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Non destructive investigation of the condition of gas turbine blades

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ABSTRACT
In order to determine the remaining life of service exposed turbine blades it is necessary to characterize the degeneration of the microstructure of the base metal during service. Since turbine blades of industrial gas turbines are kept in complete stages, non-destructive inspection (NDI) is very atractive. Hence the goal of the investigation reported here was to evaluate a NDI technique able to detect microstructural changes of the base metal.
It was found that single-stage replication (in combination with investigation in a Scanning Electron Microscope) is a relatively simple technique that fulfils all requirements. This technique can be used in-situ on uncoated buckets. For coated turbine blades local removal of the coating is necessary to perform base metal replication.

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Non Destructive Investigation of the Condition of Gas Turbine Blades

Zerstörungsfreie Zustandsermittlung von Gasturbinenschaufeln

H.J. Kolkman and G.A. Kool

In order to determine the remaining life of service exposed turbine blades it is necessary to characterize the degeneration of the microstructure of the base metal during service. Since turbine blades of industrial gas turbines are kept in complete stages, non-destructive inspection (NDI) is very attractive. Hence the goal of the investigation reported here was to evaluate a NDI technique able to detect microstructural changes of the base metal.
It was found that single-stage replication (in combination with investigation in a Scanning Electron Microscope) is a relatively simple technique that fulfils all requirements. This technique can be used in-situ on uncoated buckets. For coated turbine blades local removal of the coating is necessary to perform base metal replication.

Die Restlebensdauer von sich in Einsatz befindenden Gasturbinenschaufeln wird durch die Bestimmung von Gefügeveränderungen des Grundwerkstoffes während der Betriebszeit ermittelt. Da man versucht Turbinenschaufelstufen in kompletten Sätzen zu halten, ist die Zerstörungsfreie Untersuchung (ZfU) sehr attraktiv. Ziel dieser Untersuchung war es deshalb, die Möglichkeiten eines ZfU Verfahrens zur Bestimmung von Strukturveränderungen im Basismaterial zu bewerten. Das einstufige Oberflächenabdrukverfahren (kombiniert mit REM-Untersuchungen) zeigt sich als relativ einfaches Verfahren, das allen Anforderungen entspricht. Auf unbeschichteten Turbinenschaufeln ist dieses Verfahren direkt anwendbar. Um es auf beschichteten Turbinenschaufeln anzuwenden, muß die Beschichtung lokal entfernt werden.

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1 Introduction

Fig. 1 shows a first stage gas turbine blade (bucket) after ≈ 15,000 service hours and 1600 starts. Apparently a part of the tip has been removed by FOD (Foreign Object Damage). From a technical point of view repair is feasible. This can be done by building up the tip by welding followed by reprofiling and recoating. A certain decrease of the mechanical properties of the repaired area is acceptable, since the service stresses (mainly caused by centrifugal loading) are relatively low in the tip. Whether repair is economically attractive depends on the remaining service life. Therefore the repair house Elbar, the gas turbine manufacturer Thomassen International and the National Aerospace Laboratory NLR defined a project to determine the residual life of industrial gas turbine blades, under contract by the Netherlands Agency for Aerospace Programs NIVR.

This residual life is strongly dependent on the operating conditions (e.g. firing temperature) of the gas turbine in which the blades have been installed. Since the design life is based on a set of assumed operating conditions, the actual life may be considerably different. It is imperative that the condition of blades be assessed periodically and that the remaining life be estimated to determine what actions, if any, need to be taken to insure continued safe and reliable operation of the gas turbine. NDI methods (such as visual inspection, fluorescent penetrant dye inspection, heat tinting) are used to monitor the coating condition. This coating condition is, however, not representative for the superalloy substrate condition, among other things since the coating life is usually much shorter that the superalloy life and since the coating condition depends on the corrosive conditions in the gas turbine and the superalloy life does not. The remaining life of the blade substrate is determined by microstructural degradation of the superalloy. For both civil and military jet engines destructive investigation of turbine blades is common practice. The blades to be investigated are simply replaced by new blades or blades originating from another engine. For industrial gas turbines the situation is different: Blades are kept in complete stages. If spares are available this is usually in the form of a complete set. Hence the replacement of destructively investigated blades is very difficult and expensive. Therefore the first phase of the aforementioned project was NDI (Non Destructive Inspection) of the microstructure of turbine blades. This first phase is the subject of the present paper.

2 Microstructural degradation of nickel-based superalloys

During service the mechanical properties of nickel-based superalloys applied in gas turbine components degradate because of the microstructural processes discussed below.

The high strength of nickel-based superalloys is predominantly due to hardening by coherent ordered so-called γ'(gamma prime) precipitates - with approximate composition $Ni_3(Al,Ti)$ - embedded in the interdendritic austenitic γ matrix. In most superalloys two types of γ' particles can be distinguished (see Fig. 4 to be discussed later):

* coarse cuboidal γ', introduced during controlled cooling after solution heat treatment
* fine spheroidal γ', formed during ageing.

