39CrMoV13   | 0.35  | 0.40  | 0.10  | 3.0   | 0.08  | 0.15 | 0.10  |
| M50NiL      | 0.11  | 0.15  | 0.10  | 4.0   | 4.00  | 1.13 | 3.20  |

Fig. 1 Welder
The first stage of the research related to the determination of the optimum value of the welding current, which would allow to obtain a full melt between the welded elements and the occurrence of a phenomenon consisting in locating the weld root in the construction overlap, so that in this location welding porosities would be possible. At a later stage of the technological process, the overlap is removed by mechanical machining, together with any raisins located in it.

The criterion for determining the optimum value of the welding current was the depth of fusion.

The electron beam welding process was carried out for two variants to obtain a narrow and wide weld. The factors that directly affect the width of the weld are the debunching and oscillation of the beam as well as the speed of welding. Therefore, to obtain a narrow weld, smaller beam debunching and oscillation and higher welding speeds should be applied, whilst to obtain a wide weld, higher beam debunching and oscillation values are used, which forces the use of lower welding speeds. The electron beam welding process requires the use of the smallest possible thermal energy values to join the two materials to prevent strong heating of the welded elements. Therefore, to obtain a narrow weld, the following parameters were used: welding speed of 8 mm/s, beam debunching size at the level of −10 mA and the use of beam oscillation was abandoned.

However, to obtain a wide weld, the following parameters were used: welding speed of 4 mm/s, beam debunching size at the level of −20 mA and oscillation of the ellipse beam with dimensions of 1 × 0.5 mm.

The analysis of the melt depth for two weld variants (narrow and wide) was carried out using optical microscopy with the Axiovert 25 optical microscope.

3 Results and discussion

3.1 Determination of the optimum welding current value for a narrow weld

The test was carried out for eight welding current values: 5, 6, 7, 8, 9, 10, 11, 12 mA; the microstructures images are shown in Fig. 4.

3.2 Determination of the optimum welding current value for a wide weld.

The test was carried out for six welding current values: 8, 9, 10, 11, 12, 13 mA; microstructure images are shown in Fig. 5.

Figure 6 presents a diagram of the relation of the depth of the obtained melt to the applied current value.

Based on microstructural analysis, which allowed to determine the depth of melt and based on the diagram of relations shown in Fig. 6, the optimum melting depth specified at 7 mm was determined for both variants of the electron beam welding process. For this depth of melting, the location of the weld ridge can be observed in the technological overlap in a size sufficient to place welding shrinkage and porosity in it (Figs. 4g, 5e and f). For the remaining variants of the welding process, full smelting was not obtained (Figs. 4a, b, c, d, 5a, b) or the resulting weld was too shallow, in the overlap there is a small amount of ridges that make it impossible to store any porosity and shrinkages (Figs. 4e, 5c). However, the depth of melting for variants presented in Figs. 4h and 5f, it is too large, which creates the risk of smelting of the structural overlap and the face of the weld collapsing.
Based on preliminary studies, the optimum parameters of the electron beam welding process were established to obtain a narrow weld (variant 1) and a wide weld (variant 2), which are presented in Table 2.

After the welding process, the materials were subjected to two variants of heat treatment consisting of double tempering at 520 °C for 3 h (Variant 1A, and Variant 2A), and single freezing at − 84 °C for 3 h, combined with single tempering at 520 °C for 3 h (Variant 1B, Variant 2B).

Conducting the heat treatment process after the electron beam welding process is dictated by the need to temper the weld and the heat-affected zone (HAZ), in which during the welding process, as a result of very fast cooling, the hardening process occurs, resulting in the creation of the structure of non-tempered martensite and residual austenite. A material with such a structural composition is characterised by very high hardness and at the same time high brittleness, which excludes the possibility of using the welded materials in construction solutions.

In addition, the research also included the process of welding high-alloy low-carbon steel with medium-alloy, medium-carbon steel. During the welding process of this type of materials, alloy elements and carbon elements are mixed in the weld. Welding materials with such a different chemical composition forces the need to conduct a two-stage heat treatment after the electron beam welding process, and most often it is a tempering process at temperatures dedicated to specific materials.

The residual austenite remaining after the hardening process must be converted into tempered martensite. This can be achieved by the process of double tempering at 520 °C for 3 h, followed by single freezing at − 84 °C for 3 h, and then single tempering at 520 °C for 3 h. This process ensures the conversion of the residual austenite into tempered martensite, which results in a material with improved mechanical properties suitable for use in construction solutions.

