

# WELDING AND CUTTING

Technical journal for welding and allied processes

## Guide for Authors



Stand: 05/2026

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Please submit the following files:

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- Article images also submitted as separate files (TIFF, JPEG, PNG) with min. 300 dpi resolution, named "Fig. 1, Fig. 2"
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- Each table in an individual Word or Excel file, using file names "Table 1, Table 2, ...".
- (See also the notes in Section 2, Figures and Tables)

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Your article should contain a maximum of approx. 27,000 characters including spaces and consist of a preface, main text and references.

#### 1.2.1 Preface

The preface contains the following elements in the order listed:

- Full names of all authors without titles
- Article title: max. 100 characters including spaces
- Abstract: max. 1,500 characters including spaces; no paragraphs

#### 1.2.2 Main text

The main text should be structured to a maximum of three levels. The introduction does not require a heading.

- Section headings may contain a maximum of 40 characters.
- The main text should end with a conclusion addressing any further planned investigations and an outlook on unresolved issues or similar topics. For research papers: identify any implications for potential practice.

#### 1.2.3 References

Refer to the corresponding reference using numbers in brackets, for example:

- [1] Matting, A., and G. Jacoby: The Degradation of Metallic Materials under Cyclic Loading in Fractography. Aluminium 38 (1962), No. 10, pp. 654–61.
- [2] Neumann, A.: Welding Technology Handbook for Designers, Vol. 1, pp. 31–40. DVS Media, Düsseldorf, 1990.

All sources (including online sources) must be cited according to DIN ISO 690. Number the references consecutively in the order in which they appear in the text. Please avoid using Word's automatic reference generation if possible.

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WELDING & CUTTING | ADDITIVE MANUFACTURING

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# Electron Beam Welding of Additively Manufactured Inconel 939 – Process Characteristics and Achievable Weld Quality

Additive manufacturing technologies such as the laser powder-bed fusion provide significant potential for the fabrication of new and replacement parts for stationary gas turbines made of nickel superalloys such as Inconel 939. To enable integration of repaired components into existing assembly units and to overcome dimensional limitations, the additive manufacturing process chain must be expanded to include suitable joining techniques. This work therefore deals with the welding of Inconel 939. It compares cast sheets and sheets produced additively using laser powder bed fusion in terms of their behavior during electron beam welding. The investigation focuses on the achievable seam quality with regard to geometric irregularities and internal defects in the form of microcracks in the heat-affected zone. No differences in the formation of the seam shape between the additively manufactured material and the cast material were found when evaluating the welded samples. The highest quality level for beam-welded seams according to DIN EN ISO 13919-1 was achieved for both materials at a high welding speed of 20 mm/s. Regardless of the manufacturing method, both materials show an increase in crack susceptibility with increasing welding speed. Due to its microstructure the material from additive manufacturing has significantly fewer microcracks overall, which opens up potential for practical application.

## 1 Introduction

The advantages of laser-based powder bed fusion (PBF-LB/M) are particularly evident when geometrically complex components need to be manufactured. In addition, it offers the possibility of producing undercut, internal structures such as cooling channels and load adapted designs, which make PBF-LB/M suitable for applications involving components made of materials that are particularly difficult to machine or cost-intensive. A good example is the manufacture of stationary gas turbines, where highly developed nickel-based materials, such as the Inconel 939 (IN939) alloy, are used for the production of blades and vanes. Due to its excellent mechanical, chemical and thermal properties, this alloy with its characteristic high chromium content has established itself as the standard material for numerous applications in gas turbines [1]. Due to their dimensions and complex geometry, turbine components made of IN939 can only be reworked, manufactured or

repaired with increased effort and high costs. Previous studies have demonstrated that IN939 can be processed using additive manufacturing methods such as PBF-LB/M and that the process is potentially suitable for both the manufacture of new parts and the repair of worn components [2].

Despite significant progress in recent years, the limited build space of the machines, which restricts the possible component size, remains a challenge for the use of PBF-LB/M systems in gas turbine manufacturing [1]. To overcome this challenge, a reliable joining process for additively manufactured components made of IN939 is required. Precise beam-based welding processes, such as electron beam welding (EBW), appear to be particularly suitable for this purpose. They could enable additively manufactured components to be joined with other PBF-LB/M parts or conventionally manufactured components, thus overcoming the size limitations of powder-bed-based AM. This would also allow the integra-

tion of additively manufactured replacement parts into existing assemblies.