At elevated temperatures during service γ' coarsening and agglomeration takes place:

$$(r_t3 - r_03)^{1/3} = K(T) \cdot t^{1/3} \quad \textbf{(1)}$$

where: t : time (in s)

T	:	temperature (in °C)
r_t	:	mean γ’ radius (or half cube edge) at time t.
r_0	:	mean γ’ radius (or half cube edge) for t = 0
K(T)	:	Temperature and material dependent rate constant

In other words: the volume *change* for a given T and t is independent of the initial size.
Considerable radius changes of the γ’ spheroids can occur at relatively low service temperatures (or relatively short service times). Since the absolute mean volume changes of the spheroids and cuboids are equal, the relative volume changes of the much coarser cuboids are hardly noticeable under these circumstances. Notable changes of the γ’ cuboid size occur for relatively high service temperatures (or relatively long service times) under which conditions the γ’ spheroids dissolve. Other processes are the degeneration of grain boundary carbides and - some superalloys - the formation of brittle phases. The continuous carbide films resulting from carbide degeneration give rise to low creep ductility [1] and decreased impact resistance [2,3].
The aforementioned microstructural processes result in degradation of the mechanical properties. For instance, a diameter increase (during service) of the γ’ spheroids results in an increase of the minimum creep rate (see Fig. 2 taken from [4]). Usually a reheat treatment is applied during repair. Among other things, this restores the original γ’ distribution.
However, although significant life extensions are achieved by reheat treatments, the life subsequent to the treatment is generally less than the original rupture life, i.e. complete recovery is not generally achieved [5]. In this respect it should be mentioned that Fig. 2 refers to short term (50-200 h) creep rupture tests. Blade material evaluation and qualification of repair procedures are often based on such short term rupture tests. For the high stresses involved in short term rupture the deformation takes place in the matrix and hence is influenced by the γ’ distribution. In contrast, long term rupture life is not affected by γ’ coarsening [1] but by grain boundary microstructural features. This is since for the low stresses involved the deformation mechanism is grain boundary sliding.
It can be concluded from the foregoing that short term rupture tests are unrealistic. Hence the approach in the NIVR/Elbar/Thomassen/NLR project is not to estimate the remaining life directly from such tests, but to determine the real service temperature at critical locations from the γ’ coarsening and reassessment of component life based on the real service conditions.
The service temperature T can be determined by means of eq. (1) if the growth constant K(T) is known as function of T. Literature data are available for a number of superalloys, e.g. for the well-known blade alloy IN 738 in refs. 3 and 6-8. In the NIVR/Elbar/Thomassen/NLR project such data were determined also for the proprietary GE superalloy GTD 111.
r_t in eq. (1) is determined from the coarsened spheroids or cuboids for critical locations in the serviced blade. r_0 is determined from the unaffected γ’ distribution in the root (and can be neglected if $r_t >> r_0$). It follows that a NDI technique should at least be able to determine the radii of the γ’ spheroids in unserviced blades. Time t is known and hence K(T) can be

determined. Finally T is determined from the graph of K(T) versus T. Practical examples can be found in [9, 10]. These papers refer to destructive cross-sections. The idea of the present paper is to do the same by means of an NDI method.

3 Experimental methods and results

A serviced first stage turbine blade (Fig. 1) was made available by Stadtwerke München via Elbar. The blade was coated with a chromium diffusion layer; the substrate was IN 738. The blade had been in service for 15,329 h. The turbine inlet temperature was 920 °C. For the sake of clearness, all results presented here refer to this blade, but the procedures adopted was successfully applied to other blade and blade materials (such as the superalloy GTD 111).
The blade was cut up in several pieces for destructive and non destructive investigation.

In order to provide reference data for the NDI methods, TEM (Transmission Electron Microscopy) of thin foils was applied. As exemplified in Fig. 4, the dark field technique provides sharp black and white micrographs that are very suitable for γ’ sphere size measurements. Draw-backs are the time-consuming preparation of thin foils and of course the destructive nature of the technique.

A schematic of the NDI methods is presented in Fig. 3. All methods applied are based on the introduction of height differences by selective etching of certain phases in order to enable the detection of these phases by means of the height steps. For coated blades removal of the coating is necessary. A possibility is to strip the coating completely and to recoat the blade after the investigation. This is no problem, since stripping and recoating during overhauls is a normal procedure. Normal grinding in several steps and polishing is followed by etching.
Etching procedures for nickel-based superalloys can be classified as follows:

* chemical etching and electrochemical etching
* etching resulting in dissolution of the γ’ precipitates (whereas - in the ideal case - the γ matrix remains unattacked) and etching resulting in dissolution of the γ matrix.

