

## Characterization of Single-Crystal Turbine Blades by X-Ray Diffraction Methods

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**Abstract.** Characterization of structure defects in turbine blades is the basis for determination of the overall crystalline perfections. This work presents the possibilities of identifying casting defects by combining different X-ray diffraction techniques. The investigation was conducted on samples prepared from as-cast turbine blades airfoil and tips. It was found that X-ray topograms revealed dendritic structure and macro strain areas. The defects areas which have appeared on topograms were also investigated by X-ray diffraction mapping technique by EFG diffractometer. Additionally, the X-ray investigation was complemented by macro SEM images obtained by stitching several images of microstructure. The X-ray maps of misorientation angle and X-ray topograms revealed a deviation between the  $\langle 001 \rangle_{\gamma'}$  direction and the blade axis as well as rotation of the primary dendrite arm around this axis.

### 1. Introduction

Nickel-based superalloys are advanced materials designed to have high strength and creep resistance at elevated temperatures. For this reason, high pressure turbine blades (HPT blades), which have to withstand extreme conditions in turbine engine, are often made of directionally-solidified, single-crystal, Ni-based superalloys [1]. As these components are critical for flight safety, blade failures in gas turbine engines can have dramatic effects on the engine airworthiness [2,3]. Different blade failures can be observed during engine operations. In general, we can group them into two categories: fatigue [4,5] and creep rupture [6]. One of the most critical part of turbine blades is airfoil with shroud tips which is exposed to the highest temperatures and experience a high thermal gradient. Both types of failure are mostly dependent on the heterogeneity and crystal perfection of turbine blade airfoil.

As this part of the blade is crucial, in the present investigation we have focused on crystal quality of the samples prepared from as-cast turbine blades airfoil and tips. We have applied different X-ray diffraction methods: X-ray topography, Laue diffraction and X-ray diffraction mapping, which, as we showed in previous papers [7], are very useful for the crystal quality investigation of single crystal superalloy. Additionally we have applied electron microscopy.

### 2. Experimental

The superalloy used in this research was CMSX-4, which has a nominal composition of 6.5 Cr, 10 Co, 6 Ta, 6 W, 5.6 Al, 3 Re, 1.0 Ti, 0.6 Mo, and the balance Ni (wt.%) and consist of about 70% volume fraction of  $\gamma'$  phase. Turbine blades were grown in the  $\langle 001 \rangle_{\gamma'}$  direction at the Research and Development Laboratory for Aerospace Materials in Rzeszów University of Technology in the ALD Vacuum Technologies furnace by the Bridgman method with the 3 mm/min. withdraw rate.

The blade geometry with marked samples location for investigation is shown in Fig. 1. The maximum deviation from  $\langle 001 \rangle_{\gamma'}$  direction ( $\alpha$  angle, Fig. 1) determined by Laue diffraction was around a few degrees. All samples were prepared by electro spark cutting parallel to the XZ plane near the leading edge of blade airfoil. Surface of the samples were then prepared using the standard metallographic procedure. The X-ray topography results were obtained by Panalitical microfocus X-ray source on AGFA structurix D7 FW X-ray film. The topography geometry was set-up for back-reflection. The full description can be found in [8]. All topograms were obtained with the use of Cu  $K_{\alpha}$  200 reflection of the  $\gamma'$  phase. To complement the X-ray topography investigation, the X-ray mapping of alpha and beta angle (Fig. 1) was performed on the EFG diffractometer. The deviation angle between  $\langle 001 \rangle_{\gamma'}$  direction and the blade axis Z ( $\alpha$ ) and rotation of  $\gamma'$  phase about this axis ( $\beta$ ) were studied. Additionally, the SEM investigation was performed on JOEL JMS 6480.

### 3. Results and discussion

Figure 2 shows the typical X-ray topogram and macro SEM images obtained from prepared samples used in the investigation. The X-ray topogram images mainly consist of short horizontal lines, with different intensity, arranged parallel to the secondary dendrite arms shown on SEM images (Fig. 3a, b, bands parallel to US). Moreover, topograms revealed a macro subgrain structure with the well-defined low angle boundary marked as MM in Fig. 2a. The misorientation between subgrains I and II was about 0,8 degree. In addition, there are visible changes on the topograms in contrast with some areas which are probably caused by their local macro strain (A,B,C in fig. 2a). On the macro SEM images we were not able to distinguish changes in microstructure directly indicating the presence of a subgrain boundary, which we had shown to be possible in the previous paper [7].

