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SIMULATION OF MICROSTRUCTURE AND MODELLING OF MECHANICAL PROPERTIES OF CB2 FLUX CORED WIRES WELD METAL

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Abstract

The cast steel GX13CrMoCoVNbNB10-1-1 (CB2) developed in the European COST Projects shows the most promising properties for operating temperatures up to 620°C. Matching flux cored wires, mainly rutile with additional basic slag forming components, for welding this creep resistant steel, have been developed, too. Not only the creep properties but also the mechanical properties like impact toughness and tensile strength are of great importance for the qualification and application of the material in thermal power plants. These mechanical properties are in a close relationship to microstructural parameters like precipitates, dislocations or voids. Two different nickel content variants of the weld metal and two different post weld heat treatments have been investigated with regard to their impact on mechanical properties and microstructure. Results are presented in the paper.

Keywords: CB2 weld metal, flux-cored-wire, creep resistant steel, toughness, strength

1. Introduction

There is a large growth in the worldwide electricity demand and fossil energy is predicted to be one of the most important sources for power generation [1]. The 'International Energy Agency' has published in the 'World Energy Outlook 2013' different forecasts, how the energy demand in the next 20 years will develop – they are shown in Figure 1. It takes into account only policies enacted as of mid-2013. The 'New Policies Scenario' takes account of existing policies and declared policy intentions; and the '450 Scenario' shows an energy pathway compatible with a 50% chance of limiting the long-term increase in average global temperature to 2°C.

The report shows further that the transition away from fossil fuels will take considerable time to achieve [1]. Until then a proper improvement of efficiencies in fossil fuel power plants is not only to cover economical interest, but should also decrease the emissions of CO_2.

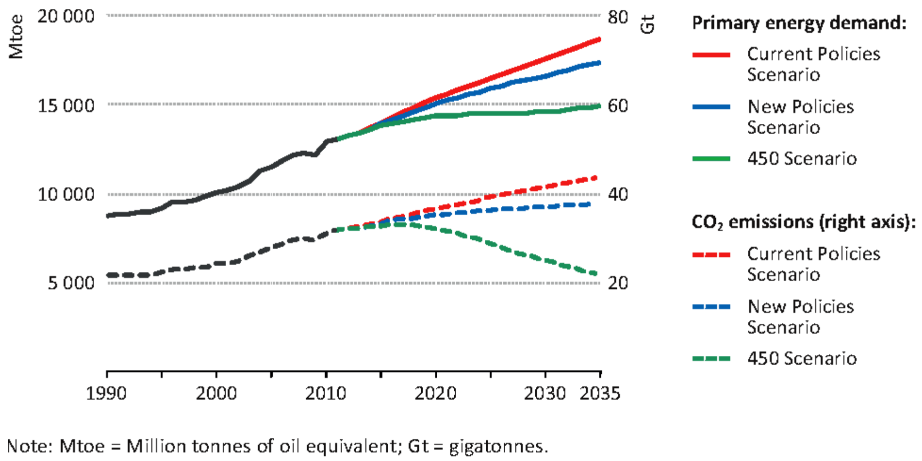

Figure 1 : World primary energy demand and related CO_2 emissions by different scenario [1]

The power generation industry is in charge to take materials which allow higher steam temperature and pressure, to reach these aims. Through improvements in the group of the 9% Cr steels during the COST project [2], steam temperatures up to 620°C in the family of creep resistant steels, are nowadays states of the art.

For the production of heavy castings for power stations, welding processes are an important part of the manufacturing procedure. A rutile, matching CB2 flux-cored wire was developed for this purpose. It has to reach the excellent creep properties of the cast base material where among other microstructural features a large PAG (prior austenite grain size) assures the creep resistance. The weld metal of the flux cored wire and its creep properties in 'short- and midterm tests' have been investigated. Results considering a variation of the nickel content are published in welding in the world [3].

The focus of this contribution is the simulation of microstructure and on first attempts of modelling mechanical properties based on experimental data. A varying Ni-content is taken into account as well as the development of the microstructure of the weld metals. Tensile tests at room temperature and impact toughness tests in a broad temperature range for this martensitic 9% Cr weld metals have been carried out, because sufficient impact toughness must be achieved for material qualification processes.