The etched surfaces can either be studied indirectly by replication or directly by means of SEM (Scanning Electron Microscopy) or AFM (Atomic Force Microscopy).

In an Atomic Force Microscope (AFM) the specimen is sticked onto a piezoelectric XYZ scanner and is scanned under a very sharp tip. Alternatively, in "stand alone" systems the tip is scanned over the specimen. AFM scans are presented as height profiles or as 2D (XY) images, where the height (Z) scale corresponds to a greyness scale.
As compared with TEM of thin foils, the γ’ sphere diameters (and volume fraction) in the AFM micrographs were too large. The main point is that the tip is not infinitely sharp. As a

consequence, the height profile is a convolution of the sphere with radius r and the tip with radius R (Fig. 5). The apparent radius of the sphere in the image is r + R instead of R. The tip radii of most commercially available cantilevers (20-40 nm, see [12] and the γ'sphere radii (≈ 30 nm, see Fig. 4 and Table 1 to be discussed later) have the same order of magnitude. Hence AFM overestimates the γ' radii considerably. In principle, correction of this error is possible provided that R is known. However, in practice the relatively cheap tips are replaced frequently and their R's vary. Fig. 5 refers to etching of the matrix. The situation might improve if the γ' precipitates are etched, but this possibility was not investigated.

The other NDI methods produced satisfactory micrographs as exemplified in Fig. 6. The SEM technique is well-known. One of the SEM's used has a specimen room that can accommodate a blade as shown in Fig. 1. Nevertheless direct SEM observation (Fig. 6a) of complete blades in SEM gives problems with specimen manipulation and hence cannot be regarded as a practical method.

A surface replica is an impression of the surface. There are many process variables for replication. To start with, the degree of etching turned out to be an important parameter. Since the γ' cuboids were rather irregular, too heavy etching resulted in irregularly shaped depressions in the surface in which the replica material was trapped. Dilution of the etchant solved this problem.

Other important variables are:

a) the material of the primary replica

   In the present investigation the following replica materials were used:

   1) a cold curing resin, supplied as powder and liquid. After mixing curing begins. A droplet of proper viscosity is placed at the location to be replicated. After completion of the curing process the frozen droplet is stripped from the surface.
   2) a cellulose acetate film. The surface to be replicated is wetted with methyl acetate. The film is placed on it and is softened by the liquid. After evaporation of the liquid the film is peeled off.

b) the method of observation

   In this investigation the following methods of observation were used:

   1) TEM investigation of two-stage replicas

      This is the traditional high resolution method. Since the primary replica is much too thick to transmit the electron beam it is coated with a thin (electron transparent) carbon layer. Coating is performed at perpendicular incidence; during coating the primary replica is rotated. After dissolution of the primary replica the (secondary) carbon replica can be studied by means of TEM. In order to enhance the contrast a replica can be shadowed. This is the deposition from an oblique angle of a thin layer of heavy metal [11]. Again, there are many variables, such as the carbon layer thickness, the shadow angle and the thickness of the heavy metal layer.

2) SEM investigation of single-stage replicas
Replicas have to be electrically conductive for SEM investigation. Therefore a heavy metal layer is sputtered. In order to avoid heating up of the replica the accelerating voltage has to be low. However, decreasing the accelerating voltage results in loss of resolution. Hence the accelerating voltage used is a compromise.

Two-stage and single-stage replicas were studied with TEM and SEM respectively. TEM has a much better lateral resolution than SEM, i.e. 0.2 and 3.5 nm for the instruments used. However, the resolution is determined by the replica and not by the instrument: The lateral resolution of a two-stage replica is ≈ 10 nm [10]. The resolution of the single-stage replicas used here was similar. γ' spheres (with diameters of ≥ 60 nm, see Fig. 4) were depicted satisfactorily in both single- and two-stage replicas, see Figs. 6b and 6c. Two-stage replication is more time-consuming and requires more skill than single-stage replication. Hence the single-stage replicas were preferred.

The main problem with single-stage replicas turned out to be heating (and consequently deformation) of the replica during SEM observation. An example is shown in Fig. 7. This problem was overcome by:

* Focusing and correcting for astigmatism at another location than where the micrograph was made.
  This is not a serious draw-back since the γ' distribution should be more or less the same everywhere.
* A delicate combination of the thickness of the layer sputtered for electrical conductivity, the accelerating voltage and the beam current.

4 Discussion

Diameters of γ' spheres measured with different methods at similar locations are tabulated in Table 1. Single-stage replication gave very satisfactory results, since SEM of single-stage replicas and direct SEM of etched surfaces yielded almost identical γ' sphere diameters. γ' spheres revealed by TEM of thin foils have slightly larger diameters. This is since in TEM the complete γ' spheres are seen in projection and for the other techniques in cross-section.