Unlike other nickel-based alloys, IN939 is only considered to be partially suitable for welding due to its higher Al and Ti content [1]. Additional uncertainties exist when welding additively manufactured IN939, as the material is already prone to hot cracking as a conventionally cast material [3]. A characteristic feature of cracks in the heat-affected zone (HAZ), which are promoted by melting reactions of secondary carbides and parts of the  $\gamma'$ -phase [4].

The cracking tendency of the alloy is already known from the application of tungsten inert gas welding (TIG) and can be addressed by selecting filler wires with lower strength [3] or by prior heat treatment [5]. Nevertheless, these measures also result in lower mechanical strength of the joint. Other approaches to post-treatment show that the resulting cracks can be closed by subsequent hot

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Table 1. Chemical composition of the powder material in volumetric percent (nickel balanced)

Al	B	C	Co	Cr	N	Nb	O	Ta	Ti	W	Zr
1.89	0.004	0.16	18.99	22.5	0.002	0.97	0.0036	1.61	3.66	2.06	0.03

isostatic pressing, as demonstrated by the work of Xie et al. [6]. However, even with this post-treatment, the sealed cracks can still be identified in the microstructure and it remains unclear whether local weakening of the matrix has a negative impact on the overall mechanical properties. In addition, there is a risk that deviations in the material properties caused by the additive manufacturing process may have additional negative effects on the quality of the joint or even promote the formation of defects.

The use of a beam welding process such as EBW, with a small HAZ, and precise control of the seam geometry, appears to be suitable for IN939, as Ni alloys with high fractions of precipitation phases are more prone to cracking in the HAZ [7]. Welding in a high vacuum also appears to be advantageous for process optimization, as the influencing factors of shielding gas coverage and oxidation do not affect the joining process. Initial investigations have already shown that EBW has great potential for joining additively manufactured components made of IN939. For example, an investigation involving test welds on 3 mm thick sheets from the PBF-LB/M process showed that the tendency to cracking in the HAZ is partly parameter-dependent and can be limited to the microscale [8]. However, there is still a lack of process understanding for practical applications, necessitating a more detailed investigation into the occurrence of microcracks, possible seam quality for greater sheet thicknesses, and the interactions between the welding process and the additive manufacturing.

## 2 Materials and methods

### 2.1 Manufacturing of the PBF-LB/M samples

The additive manufacturing process was carried out on a SLM 280HL system. A total of 12 test sheets measuring 117 mm × 30 mm × 7 mm were produced



Fig. 1. Test setup: Left: Clamping of the sample sheets; Right: View into the vacuum chamber of the K30 (© Fraunhofer IPT)

for welding tests under a protective gas atmosphere of argon 5.0 with an oxygen content of less than 0.2 %. A substrate plate measuring 280 mm × 280 mm made of X15CrNiSi25-21 was used for sample production without additional preheating. The samples were distributed evenly on the substrate plate. In order to restrict the contact line with the cooler, all samples were rotated by 12.5° around their z-axis. According to the delivery note of the manufacturer, the powder material used for production had the chemical composition shown in Table 1. The particle size distribution according to ASTM B822 showed values for  $d_{10}$ ,  $d_{50}$  and  $d_{90}$  of 23 µm, 36 µm and 50 µm. The samples were produced using constant manufacturing parameters with a laser power of 250 W, a scanning speed of 180 mm/s, and a hatch spacing of 0.08 mm. Taking into account the intended layer thickness of 0.04 mm, this results in a volume energy density of 66 J/mm<sup>3</sup>. The parameters were selected to match the optimum values for IN939 determined in previous studies [9]. After sample production, standardized post-processing steps were carried out in the form of wire EDM to detach the samples from the substrate plate as well as solution annealing.

### 2.2 Electron beam welding

An EBG-15-150 K30 system from the manufacturer pro-beam was used for conducting the welding tests. The samples were clamped onto a work platform in the vacuum chamber using a machine vice. All samples were cleaned with acetone prior to welding. Fig. 1 shows the test setup.