2. Material

2.1. Chemical Composition

Mechanical properties tests of the base material CB2 and of two filler metal compositions with different nickel contents have been carried out. The chemical composition of a CB2 trial melt has been taken from the PhD Thesis Schaffernak [4] and is listed in the first line of Table 1. The nominal chemical composition of the weld metals are listed in lines two and three of the same table [3]. The nickel content of the weld metal was varied to investigate its influence on the mechanical properties with focus on the Charpy-V-impact toughness.

Material	C	Mn	Cr	Mo	Si	Ti	Ni	Nb	N	V	Co	B
CB2	0.12	0.88	9.20	1.49	0.20	0.002	0.17	0.06	0.02	0.21	0.98	0.011
WM 1	0.10	0.90	9.0	1.50	0.20	0.03	0.2	0.03	0.02	0.2	1.0	0.005
WM 2	0.10	0.70	9.0	1.40	0.20	0.03	0.7	0.03	0.02	0.2	1.0	0.006

Table 1 : Chemical composition of the CB2 base metal and the nominal chemical composition of two different weld materials, all values in wt%

2.2. Welding Procedure

CB2 base metal plates of 20 mm thickness with U shaped weld preparation were filled with two different CB2 flux-cored-wires by multilayer welding. The new formed weld metals thereby were produced as joining weld (neglecting a root pass). The used welding parameters are given in [5].

Samples were taken in ‘as welded’ condition and after post weld heat treatment of 730 C/8h and 730°C/24h, respectively. The sample grid is shown in Figure 2.

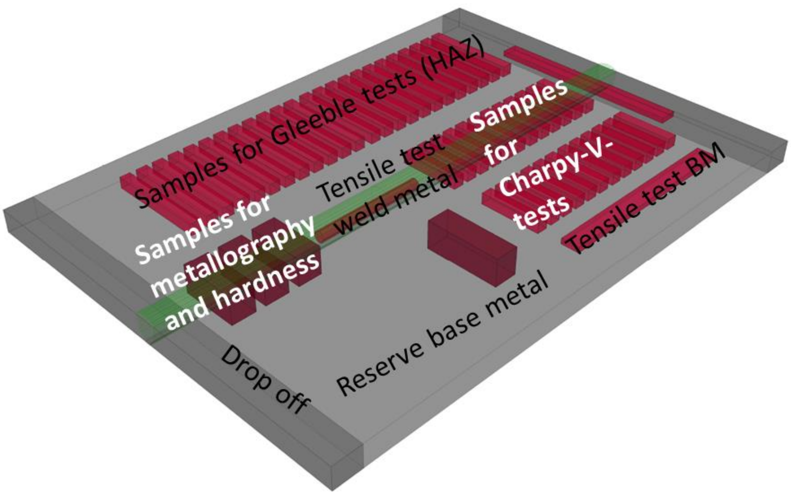

Figure 2 : Schematic view of welded plate with sample grid.

The Gleeble tests for simulating the heat affected zone (HAZ) and for studying the influence of welding parameters on the mechanical properties of HAZ were conducted in the frame of the diploma thesis of Sarić [6].

3. Experiments and Results

All tests performed on the two weld metals and on base metal are shown in Table 2. To avoid confusion, the Gleeble-simulated HAZ tests are not listed in this table.

Microscopic investigations and MatCalc simulations of the BM in different creep conditions have been done by Ramskogler [7]. Comparisons between BM, HAZ and WM1 of the crept samples are already published [8].

Material	"as welded"	PWHT short (730°C/8h)	PWHT long (730°C/24h)	Crept samples (625°C/~6500h)
CB2 Base metal (BM)	Mech. tests, LOM, SEM, MatCalc			LOM, SEM, EDX, MatCalc [7]
Weld metal 1	Mech. tests, LOM, SEM, TEM, MatCalc			LOM, SEM, EDX, TEM, MatCalc
Weld metal 2				

Table 2 : Test matrix of base metal and the two weld metals under different treatment conditions. LOM…light optical microscopy; SEM…scanning electron microscopy, EDX… energy dispersive X-ray spectroscopy, TEM… transmission electron microscopy; MatCalc [9]*…numerical precipitation simulations*

The focus for the next pages is to compare the two different weld metals in two different PWHT states.