The γ' spheres at the leading edge at midspan have coarsened slightly (as compared with the root). It follows from this coarsening (Table 1) and the aforementioned service life that the rate constant K(T) in eq. (1) is 0.12 nm $s^{-1/3}$. The lowest value found for IN 738 in the literature was 0.37 for 750 °C in [7]. Hence the service temperature for the blade shown in Fig. 1 was lower than 750 °C. This can be regarded as a very low temperature.

Similar data are being collected for a number of blades with different service lifes and for many locations per blade. In the next phase of the project the residual lifes will be determined. Despite the aforementioned low service temperature the internal surfaces of the hollow blade exhibited severe degradation, see Fig. 8. Therefore a following project will be devoted to internal coating.

5 Conclusion

Single-stage replication is a relatively simple technique, very suited for the non-destructive microstructural investigation of service exposed gas turbine blades.

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Table 1

Diameters of γ' spheres at different locations in IN 738 gas turbine blade, determined by different methods.

Tabelle 1

Durchmesser von γ' Kugeln an verschiedenen Stellen in IN 738 Gasturbinenschaufeln anhand unterschiedlicher Verfahren bestimmt.

	TEM (thin foils)	direct SEM (etched surface)	SEM of single stage replica
root	66 ± 18	60 ± 16	61 ± 13
leading edge at midspan		68 ± 15	69 ± 13

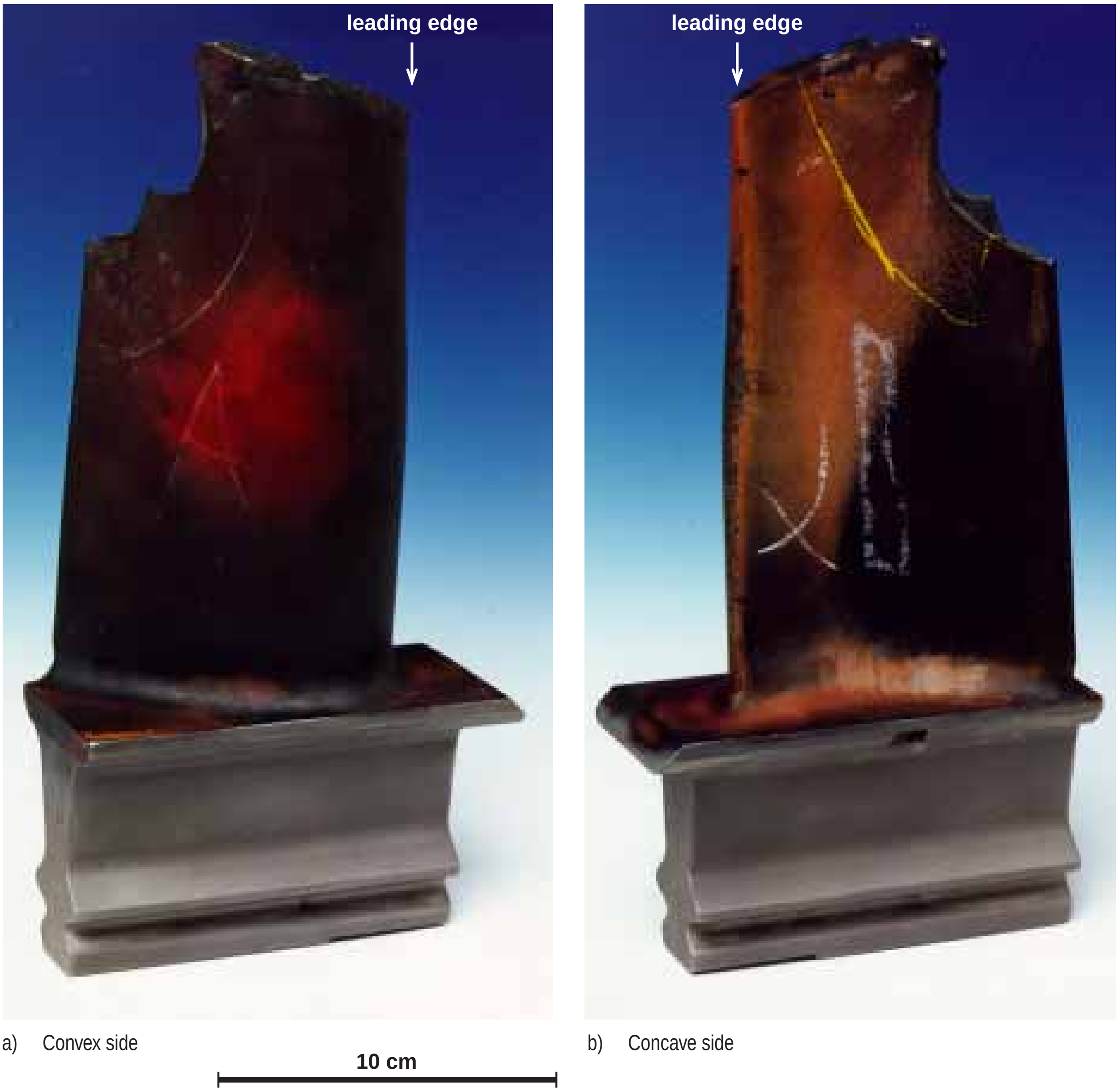


Fig. 1 Macrographs of the first stage gas turbine blade investigated.

