

Creep Behaviour of Thick and Thin Walled Structures of a Single Crystal Nickel-Base Superalloy at High Temperatures – Experimental Method and Results

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Abstract

Creep behavior of the single crystal nickel-base superalloy René N5 is investigated as a function of material thickness. The results point out that reducing the thickness from 1.0 to 0.2 mm leads to both shorter creep lives and much higher overall creep strain rates of thin specimens. The orientation of the specimen is an important factor too but has a weaker influence on creep behavior under the given test conditions than the specimen thickness.

Introduction

Single crystal nickel-base superalloys are used in blades and vanes of stationary gas turbines and aero engines. Their lifetimes are mainly limited by fatigue, creep and hot corrosion at elevated service temperatures. To increase lifetime a possible strategy is to reduce the material temperature by cooling. In order to optimize both the cooling efficiency and the weight of fast rotating turbine blades a general trend is to reduce the wall thickness of the hollow investment casting parts.

The relation between creep properties and section thickness was rarely investigated [1-10]. For the polycrystalline nickel-base superalloy PWA 1484 Duhl [1] found a five fold reduction of creep rupture life if the specimen thickness is diminishing from 4 to 0.5 mm which mainly depend on grain size and micro structural defects. Doner and Heckler [3, 4] observed in uncoated single crystal CMSX-3 a 30% loss in creep rupture life if the wall thickness was reduced from 3.18 to 0.76 mm at 982°C and if the stress level was below 275 MPa. They also found that the time to reach 1% strain was unaffected by wall thickness at a constant stress level. Seetharaman and Cetel [6] reported similar results for single crystal PWA 1484 with wall thicknesses of 1.76 and 0.38 mm respectively and stresses below 275 MPa at 982°C. They concluded that oxidation and the more constrained plastic deformation are the major contributions for early failure of thin specimens. Doner and Heckler [3, 4] found that creep rupture properties of aluminized nickel-base superalloys are less influenced by the specimen thickness. By contrast Seetharaman and Cetel [6] mentioned a loss of creep rupture lifetime of 30-40% with a thickness reduction from 1.52 to 0.25 mm for coated Knowledge and understanding of the creep behavior is a fundamental prerequisite for component life-time predictions. Therefore the effect of thickness reduction on the creep properties of uncoated and aluminized single crystal nickel-base superalloy René N5 is investigated in this study. In addition deviations from the [001] orientation are incorporated into this study which is part of a ongoing research carried out for the next years.

Experimental

A cast and heat-treated single crystal plate of René N5 was provided. Chemical composition is found elsewhere [11]. The plate was oriented by Laue back scattered diffraction and several slices with an angle of 16° off the [001] zone axis towards the

<011> direction and in exact [001] orientation were cut by wire electrical discharge machining. Observations of Sass et al. [12] have shown that the influence of orientation deviation towards the <011> direction is less severe than deviation towards the <111> direction. Two series of thick and thin tension specimens (geometries 95×3×1 mm³ and 95×4×0.2 mm³ respectively) were cut from the 16° miss-oriented slice and two specimen series (geometries 95×3×1 mm³ and 95×4×0.3 mm³ respectively) were cut from the [001] oriented slice.