During the welding tests, the vacuum in the chamber ranged from 0.5 · 10<sup>-6</sup> mbar to 2 · 10<sup>-6</sup> mbar. To benchmark the welding behavior of the additively manufactured material, 12 bead on plate welds were performed on sheets manufactured using PBF-LB/M and conventional IN939 cast material. The welding parameters were selected based on preliminary tests so that complete penetration could be achieved in all cases. The cast sample sheets were cut to a size of 114 mm × 28 mm × 7 mm using wire EDM. The bead on plate welds were performed in sharp surface focus in the form of a 10 mm long seam at a constant acceleration voltage of 120 kV. Table 2 provides an overview of the experimental design. Three different welding speeds and four levels of energy per unit length were tested. The beam current was increased stepwise in order to achieve identical energies

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Table heading

Table

Figure min. 300 dpi

Caption

Subheadline

grain, as shown in accordance with other sources from welding technology [4].

The risk of severe cracking therefore increases with the grain size of the microstructure. Mashhuziar et al. investigated the effect of preliminary heat treatments on the microstructure of IN939 during TIG. A key observation was the influence of heat transfer, which primarily affected the formation of microcracks via the size and proportion of the primary  $\gamma$  phase in the microstructure [7]. In general, it has been shown that refining the microstructure of nickel superalloys with a high proportion of precipitation phases reduces their susceptibility to cracking, e.g. through solution annealing. Ultimately, the volume ratio of the grain boundaries to the rest of the microstructure is crucial. In coarser grain structures, the grain boundaries account for less volume compared to the rest of the matrix, which means that precipitates at the grain boundaries grow into larger areas and the risk of cracks increases [1].

Differences can also be observed in the location of the microcracks. For example, cast IN939 tends to show increased cracking in the area of parallel seam edges. In the PBF-LBM material, on the other hand, cracks tend to concentrate at the seam head or, less frequently, at the seam root. These characteristic differences in crack distribution can be advantageous for the practical use of EBW on PBF-LBM components. For applications where cracks can only be removed by conventional machining post-processing methods, they can be displaced from the middle part of the weld seam towards the root and head areas by adjusting the welding parameters. A significant proportion of the cracks could then be eliminated by planning for additional material on the components and a removal of crack-sensitive areas via machining.

However, it should be noted at this point that the defects found in the form of microcracks do not constitute a criterion for exclusion in the final weld seam assessment and classification of seam quality in line with DIN EN ISO 13919-1. According to the definition in the standard, cracks are only classified as such if

they are visible at a magnification of 10x. In the case of the present work the defects observed are limited to the microscale. They can only be identified under a microscope at a magnification of 25x and their occurrence is a known phenomenon for IN939. Even by adjusting the welding process and using special filler materials, these cannot be completely eliminated even in conventional welding technology like TIG [6]. For practical applications of electron beam welding, the higher welding speed range is therefore recommended despite the greater tendency to cracking. The reason for this is that the best geometric seam quality is obtained in this range and high productivity can be achieved thanks to shorter welding times. In addition, the acceptability of inevitable microcracks should be considered depending on the application and material specifications.

#### Summary

This paper dealt with electron beam welding of components manufactured using PBF-LBM. The investigations focused on the achievable seam quality, the type and shape of seam irregularities that occur and process characteristics in comparison to conventional cast components. The following conclusions can be drawn from this:

- Additive manufactured IN939 produced by PBF-LBM and conventionally cast IN939 do not differ in the geometry of electron beam welded seams with identical welding parameters.

Both types of material are prone to microcracks in the HAZ, which start at the fusion line and grow along the grain boundaries into the base material. In cast material, cracks tend to form more frequently in the area of the parallel seam edges, while in PBF-LBM material, more cracks can be observed in the area of the head and root.

During welding, the cast material exhibits a significantly higher proportion of microcracks compared to the material produced using PBF-LBM. The reason for this is the finer microstructure resulting from the additive manufacturing process and post-processing. This limits the proportion of

low-melting precipitates at the grain boundaries.

There is a significant correlation between crack tendency and welding parameters. In the examined process range, particularly high welding speeds resulted in higher crack lengths. The cause of this is believed to be the resulting increase in the temperature gradient and a more unfavorable distribution of local strains in the heat-affected zone.

Irregularities in the weld seams manifested themselves as underfill and excessive penetration. These can be reduced by increasing the welding speed and are optimal at the highest level of 20 mm/s in the tested parameter range. When evaluating the samples according to the DIN EN ISO 13919-1 standard for beam welding, the results clearly show that setting the welding speed rate to 20 mm/s allows all welded PBF-LBM samples to be assigned to the highest quality level B.

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**Summary**  
at the end of the article

**Acknowledgement**  
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