Abb. 1 Makroskopische Bilder der untersuchten Gasturbinenschaufel der ersten Reihe.

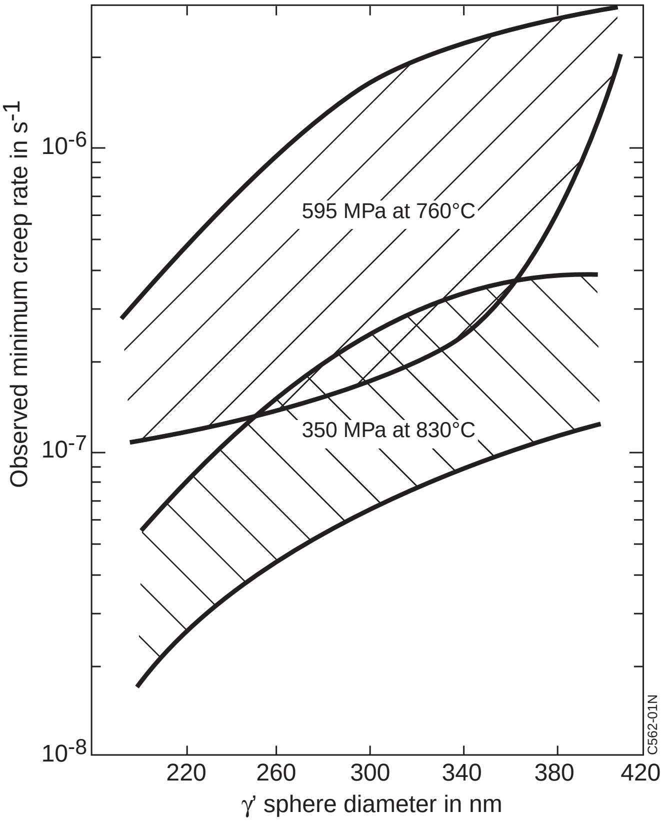


Fig. 2 Relationship of γ' sphere diameter and minimum creep rate in IN 738 gas turbine blades [4].

Abb. 2 Zusammenhang von γ' Kugeldurchmesser und minimaler Kriechgeschwindigkeit in IN 738 Gasturbinenschaufeln [4].

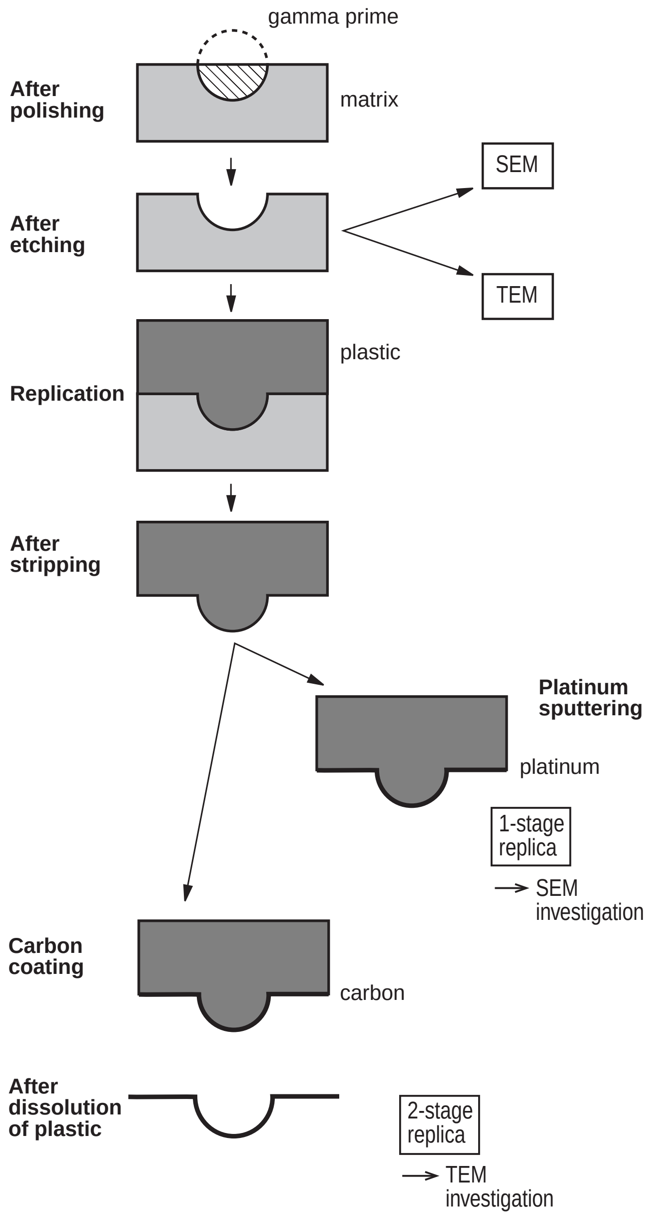


Fig. 3 Schematic of the NDI investigations.