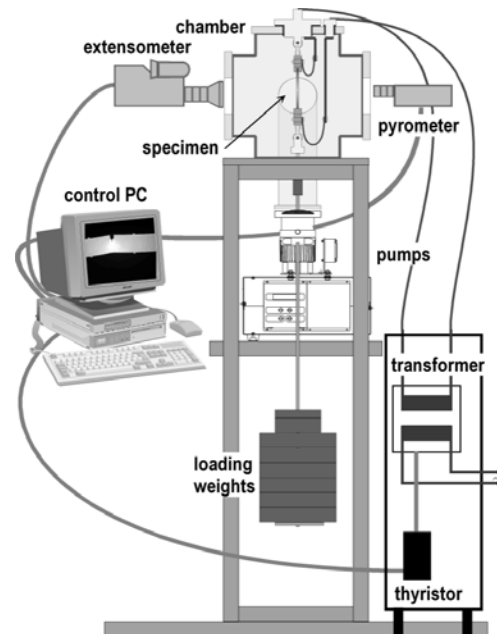
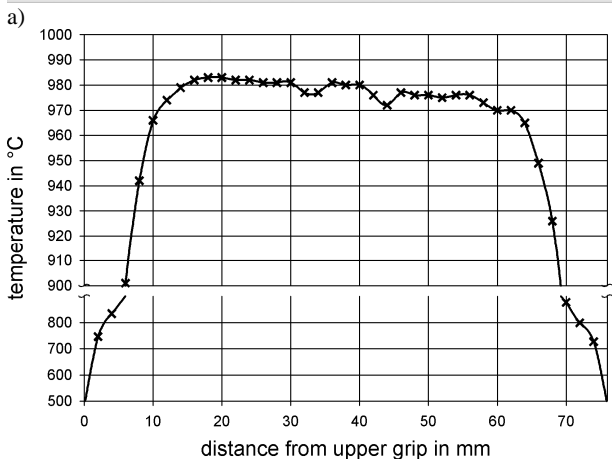
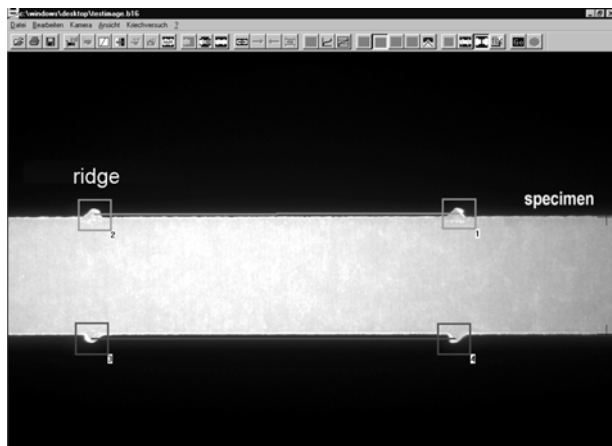


Fig. 1: Scheme of ultra-high temperature test facility.

Specimens were tested with an 40 µm aluminum coating and without coating. Constant load tensile creep test were performed at 980°C for three stress levels, 230, 270 and 300 MPa till rupture of the specimens. The raw data was fit with Bezier splines [13] and the results for different specimen thicknesses in both orientations and with different surface conditions are presented. Proprietary test facilities with Ohmic heating [13-16] were used in this study. The test facilities permit tests either in air, vacuum or under a protective gas atmosphere. A scheme of the test facilities is given in Fig. 1. Strain between ridges in the central zone of the specimen (Fig. 2a) is measured with sub pixel accuracy by means of a CCD camera controlled by the software *SuperCreep* [13-16]. At a maximum measurable strain of $\epsilon \approx 60\%$, an error of $\Delta\epsilon \approx \pm 7 \cdot 10^{-4}$ for a single strain measurement was determined [14,15]. By mean filtering over about 1500 single measurements

or 60 s respectively an error of the mean strain of $\Delta\bar{\epsilon} \approx \pm 3 \cdot 10^{-5}$ was deduced [15].

Temperature is controlled with a dual color pyrometer to overcome problems due to unknown emissivity. The temperature distribution at the specimen was measured by a second pyrometer (Fig. 2b). The temperature at the specimen centre was 980°C whereas at the ridges slightly lower temperatures of about 975°C were measured. In a zone 30 mm around the specimen centre the temperature was $980 \pm 5^\circ\text{C}$.

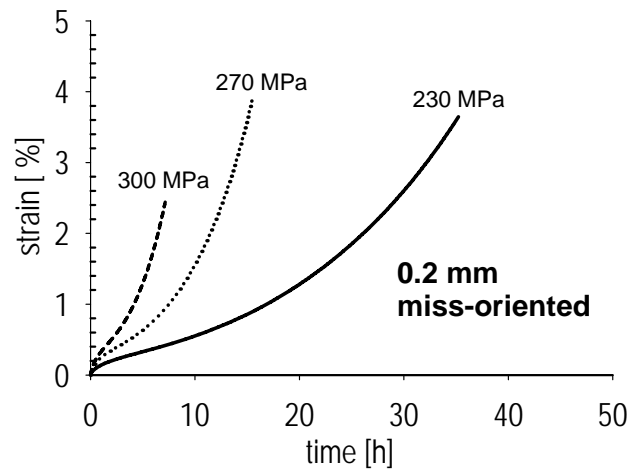


b) Fig. 2:
a) Bright specimen at 980°C with 4 ridges for strain measurement.
b) Temperature distribution along a René N5 specimen. The distance between grips was 75 mm.