3.1. Mechanical tests

In general, the 'as welded state' is not comparable to the 'finished' heat treated material or the base material in regard to the mechanical testing, because the fresh martensitic structures without any tempered regions are extremely hard and brittle. For that reasons, weld metal without treatment, for creep resistant steels, cannot be used in industrial applications.

3.1.1. Tensile Tests

A comparison of the two weld metals with base metal after PWHT is depicted in Figure 3. Just three measurements of the BM are compared; the two with the shorter fracture elongation were measured after a long PWHT and that one with the highest strength were measured after a short PWHT.

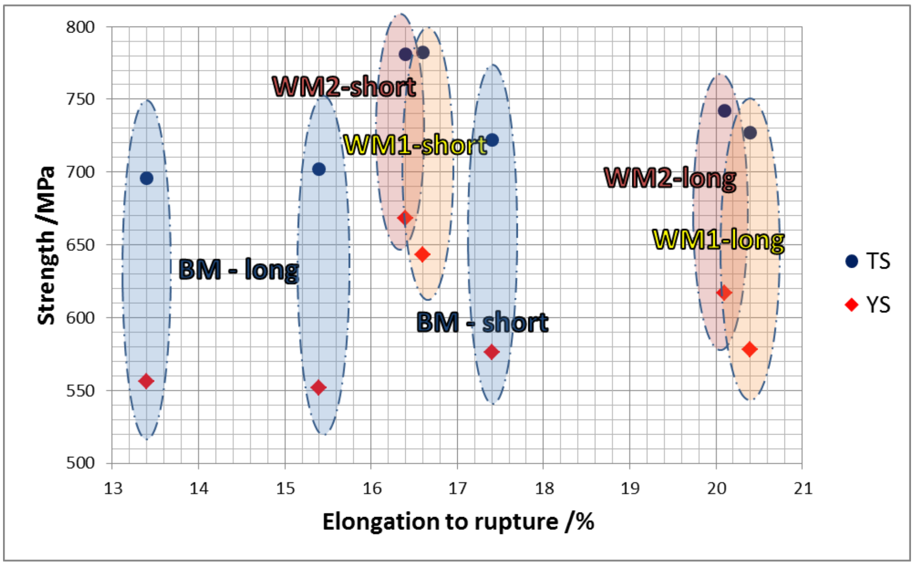

Figure 3 : Tensile strength (TS) and yield strength (YS) on y-axis of base metal and weld metals, in relation to their elongation to rupture values on x-axis

Weld metals with short treatment show less fracture elongation and have higher strength values compared to weld metals with longer PWHT. The tested base metal has the lowest fracture elongation as well as the lowest strength level. Exception is the base metal sample with short treatment. Here, the tensile strength and the yield strength are on the same level as on sample WM1-long and the fracture elongation is even higher, as it is on short treated weld metal samples. The differences in fracture elongation between the two weld metals are rather small, but a longer treatment shifts the fracture elongation - systematically to higher values.

3.1.2. Toughness tests

Toughness was mainly measured by using the Charpy-V-impact-test procedure. The used testing apparatus (300J max energy) is instrumented. Instrumentation details: In the hammer fin inside, resistance strain gauges (RSG) are implicated. The received signal is forwarded into the bridge circuit of a transient recorder with a measuring rate of 1MS/s (MegaSamples/second), transformed into a load value and recorded. Displacement measurement is positioned directly under the sample position and carried out through an eddy current sensor; these data are also recorded from the transient recorder.

Charpy-V-tests have been done for a broad range of testing temperatures, because it's well known, that the martensitic-ferritic bcc (body-centred-cubic) structure has a distinct transition region. This means that the amount of energy, the material can absorb and convert into plastic deformation before it breaks, is much lower at low temperatures. In Figure 4 (left), four measured Charpy-V-test series from -50°C to +160°C and their approximated sigmoidal shaped curves [10] are shown. Weld metals 1 and 2 in the two different post weld heat treatment conditions (short and long) are compared.

As expected, the highest impact values and the lowest transition temperatures are reached with a longer post weld heat treatment (PWHT). Additionally, it can be seen, that in all two PWHT cases, the higher Ni-variant (WM2) reveals higher impact values and lower transition temperatures compared to WM1.