Abb. 3 Schematische Darstellung der ZfU Untersuchungen.

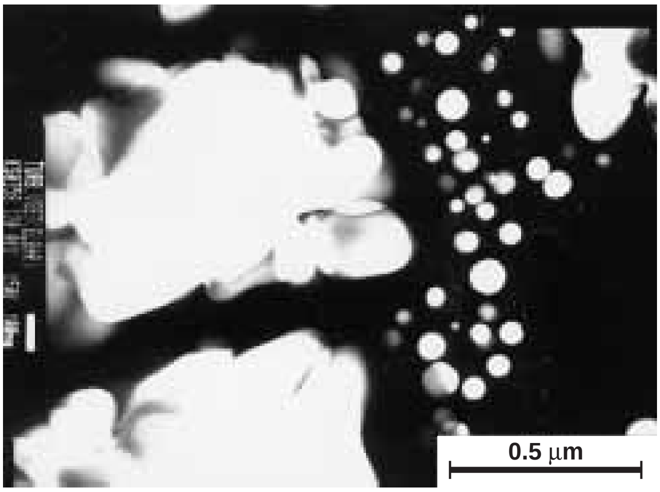


Fig. 4 Destructive investigation: dark field TEM micrograph of thin foil taken from IN 738 blade root. Note the relatively coarse γ' cuboids on the left-hand side and the fine γ' spheres on the right-hand side.

Abb. 4 Destruktive Untersuchung: TEM Dunkelbild einer durchstrahlbaren Folie einem IN 738 Schaufelfuß entnommen. Auffällig sind die relativ groben, würfelförmigen γ' Ausscheidungen zur Linken und die feinen γ' Kugeln zur Rechten.