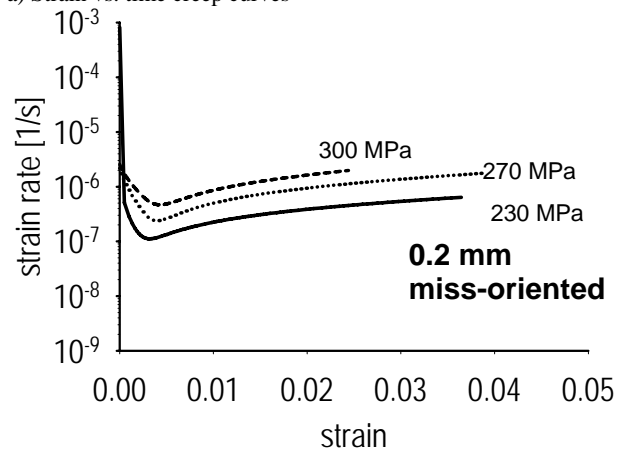
Results

Creep tests on 16° miss-oriented René N5 specimens

0.2 mm as well as 1 mm thick specimens show typical creep curves with decreasing creep rate until minimum creep rates are reached followed by steadily increasing creep rate (Fig. 3 and 4). Minimum creep rates of thin specimens are about one order of magnitude higher than 1.0 mm thick specimens (Fig. 3b and 4). Strain to failure remained below 5% for 0.2 mm thick specimens under all applied loads, whereas fracture strains were always above 20% for 1 mm thick specimens (Fig. 4). By reduction of specimen thickness from 1 to 0.2 mm the creep rupture life is reduced by a factor of 4 to 5.



a) Strain vs. time creep curves



b) Strain rate vs. strain creep curves
Fig. 3: René N5, 16° miss-oriented, 0.2 mm, 980°C.

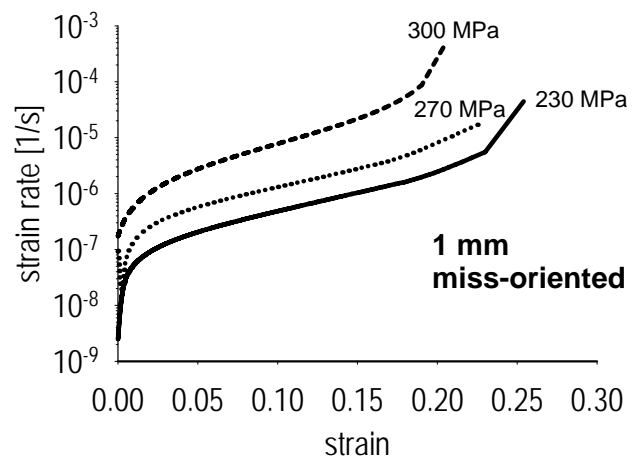


Fig. 4: Strain rate vs. strain creep curves, René N5, 16° miss-oriented, 1.0 mm, 980°C.

Creep tests on 16° miss-oriented and aluminised René N5 specimens

Fig. 5 shows the creep behavior of 1.0 mm thick samples with aluminised coating. A comparison between aluminised and not aluminised specimens (Fig. 4 and 5) reveals no systematic improvement in rupture times for coated 1 mm thick samples.

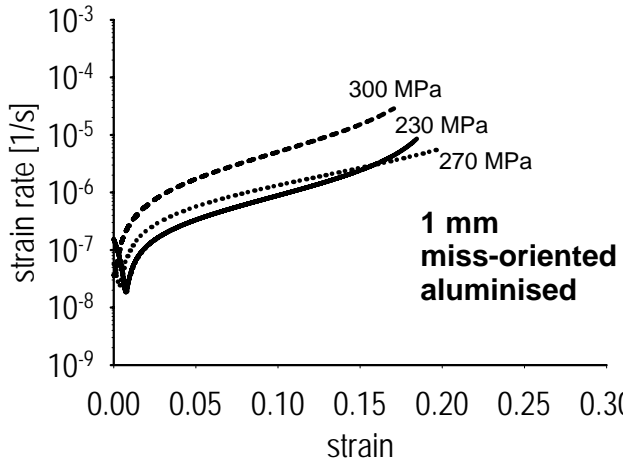


Fig. 5: Strain rate vs. strain creep curves, René N5, 16° miss-oriented, aluminised, 1.0 mm, 980°C.