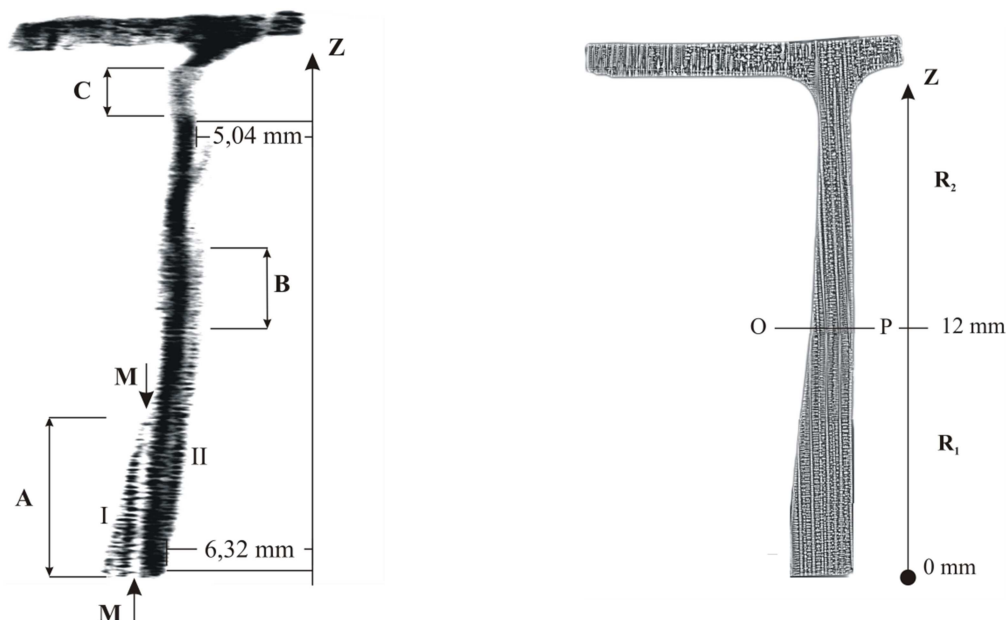


Fig. 2. Typical X-ray topogram (a), and macro SEM images (b) of the airfoil with tip samples.

It was shown that dendritic arrangement changes from Z about 12 mm (above OP line Fig. 2b, Fig. 3). This defect was probably caused during the casting procedure. In comparison to areas A and B, primary dendrite arms in area C (Fig. 2a) deviate about few degrees from Z axis ( $\delta$  in Fig. 3c). This deviation appeared as blurring and lower intensity of contrast on topogram in area C. However, contrast blurring of the B area was probably caused by changes in density and arrangement of secondary dendrite arms above the line US (Fig. 3b).

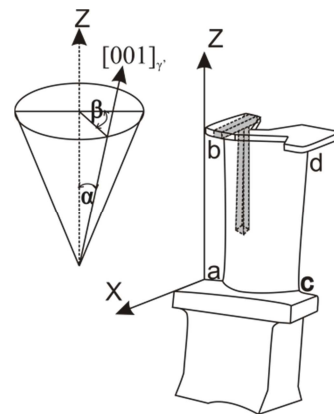


Fig. 1. Sample geometry with marked samples location (grey region). ab – leading edge; cd – trailing edge.