![Fig. 4](image-url)  The microstructure of the welded joint obtained in the electron beam welding process for welding current a 5 mA, b 6 mA, c 7 mA, d 8 mA, e 9 mA, f 10 mA, g 11 mA, h 12 mB, for the welding speed of 8 mm/s and beam debunching of − 10 mA. Kalling’s reagent was used for etching.
Fig. 5 The microstructure of the welded joint obtained in the process of electron beam welding for welding current \(a\) 8 mA, \(b\) 9 mA, \(c\) 10 mA, \(d\) 11 mA, \(e\) 12 mA, \(f\) 13 mA, for the welding speed of 4 mm/s and the beam debunching of −20 mA and the ellipse oscillation of the beam 1×0.5 mm. Kalling’s reagent was used for etching.
be achieved in two ways, as a result of double tempering or as a result of a single freezing combined with subsequent tempering. Bypassing one of the long-term stages of heat treatment by tempering in the technological operations, carried out in a vacuum furnace creates the possibility of significantly reducing production costs. Replacement of the process of tempering the residual austenite, with the freezing process, should create in the material the structure of the non-tempered martensite, which can be transformed in the process of single tempering into tempered martensite, i.e. the component of the structure expected for the weld material and the heat-affected zone (HAZ).

3.3 Micro-hardness analysis

To fully characterise the impact of welding parameters and two-stage heat treatment on the mechanical properties of the materials welded, a measurement of micro-hardness on the weld cross-section and HAZ was carried out. Micro-hardness tests for each welding variant were carried out for three distances from the surface of the material: 0.15 mm from the top surface and the bottom surface and in the centre of the weld, which was caused by the funnel shape of the weld.

Table 2 Parameters of the electron beam welding process

| Variant   | Welding current, mA | Welding speed, mm/s | Beam oscillation, mm | Beam dechannising, mA |
|-----------|---------------------|---------------------|----------------------|-----------------------|
| Variant 1 | 10.5                | 8                   | 0                    | −10                   |
| Variant 2 | 12.5                | 4                   | 1 × 0.5              | −20                   |

The study was conducted using a Shimadzu micro-hardness tester. Figures 7, 8, 9 and 10 show the distribution of micro-hardness on the cross-section of the weld and the heat-affected zone for the analysed areas and variants.

Based on the analysis of micro-hardness distribution, it was found that for all analysed variants, a clear, typical decrease in hardness can be observed in the heat-affected zone, both for the material made of 39CrMoV13 grade steel and for the material made of M50NiL grade steel. This phenomenon is related to the steel tempering process in the heat-affected zone, which occurs during the electron beam welding process.

For the welding process variant in which a wide weld is obtained, the minimum hardness value for 39CrMoV13 grade steel in the heat-affected zone is in the range of
400–435 HV0.5, whilst for M50NiL grade steel, it is in the range of 370–390 HV0.5.

For the welding process variant in which we narrow-weld is obtained, the minimum hardness value for 39CrMoV13 grade steel in the heat impact affected is in the range of 440–490 HV0.5, whilst for M50NiL grade steel, it is in the range of 380–420 HV0.5.

The weld hardness values, regardless of the type of heat treatment that the material underwent after the welding process, are in the range of 500–570 HV0.5, for both weld widths. The obtained results allow to state that it is possible to replace the heat treatment process consisting in double tempering the obtained welded joint at 520 °C for 3 h, with a process of single freezing at − 84 °C for 3 h, combined with single tempering at 520 °C for 3 h, without a significant change in the values of the weld hardness. The hardness of the joint made is also not significantly affected by the width of the joint obtained, and thus the degree of mixing of the joined materials.

### 3.4 Analysis of nondestructive testing

Nondestructive tests of the weld were carried out using the radiographic (RT) method on the Varian NDI-22 device, equipped with a Varex Imagin lamp. These tests were carried out to assess the quality of the welded joint, obtained in accordance with the parameters determined in the tests, for the presence of discontinuities and internal defects.

The standard for the evaluation of the results of X-ray examinations was the internal Pratt & Whitney standard, in which the maximum fracture length was 0.5 mm and the porosity of individual parts was up to 0.75 mm. Samples for radiographic testing and surface roughness analysis were taken from welded cylinder-shaped samples. The samples were machined in the turning process with an outer diameter equal to 80 mm and an inner diameter of 74 mm. The turning process was carried out to remove the assembly tab necessary for the positioning of the samples in the welding process. The cross-section of welds after the machining process is shown in Figs. 11 and 12.

As a result of the research, several dozen radiographs were obtained, a sample radiograph is shown in Fig. 13.