Creep tests on [001] oriented René N5 specimens

Very important for creep resistance is the orientation of a single crystal sample. Results for specimens without coating are presented in Fig. 6 and 7.

Specimen thickness has also an influence on creep rupture time and rupture strain for [001] orientation, however the effect is strongest at low stress of 230 MPa where the creep time was reduced by a factor of 2. Rupture strains of 0.3 mm thick specimens were generally lower than for 1.0 mm thick specimens while minimum creep rates do not change significantly for the same load (compare Fig. 6 and 7).

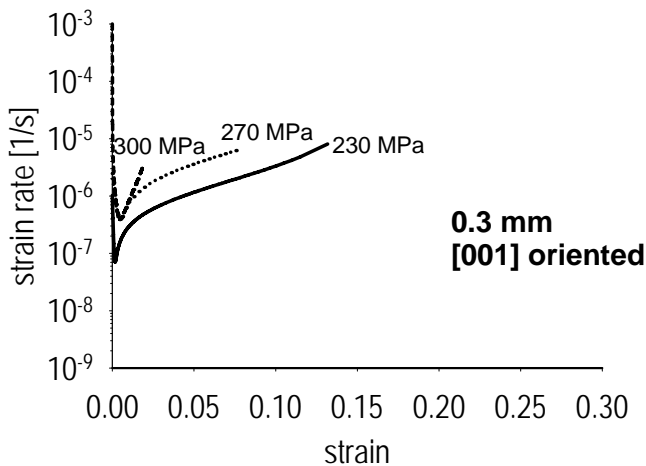


Fig. 6: Strain rate vs. strain creep curves, René N5, [001] oriented, 0.3 mm, 980°C

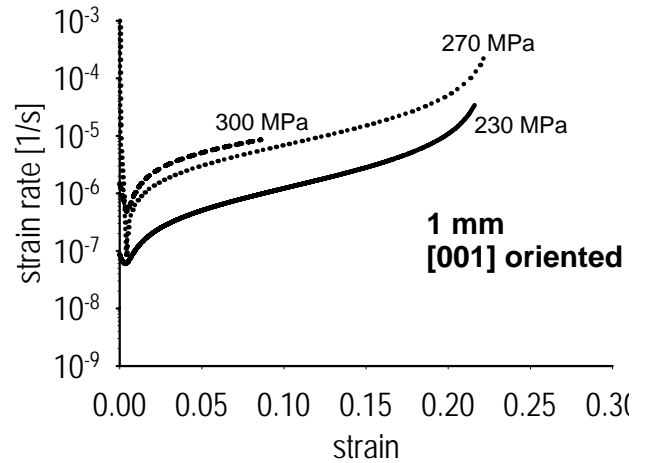


Fig. 7: Strain rate vs. strain creep curves, René N5, [001] oriented, 1.0 mm, 980°C

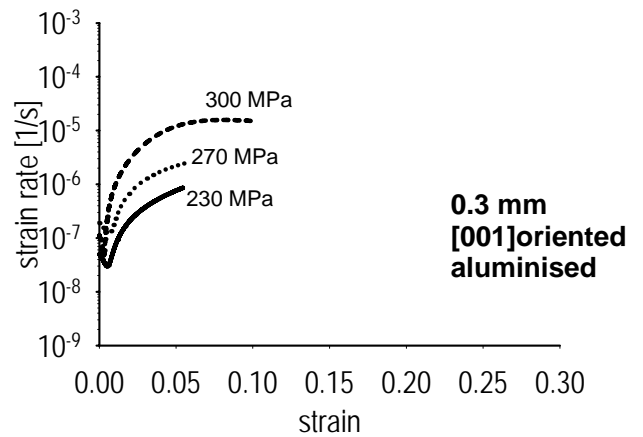


Fig. 8: Strain rate vs. strain creep curves, René N5, [001] oriented, aluminised, 0.3 mm, 980°C

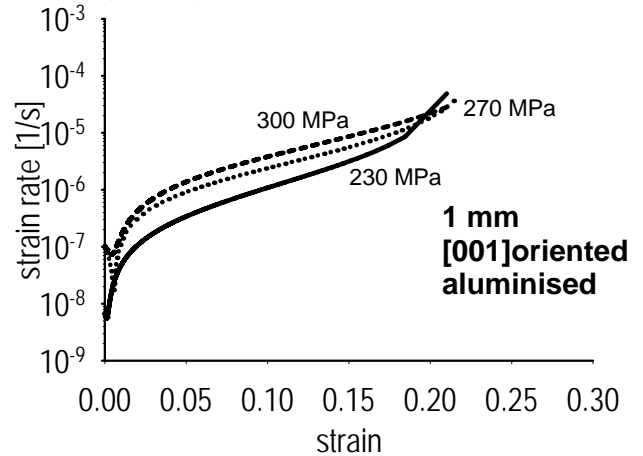


Fig. 9: Strain rate vs. strain creep curves, René N5, [001] oriented, aluminised, 1.0 mm, 980°C