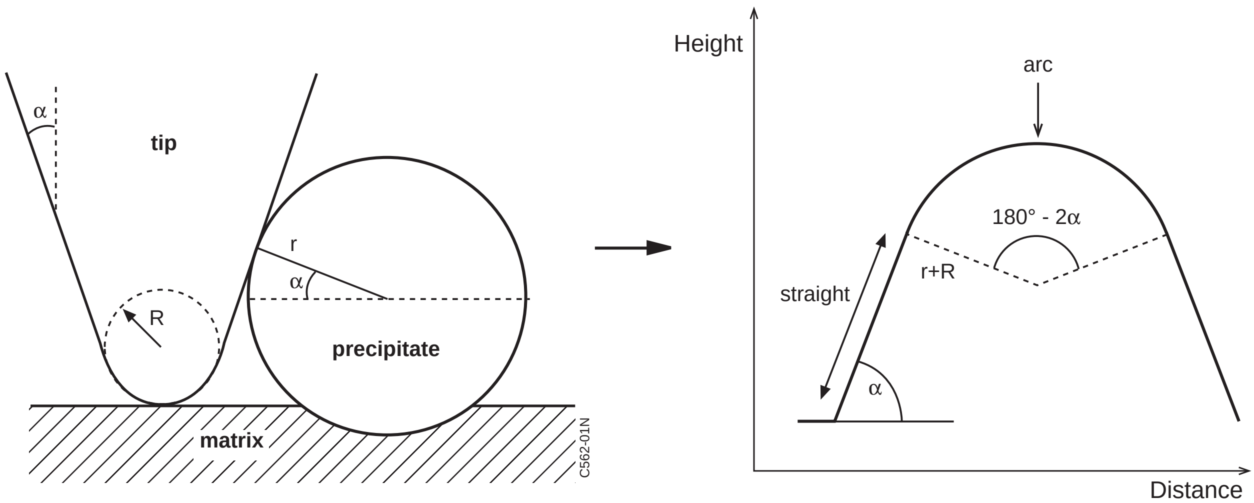
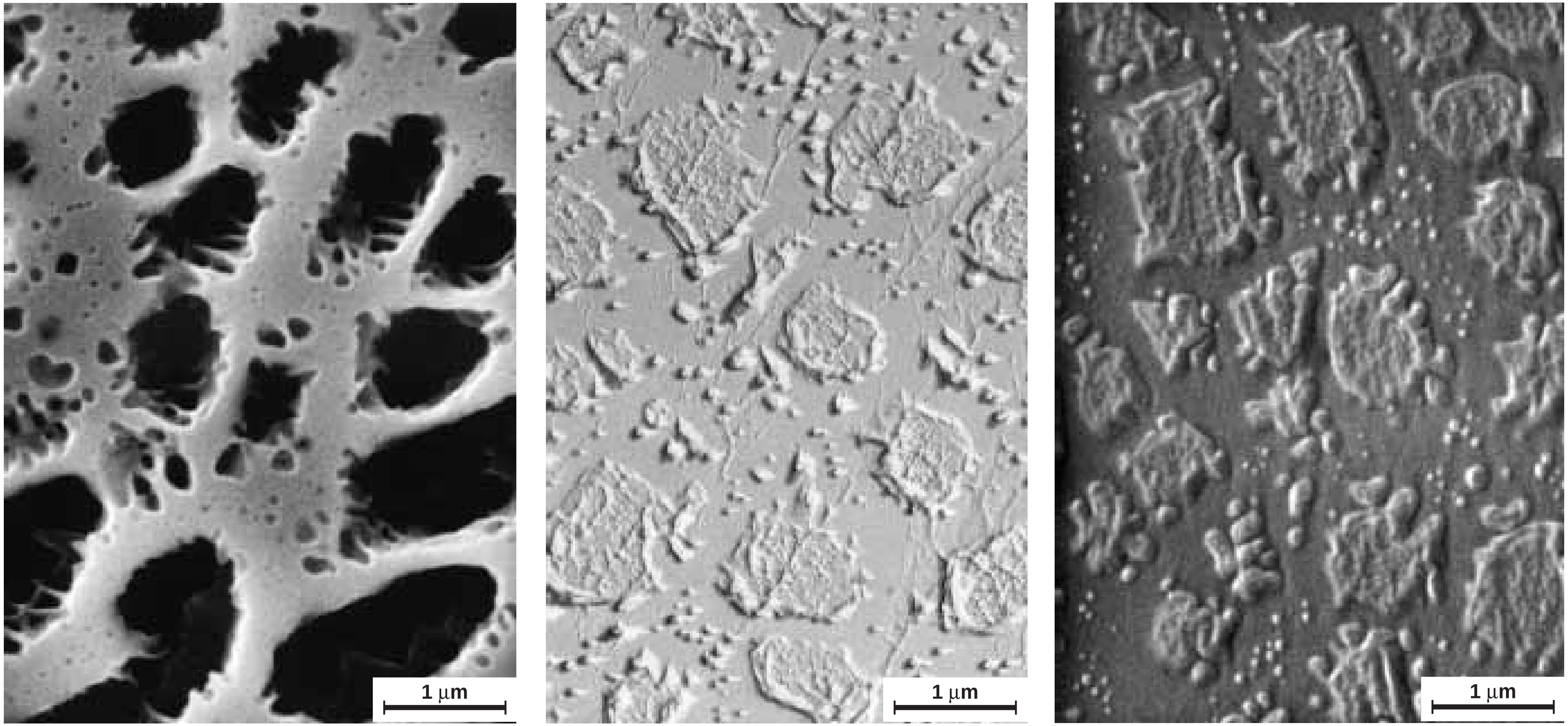


Fig. 5 Imaging of a spherical precipitate in an etched matrix by AFM.

Abb. 5 AFM Abbildung einer kugelförmigen Ausscheidung in einer angeätzte Matrix.



a) direct SEM observation of etched surface

a) direkte REM Beobachtung einer geätzten Oberfläche

b) two stage replica investigated by means of TEM
(shadow direction from left to right)

b) zweistufiger Oberflächenabdruck beobachtet mit TEM
(Beschattungsrichtung von links nach rechts)

c) single-stage replica investigated by means of SEM

c) einstufiger Oberflächenabdruck beobachtet met REM

Fig. 6 Microstructure of IN 738 blade root as revealed by NDI methods at the same magnification.

Abb. 6 Mikrostruktur eines IN 738 Schaufelfußes beobachtet mit unterschiedlichen ZfU Methoden bei gleicher Vergrößerung.