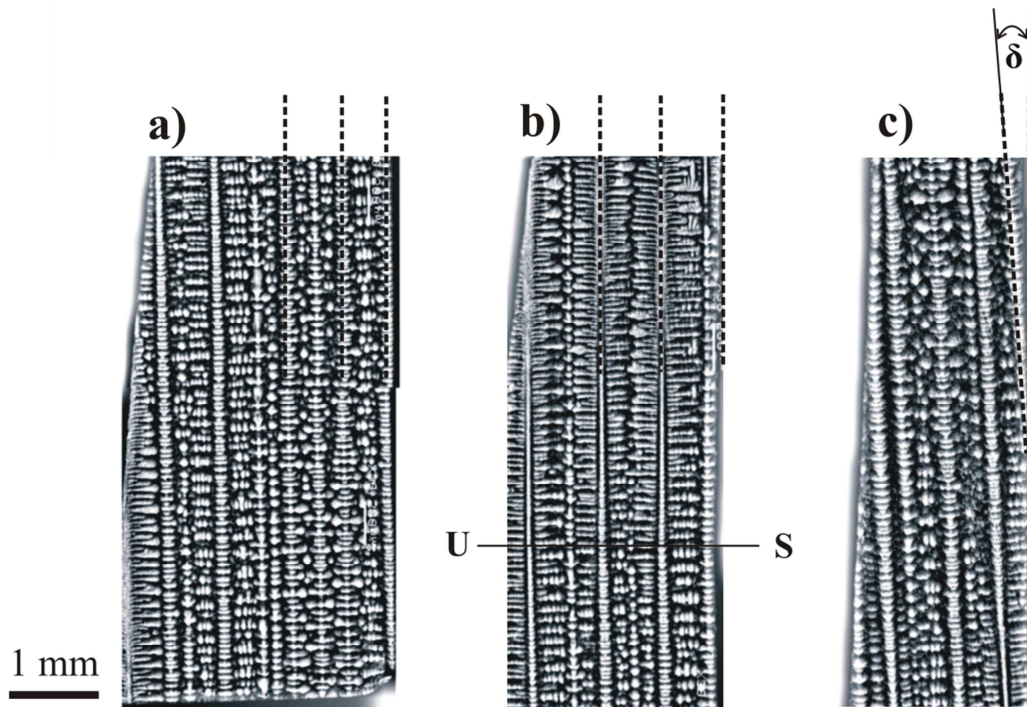


Fig. 3. SEM images of A(a), B(b) and C(c) areas marked in the Fig. 2

The X-ray diffraction mapping conducted on the EFG diffractometer was obtained only from region R1, the diffractometer was not able to collect data from X-ray reflexes in R2. The results revealed the same subgrain structure on both maps alpha and beta angle. The misorientation between subgrain ( $\alpha$ ) was about 0,8 degree which was confirmed by both X-ray topography and X-ray diffraction mapping methods. The beta angle shows continuous decreasing of around 22 degree within subgrain II. It was caused by the rotation of dendrites along the Z axis. The bending of the X-ray topography images could also be the reason of that rotation. The topogram shows bending (Fig. 2a in respect to the Z axis) which was not caused by the real shape of the sample (Fig. 2b).

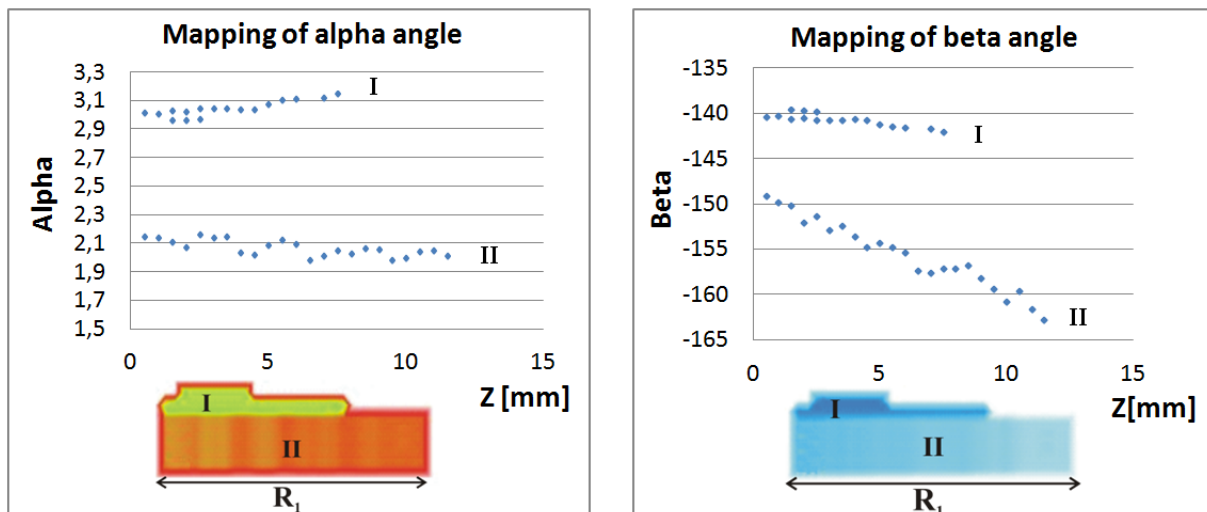


Fig. 4.  $\alpha$  and  $\beta$  angle changes along the Z axis determined by X-ray diffraction mapping.

#### 4. Conclusion

- By the X-ray topography method, it is possible to investigate crystal quality of prepared samples from turbine blades and reveal defects impossible to be determined by SEM investigation
- X-ray topography revealed subgrain structure of prepared samples confirmed by X-ray diffraction mapping. However, only X-ray topography shows the exact path of low angle boundary. The misorientation between subgrains was about 1 degree.
- Phase  $\gamma'$  is rotating along the Z axis of the blade and increases with the distance from the grain selector. The deviation of the primary dendrite arms from the blade axis is changing near the tip of the blade. With both of those changes in orientation the macro strain of the lattice occurred.

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