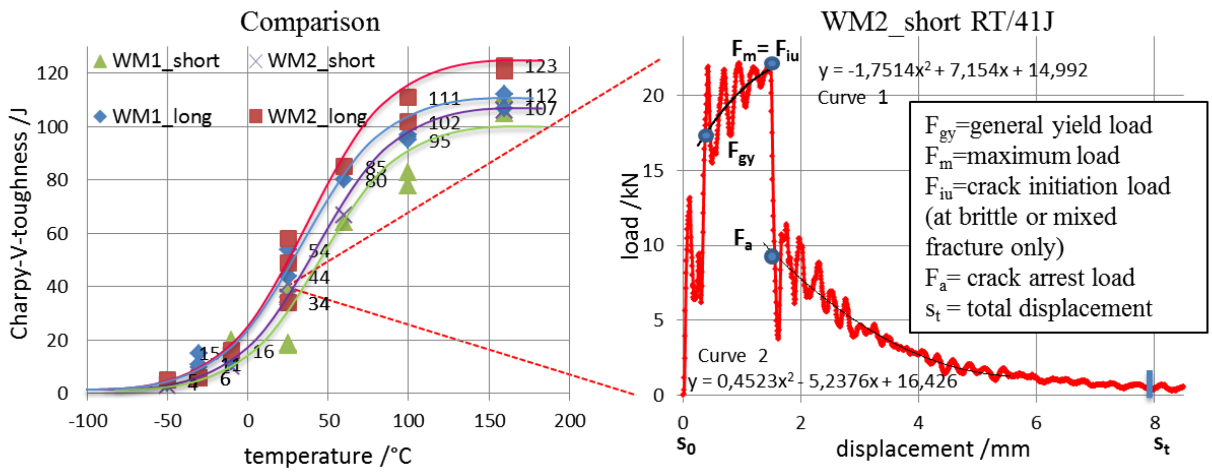

Figure 4 : (Left): Impact toughness values of WM1 (weld metal 1) with low nickel content and WM2 (weld metal 2) with high nickel content and two different PWHT conditions (8h/730°C – short; 24h/730°C – long) are compared over a temperature range from -50°C to 160°C. (Right): One instrumented measurement at RT with 41J, evaluated acc. [11]

The toughness improving nature of nickel is well known [10]; one possible reason for this effect is the grain and structure fining behaviour of this element. Grain size measurements of the normalized regions of the weld metals, show a difference of 25% between the weld metals; WM1 is coarser than WM2. The finer the grain is, the higher the toughness rises.

During all Charpy-V tests, load-displacement curves have been recorded and evaluated – see Figure 4 (right). Evaluation of characteristic forces was carried out according EN ISO 14556 [11]. So, more information about fracture behaviour than in a regular Charpy-V test can be obtained [12]. The integral under the curve represents also the absorbed energy. Additionally, a relation to the crack initiation and crack arrest can be drawn [13].

In weld metals with long heat treatment, fracture toughness tests with single-edge bend (SEB) samples according ASTM E 1820-08 [14] have been carried out. These results are already presented [15].

3.2. Metallography

In addition to light optical microscopy (LOM) also different electron microscopy investigations have been done. Several pictures of LOM are published in [3]. Under the light microscope no significant differences can be found related to nickel content or PWHT.

3.2.1. Scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDX)

On the one hand, polished and etched microsections have been investigated and on the other hand, fracture surfaces of broken Charpy-V-samples were studied in detail under the scanning electron microscope. The most ductile and tough specimen (test at 160°C sample temperature) of both weld metals are depicted in Figure 5 and Figure 6.

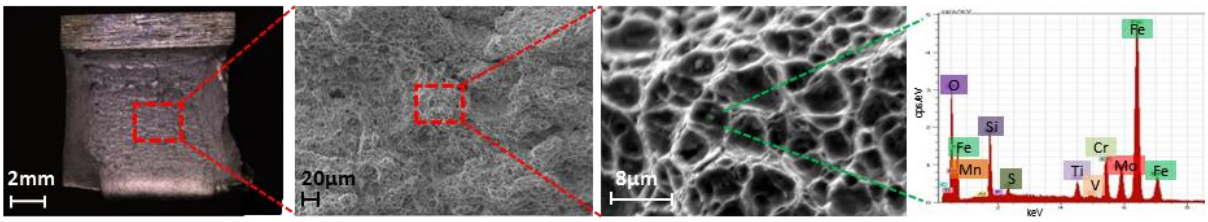

Figure 5 : Fracture Surface of WM1-short tested at 160°C with SEM studies of the very ductile fracture and an EDX scan of a representative particle, Charpy-V-toughness: 105 J