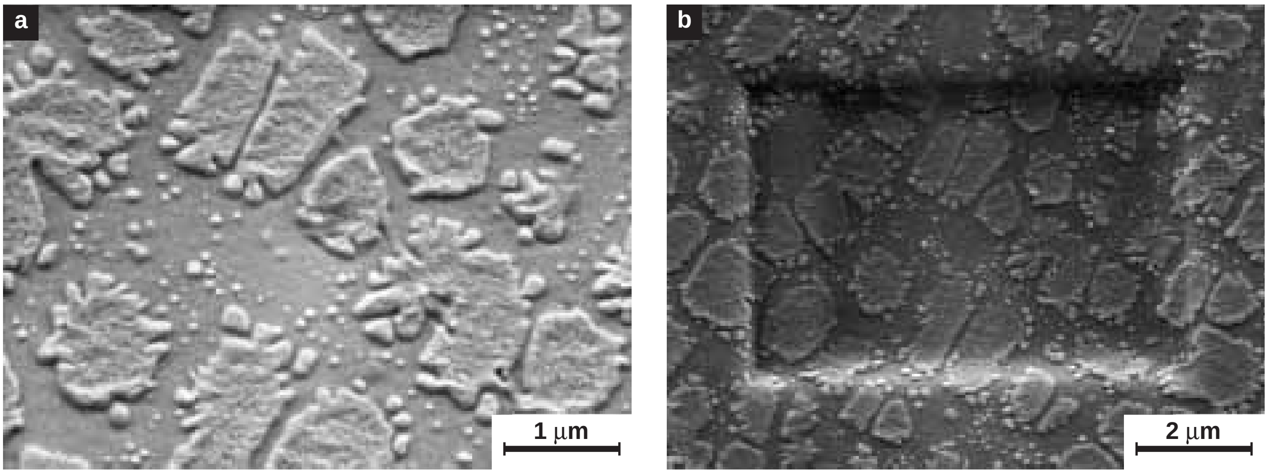


Fig. 7 SEM micrograph of single-stage replica. During photographing at high magnification (figure 7a) the illuminated area was deformed by heating up the electron beam as seen at lower magnification in figure 7b.

Abb. 7 REM Aufnahmen eines einstufigen Oberflächenabdruckes. Während des Fotografierens bei hoher Vergrößerung (Abb. 7a) wurde der belichtete Bereich durch den Elektronenstrahl aufgeheizt und plastisch verformt. Dies ist bei geringer Vergrößerung (Abb. 7b) zu erkennen.

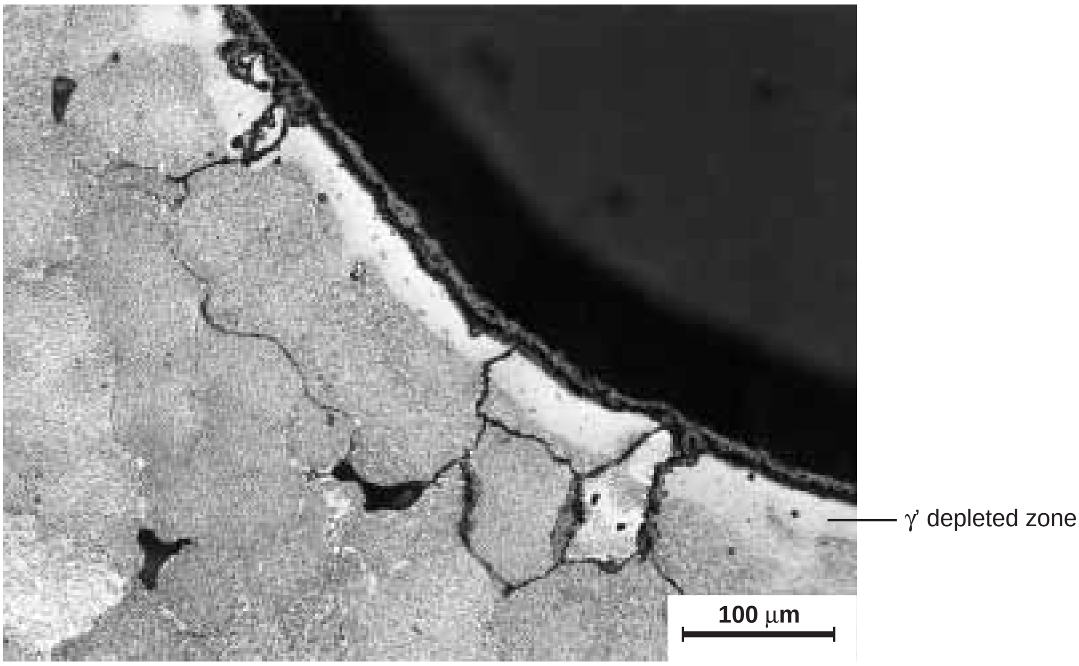


Fig. 8 *Optical micrograph of the (uncoated) internal surface of the blade shown in figure 1. Note the corrosion layer, the γ' depleted zone and the intergranular cracks. In contrast to this degradation, the external surface was protected well by by the coating.*

Abb. 8 *Lichtmikroskopische Aufnahme der (unbeschichteten) Innenfläche der in Abb. 1 gezeigten Schaufel. Bemerkenswert ist die Korrosionschicht, die γ'-freie Zone und die interkristallinen Risse. Im Gegensatz zu dieser Degeneration wurde die Außenfläche durch die Beschichtung gut geschutzt.*