On the basis of radiographic analysis of all radiographs obtained in the study, it was found that there were no internal defects in the welds regardless of their width. These tests confirm the possibility of obtaining a weld without discontinuities and internal defects, in the process of electron beam welding in accordance with the parameters determined in the tests, regardless of the joint width obtained.

![Fig. 11 Image of the weld microstructure for the variant: narrow weld. Kalling’s reagent was used for etching.](image-url)
3.5 Analysis of the chemical composition of the weld

To assess the degree of mixing of alloying elements in the weld, after the electron beam welding process, for two variants of the obtained narrow and wide welds, chemical composition tests were carried out using the method of energy-dispersive X-ray spectroscopy (EDX). The tests were carried out in the central part of the weld in three places: at the top, at the centre and at the bottom of the weld. The test results are shown in Tables 3 and 4. Elements whose content in the initial chemical composition of both joined materials differed significantly, i.e. V, Cr, Mn, Ni and Mo, were analysed.

The analysis of the results of the chemical composition tests of the central part of the weld, both for the wide and narrow weld, shows a similar weight share of the analysed alloy elements. This is due to the specificity of the electron beam welding process, in which a steam hole is created as a result of the action of the electron stream, which is closed under the impact of capillary forces. During the interaction of the electron beam, a very small amount of material is melted, which is mixed in a very short period of time. This effect can be observed by analysing the weight shares of alloy elements in the chemical composition of the weld, for which the content in the initial chemical composition of both combined materials differed significantly, i.e. V, Cr, Mn, Ni and Mo. These values are higher than the average value resulting from the chemical compositions of both welded steels. This relationship was observed for all elements analysed in the study. It was noted that the degree of mixing of the alloy elements in the weld does not affect its width. The degree of mixing is sufficient and suitable for both narrow and wide welds.

![Fig. 12 Image of the weld microstructure for the variant: wide weld. Kalling’s reagent was used for etching](image)

![Fig. 13 Sample radiograph depicting a wide weld, b a narrow weld](image)

| Reading location | The weight share of the element in the chemical composition, % | V | Cr | Mn | Ni | Mo |
|------------------|------------------------------------------------|---|----|----|----|----|
| Top              | 0.61 4.02 0.43 2.05 3.87                          |   |    |    |    |    |
| Centre           | 0.93 4.19 0.41 2.22 3.35                          |   |    |    |    |    |
| Bottom           | 0.74 3.96 0.39 2.36 2.73                          |   |    |    |    |    |
| Average value    | 0.76 4.05 0.41 2.21 3.31                          |   |    |    |    |    |

Table 3 The weight share of elements in the chemical composition of the weld, for the variant: narrow weld

| Reading locations | The weight share of the element in the chemical composition, % | V | Cr | Mn | Ni | Mo |
|-------------------|------------------------------------------------|---|----|----|----|----|
| Top               | 1.04 3.65 0.32 2.48 2.95                          |   |    |    |    |    |
| Centre            | 0.89 3.92 0.41 2.30 3.52                          |   |    |    |    |    |
| Bottom            | 0.88 4.40 0.27 2.22 3.41                          |   |    |    |    |    |
| Average value     | 0.93 3.99 0.33 2.33 3.29                          |   |    |    |    |    |

Table 4 The weight share of elements in the chemical composition of the weld, for the variant: wide weld
3.6 Analysis of mechanical properties

Mechanical treatment of samples intended for testing mechanical properties introduces and shapes the surface mini-carbons, i.e. it affects the surface layer, which may affect the obtained values of mechanical properties.

Therefore, before starting the study of mechanical properties, the surface roughness was measured for all variants of the welding process analysed in the article. The tests were carried out with the use of the Profilometr Form Talysurf 50e. The tests were carried out in the area of the weld and the heat-affected zone, on a measuring section equal to 5 mm. The test results are presented in Table 5.

![Fig.14 The shape and dimensions of samples use for analysis of mechanical properties](image)

Table 5 The results of surface roughness tests for the analysed variants of the electron beam welding process in the area of the weld and the heat-affected zone, in the measuring section equal to 5 mm

| Place of measurements | Variant | \( R_a, \mu m \) |
|-----------------------|---------|-----------------|
|                       |         | 1A   | 1B   | 2A   | 2B   |
| Outer diameter        |         | 1.20 | 1.15 | 1.10 | 1.12 |
| Inner diameter        |         | 1.10 | 1.18 | 1.09 | 1.13 |
| lateral surface no 1  |         | 0.80 | 0.91 | 0.89 | 0.95 |
| lateral surface no 2  |         | 0.85 | 0.90 | 0.90 | 0.91 |

During the tests, the samples were destroyed in the heat-affected zone of the material made of M50NiL steel for all the variants of the welding process and the subsequent treatment, analysed in the tests. The assumptions about initiating a crack at this exact spot could be drawn from the analysis of the micro-hardness distribution on the weld cross section (Figs. 7, 8, 9 and 10). The lowest micro-hardness values were recorded in the heat-affected zone for M50NiL steel.