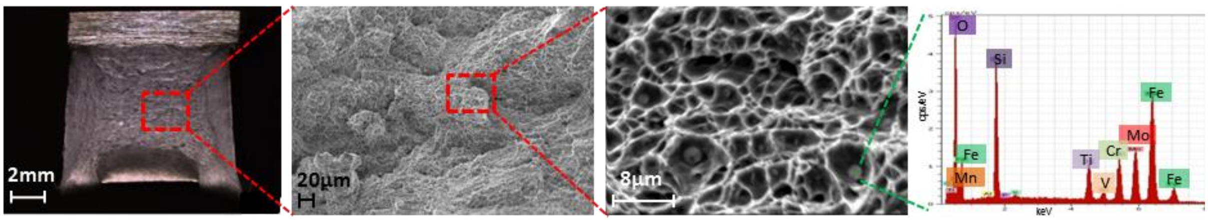

Figure 6 : Fracture Surface of WM2-short tested at 160°C with SEM studies of the very ductile fracture and an EDX scan of a representative particle; Charpy-V-toughness: 106 J

All samples tested at high temperatures, show a ductile fracture with macroscopic shear lips and dimples on the fracture surface. In these dimples particles or inclusions can be seen. EDX spectroscopy revealed that they are mostly oxides with background iron signals. SiO_2 as well as mixed oxides with Mn, Si and Ti [16] were found in the fracture dimples.

3.2.2. Transmission electron microscopy (TEM),

The TEM investigations have been carried out with the energy filtered (EFTEM) method. Additionally, EDX and EELS investigations were performed for characterisation of precipitates. Some EFTEM images of the 'as welded' WM1 are depicted in Figure 7.

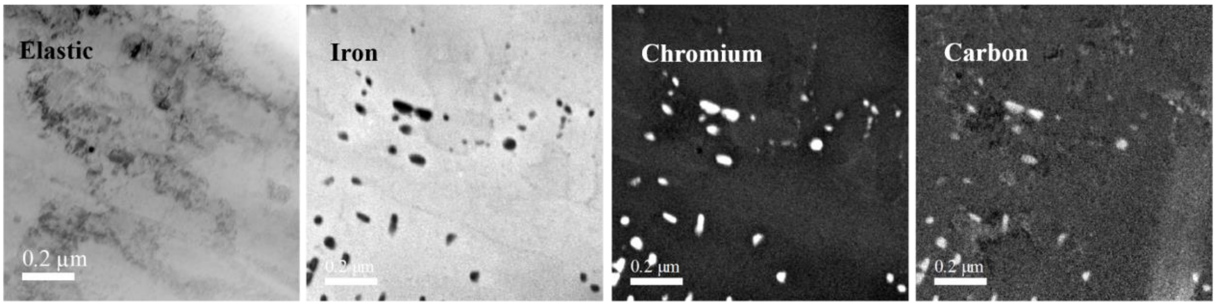

Figure 7 : EFTEM Images of WM1 in the as welded condition with Cr-carbides

First image is of elastic scattered electrons. With the possibility to filter the energy-wavelength the different elements can be distinguished. The matrix consists of iron – this can be seen on the bright 'iron-image'. The precipitates are Cr-carbides, as it can be seen on the chromium and carbon image. In this contribution, just the as welded condition is shown, because the work is still in progress.

3.3. Simulation

The precipitate evolution can be simulated with the thermo-kinetic software MatCalc [9]. The used CALPHAD based thermo-dynamic databases for equilibriums and kinetic simulations are a development 'prebeta' product from the MatCalc team [17] at the Technical University Vienna. Calculation results are discussed and compared with experimental findings in the next section.

4. Discussion and Comparison

4.1.1. Microstructure WM1 simulated and TEM investigated after welding

The precipitation evolution simulation of the welding process of WM1 is depicted in Figure 8 and compared with the evaluated TEM measurements.