Table 1: Data for rupture lifetime [h]/minimum creep rate [$10^{-9} s^{-1}$] as function of thickness and coating for RenéN5 single crystals at 980°C testing temperature

Wall-thickness [mm]	Stress levels [MPa]	no coating		aluminised
		16° miss-oriented	[001] oriented	[001] oriented
0.2/0.3	230	35/112	45/71	115/29
	270	16/239	12/383	33/122
	300	7/467	6/391	24/46
1	230	302/2.4	110/59	321/5.4
	270	117/19	19/376	103/17.4
	300	21/117	9/485	60/73

Creep test on [001] oriented and aluminised René N5 specimens

Comparing Fig. 8 and Fig. 9 reveals that 1 mm thick aluminised specimens reach higher rupture strains and lower creep rates than 0.3 mm thick samples. All 1 mm thick specimens rupture after reaching about 20% strain. Thin samples only reach 5% for lower stress levels and 11% for 300 MPa. Minimum creep rates of thick samples are lower than for thin samples. Aluminised and [001] oriented samples show higher creep rupture times and lower minimum creep rates than not aluminised samples if the stress was referred to the remaining cross sectional area without TGO.

Discussion

The results pronounce that the creep behavior is strongly influenced by the surface to volume ratio of the specimens. The time to reach 1% creep strain which was mentioned in [3,4,6] to be independent of wall-thickness could be approved for non coated specimens at a stress level of 300 MPa for 16° miss-oriented specimens.

16° miss-oriented René N5 specimens

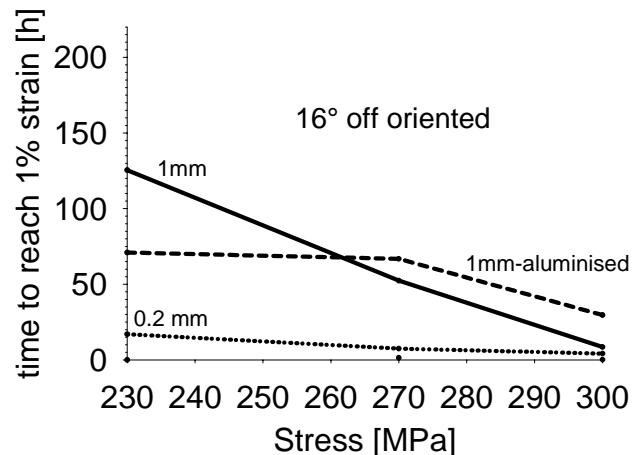


Fig. 10: René N5 with 16° misorientation. Times to 1% creep strain.

[001] oriented René N5 specimens

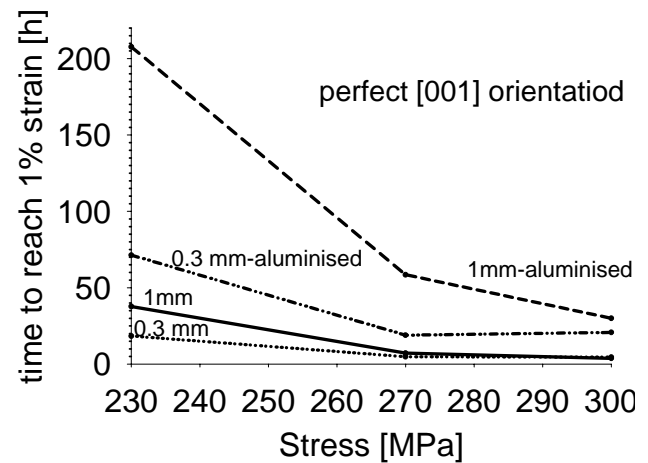


Fig. 11: René N5 with an [001] orientation. Times to 1% creep strain.

For [001] oriented René N5 specimens the time to reach 1% creep strain was roughly equal for not aluminised specimens for all levels tested here. For aluminised specimens the time to reach 1% creep strain was dependent on wall-thickness.