It was found that both the change in the width of the weld and the type of heat treatment after the welding process have little impact on the obtained values of tensile strength. The maximum difference between the tensile strength values reaches approximately 40 MPa for the W2AT and W2BT variants.

On the other hand, a significant impact of the weld width obtained in the welding process on the conventional
plasticity limit values (approx. 80 MPa) was found. The
registered value of the conventional plasticity limit for
variants with a narrow weld reached significantly higher
values, which is the result of the narrower heat-affected
zone obtained in the welding process. However, no sig-
nificant impact of the heat treatment carried out after the
welding process on the value of the conventional plasticity
limit was found. For the variant of heat treatment consist-
ing in the freezing process and subsequent single temper-
ing, a slightly higher value of the conventional plasticity
limit was obtained, both for a narrow and a wide weld
in relation to the variant of heat treatment consisting in
double tempering.

3.7 Fractographic analysis

Fractographic tests were performed using the scanning
microscope JSM—5400, fractures of samples obtained in
strength tests were analysed. Images of microstructures of
fractures for the variants analysed in the study are presented
in Figs. 16, 17, 18 and 19.

Fractographic analysis makes it possible to state that in
each of the analysed cases we are dealing with a mixed frac-
tures: ductile and trans-crystalline. The difference in fracture
levels for the variant of the welding process in which the
narrow weld was obtained is clearly smaller than for the
variant in which the wide weld was obtained.

Fig. 16 Fractography for the fraction for welding variant I (narrow weld) after heat treatment by single freezing at – 84 °C for 3 h, combined
with single tempering at 520 °C for 3 h; (a). 1000× (b). 750×
4 Summary

The conducted research allowed to state that it is possible to join steel with such different chemical compositions as analysed in the work, with the use of the electron beam welding process, without generating internal defects, i.e. porosity and cracks in the heat-affected zone.

No significant impact of the width of the weld generated was observed on the value of micro-hardness in the weld, regardless of the heat treatment applied.

On the other hand, the width of the weld generated in the welding process affects the minimum micro-hardness values in the heat-affected zone, regardless of the heat treatment applied.

Higher values were observed for the narrow weld.

The analysis of the distribution of alloy elements in the weld axis allowed to conclude that the degree of mixing of alloy elements in the weld is not impacted by its width.

The strength tests carried out indicate that the values of tensile strength for all variants analysed in the work are...
similar. No impact of the width produced in the weld process and the type of heat treatment applied on the values of tensile strength was observed. However, differences in the values of the conventional plasticity limit were found depending on the width of the weld produced and the type of heat treatment carried out. Significantly larger differences in the values of this parameter were noticeable for the variant in which a narrow weld was produced in relation to the variant in which a wide weld was obtained, about 80 MPa, for the same heat treatment variants.

Based on the tests carried out, it should be stated that it is possible to replace the heat treatment process after the electron beam welding process consisting in double tempering in a vacuum furnace, at temperature of 520 °C for 3 h, heat treatment process consisting in a single freezing at −84 °C for 3 h combined with single tempering at temperature of 520 °C for 3 h, without a clear decrease in the level of mechanical properties of the materials being joined. After such heat treatment, a higher value of the conventional yield strength is observed by about 20 MPa, compared to traditional heat treatment. It is recommended to conduct a welding process, enabling to obtain a narrow weld, because for this variant higher values of the conventional plasticity limit, higher values of the minimum hardness in the heat-affected zone and a lower width of the heat-affected zone were observed.

The omission in technological operations of the heat treatment stage consisting of tempering at temperatures of 500–550 °C, for a long period of time associated with heating, tempering and cooling of the material in a vacuum furnace (ca. 7 h) and replacing it with a freezing process carried out in a relatively shorter time, using devices with lower energy intensity, is an important economic factor in the design of the electron beam welding process and the production of parts for design applications.

**Author contributions** This article is the work of several authors, the individual contributions are subsequently listed: conceptualization, ZW and SW; validation, AG, JM and PW; investigation, ZW, SW, PW, JM and AG; formal analysis, AG and PW; writing—original draft preparation, SW; writing—review and editing, ZW and JM; visualisation, JM and PW; supervision, ZW; project administration, SW and AG. All authors have read and agreed to the published version of the manuscript.

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**Declarations**

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