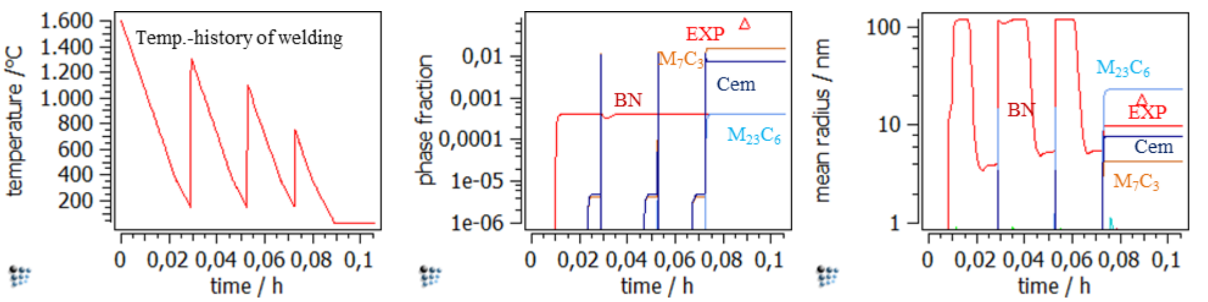

Figure 8 : Precipitation simulation of multilayer welding, WM1 with comparison of the measured Cr-carbide values (red triangles), concerning the phase fraction and the mean radius of precipitates

The calculation underestimates the phase fraction a bit, or the measured and evaluated TEM data overestimate the Cr-carbide phase fraction, because only very small regions are investigated using TEM, questioning the statistical significance. The mean radius is in a good correlation. Experimentally a mean radius of 18.5 nm was measured whereas the calculated value of $M_{23}C_6$ is 23 nm. After welding simulation, most of the precipitates are carbides ($M_{23}C_6$, M_7C_3 and cementite), just a small amount of boron-nitrides reveals.

4.1.2. Microstructure WM1 and WM2 after PWHT

After PWHT, the cementite has dissolved completely but the M_7C_3 carbides are still stable. The $M_{23}C_6$ carbides grow during heat treatment in quantity (from 0.04 to 0.54 – WM1) and in extension (from 23nm to 384 nm – WM1), as it can be seen in Table 3.

Phase fraction /%	$M_{23}C_6$	M_7C_3	BN	NbC	VN	Matrix (ferrite)
WM1	0.54	1.78	0.04	0.01	0.00	97.62
WM2	1.46	0.63	0.07	0.00	0.00	97.84
Mean radius /nm						
WM1	384	196	121	179	0	
WM2	319	160	195	163	0	

Table 3 : Comparison of phase composition and mean radius of precipitates of the two weld metals after long PWHT

There are differences between the two weld metals in forming and developing carbides. The MX precipitates have small quantities; they grow and coarsen slowly in both weld metals. BN is neither large nor in great quantities, in both metals, but it has a tendency to coarsen fast. In simulation BN arise in small quantities, but the ongoing experimental investigations show no indication for boron nitrides in these weld metals at all.

5. Conclusion

Based on the observations presented in this contribution, the following conclusions can be drawn:

5.1.1. Strength and fracture elongation

Weld metals with short PWHT have higher strength values and less fracture elongation compared to weld metals with longer PWHT.

5.1.2. Toughness

- Highest impact values and lowest transition temperatures are reached with a longer PWHT. Also a higher Ni-content (WM2) reveals higher impact values and lower transition temperatures, compared to the lower Ni-content (WM1).
- The finer the grain size of the matrix is, the higher the toughness rises.
- Experimental values of regular and instrumented Charpy-V-tests have been evaluated, some connections with the microstructural behaviour has been shown, e.g.dimples with inclusions in ductile fracture surfaces.

5.1.3. Microstructure

In the 'as welded' state of WM1, EFTEM investigations revealed a dominance of Cr-carbides. Numerical precipitate simulations executed with MatCalc, confirmed this development.

6. Outlook

- The relation between precipitate-status and yield strength, based on precipitation strengthening and solid solution strengthening, is well known and discussed in literature [18,19]. So in a next step, with trustworthy simulations, some strength parameters can be derived in this ongoing work.
- Through known damage and toughness models from literature [20-22] and new approaches, connections between microstructural parameters as precipitates, inclusions and dislocations will be drawn and a prediction of the toughness should be enabled.
- Microstructural precipitate considerations will not sufficiently describe the material in view to toughness considerations. Here, in a 'next' approach, other parameters as dislocations must be taken into account.

7. Acknowledgement

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