Conclusions

The creep behavior of single crystal René N5 at 980°C was investigated as function of sample thickness, orientation and coating conditions.

- First results point out that reducing the wall thickness from 1.0 to 0.2 or 0.3 mm leads to lower creep rupture strains, lower life times and higher minimum creep strain rates.
- The creep behavior of 16° miss-oriented compared to perfect orientation are similar.
- Not aluminised René N5 specimens are less influenced by thickness changes.

Further investigations on microstructure especially of surface features will be carried as described in [17] in order to further understand the mechanics leading to these observations.

Acknowledgements

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References

- [1] D.N. Duhl: "Directional Solidified Superalloys", in *Superalloys II*, C.T. Sims, N.S. Stoloff, and W.C. Hagel, (Eds.), (John Wiley, New York, 1987), 189-214
- [2] P.J. Henderson: "Creep of coated and uncoated thin section CMSX - 4", *Materials for Advanced Power Engineering* (Forschungszentrum Juelich GmbH, 1998), 1559-1568
- [3] M. Doner and J.A. Heckler: "Effects of Section thickness and Orientation on creep rupture properties of two advanced single crystal alloys", in *SAE Technical Paper 851785*, (Society of Automotive Engineers Inc., 1985)
- [4] M. Doner and J.A. Heckler: "Identification of Mechanisms responsible for Degradation in thin-wall stress rupture properties", in *Superalloys 1988, Proceedings of the 6th International Symposium on Superalloys* (The Metallurgical Society, Warrendale, PA, 1988), 653-662,

- [5] N. Roy and R.N. Ghosh: "Modelling effects of specimen size and shape on creep of metals and alloys", *Scripta Materialia*, 36 (12) (1997), 1367-1372,
- [6] V. Seetharaman and A.D. Cetel: "Thickness debit in creep properties of PWA 1484" in *Superalloys 2004*, ed K. A. Green et al., (TMS,2004), 207-214,
- [7] M.C. Pandey and D.M.R. Taplin: "Prediction of lifetime in thin sections of a nickel base superalloy", *Scripta Metallurgica et Materialia*, 31 (6) (1994), 719-722,
- [8] P.J. Henderson: "Creep of single crystal Ni-base superalloy in thick and thin section forms" in *Creep and Fracture of Engineering materials and structures*, ed. J.C. Earthman and F.A. Mohamed, (1997), 697-706
- [9] A. Baldan: "On the thin-section size dependent creep strength of a single crystal nickel-base superalloy", *Journal of Materials Science*, 30 (1995), 6288-6298,
- [10] A. Baldan: "Combined effects of thin-section size, grain size and cavities on the high temperature creep fracture properties of a nickel-base superalloy", *Journal of Materials Science*, 32 (1997) 35-45,
- [11] Y. Koizum: "Database of Creep Propertiy for Nickel-Base Single Crystal Superalloys, RenéN4, RenéN5 and CMSX-4", *Journal of Japan Inst. Metals*, 40 (2) (2006), 176-179
- [12] V. Sass, U. Glatzel, M. Feller-Kniepmeier: " Anisotropic creep properties of the Nickel-base superalloy CMSX-4", *Acta materialica*, 44 (5) (1996), 1967-1977
- [13] R. Völkl, D. Freund, B. Fischer: "Economic Creep Testing of Ultra-High Temperature Alloys", *Journal of Testing & Evaluation*, 31 (1) (2003), 35-43
- [14] R. Völkl, B. Fischer: "Mechanical Testing of Ultra-High Temperature Alloys", *Mechanical Testing*, 44 (2) (2004), 121-127
- [15] R. Völkl, , B. Fischer, M. Beschliesser and U. Glatzel, „Evaluating strength at ultra-high temperatures – methods and results“ *Materials Science & Engineering A*, in press 2008
- [16] B. Fischer, S. Vorberg, R. Völkl, M. Beschliesser, A. Hoffmann: "Creep and tensile tests on refractory metals at extremely high temperatures", *Int. Journal of Refractory Metals & Hard Materials*, 24 (2006), 292-297
- [17] S. Wöllmer, T. Mack, M. Göken, S. Zaeferrer, U. Glatzel: "Characterization of Phases of Aluminized Nickel Base Superalloys", *Surface and Coating Technology*, 167 (2003), 83-96