THERMAL FATIGUE AND SOFTENING BEHAVIOR OF HOT WORK TOOL STEELS

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Abstract The present paper concentrates on the thermal fatigue and softening behavior, which are the most relevant damage mechanisms in tools for hot working applications.

A new thermal fatigue testing facility, which is based on a pulsed diode laser as surface heating source, is used to characterise the thermal fatigue behavior of a hot work tool steel. Various temperature cycles are applied to study the effect of the maximum temperature, the temperature range and the heating time. To prevent undesired oxidation of the sample the tests were

carried out under high vacuum. The rear of the specimen was kept on constant temperature using a heating/cooling device.

Isothermal annealing tests were performed in an in-situ hot hardness testing facility in order to study the thermal softening behaviour. All experiments were done at the hot work tool steel DIN X 38 CrMoV 53

Keywords: hot work tool steels, thermal fatigue, softening, hot hardness testing

INTRODUCTION

Hot work tool steels are usually used for tools in manufacturing processes which are working at elevated temperatures, e.g. hot forging and die-casting. Their suitability for this application is based on an extraordinary combination of high strength, thermal stability and a remarkable toughness.

The tool life depends on several factors such as microstructure of the tool material which results from the chemical composition and the heat and surface treatment, the tool design and the operating conditions of the tool during use. Wear, mechanically and thermally induced plastic deformation and thermal fatigue are the main damage mechanisms. The absolute temperature and the temperature range at the tool surface play the most important role in regard to the damage [1, 2]. Under usual operating conditions softening due to microstructural changes and crack formation caused by thermal fatigue are the result of the cyclic thermal loading.

In the fully heat treated condition the microstructure of hot work tool steels consists of a tempered martensitic matrix in which primary carbides and secondary hardening carbides are embedded. Size and volume fractions of the secondary hardening carbides have main influence on the hardness and the thermal stability of the material [3, 4]. At elevated temperatures the secondary hardening carbides coarsen to minimize their interfacial energy. In most cases coarsening is controlled by volume diffusion, which is known as Ostwald ripening [5, 6, 7]. In this process the larger carbides grow on the expense of smaller ones which is accompanied by a decrease of the hardness.

While softening due to precipitate coarsening is an effect of the absolute temperature, thermal cycling in presence of temperature gradients leads to a thermal fatigue loading. The resulting elastic and plastic deformation can be understood as the response of the material to the applied inhomogeneous thermal loading [8]. Cyclic loading of metals and alloys causes changes in their structure and consequently changes in their properties due to cyclic

hardening and/or softening. The thermal fatigue process can be divided into three partly overlapping stages: (a) cyclic hardening and/or softening, (b) nucleation of fatigue cracks and (c) propagation of fatigue cracks.

In the present paper thermal fatigue experiments and isothermal softening experiments were performed to characterise the behaviour of the hot work steel DIN X 38 CrMoV 5-3. Additional FEM simulations were employed to determine the cyclic thermal loading. Microstructural modelling was used to estimate the effect of the thermal cycles on the microstructural changes.

EXPERIMENTAL

THERMAL FATIGUE TESTING

A specially designed thermal fatigue testing facility was developed to investigate the thermal fatigue behaviour of tool steels, see Fig. 1.

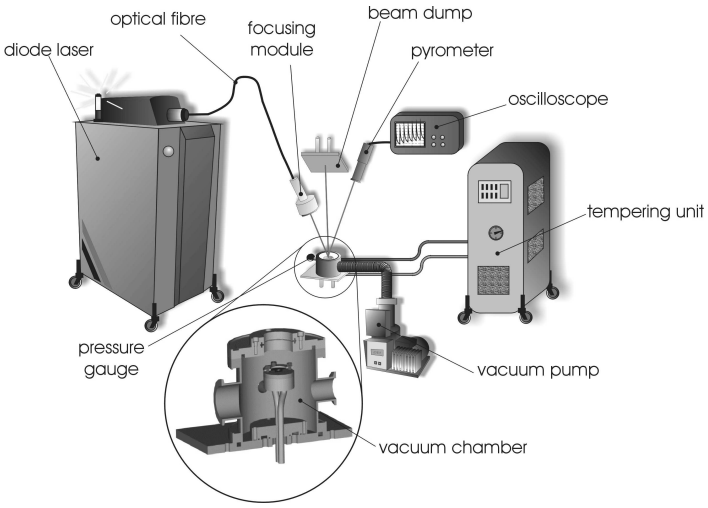


Figure 1. Thermal fatigue testing facility.

A disk shaped specimen is tested in a vacuum chamber to prevent oxidation of the heated surface. The tests are carried out under vacuum at a pressure lower than 3.10^{-6} mbar. No significant oxidation is observed even for the longest testing time of seven days. The sample is mechanically fixed on a temperature-controlled copper mounting system, which is held at a

constant temperature of 200 $^{\circ}C$. Cyclic surface heating is performed using a pulsed diode laser beam with a maximum power of about 1,8 kW. The laser radiation is guided via an optical fibre, a focussing unit and a transparent window to the specimen. A circular area with a diameter of about 1 mm is irradiated. The reflected laser radiation is absorbed in a water-cooled beam dump. The temperature in the interaction zone is controlled with a pyrometer with an operating range from 250 to 1300 $^{\circ}C$ and a response time of 15 µs. A spectral filter in the optical system of the pyrometer prevents effects from the reflected and scattered laser radiation. An oscilloscope is used to display the thermal cycles and to provide an interface to a PC [9].

For the thermal fatigue studies different pulse energies were chosen in order to achieve maximum surface temperatures of 475, 575 and 650 $^{\circ}C$ at irradiation times of 1.5 and 4.5 s with a break between the pulses of 1.5 s. All tests were performed at a background temperature of 200 $^{\circ}C$.

HOT HARDNESS TESTING

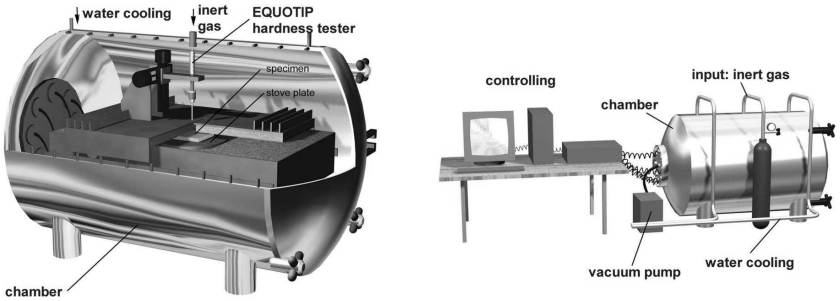
In the present paper the isothermal hot hardness experiments were carried out on a semi-automatic hardness tester. Details about the hardness tester are reported elsewhere [10].

The principle of the hot hardness testing is that of a scleroscope. The hardness is characterised by a so called LDL value which can be converted into Vickers hardness. To avoid undesired oxidation the sample is tested in a water cooled chamber which can be evacuated and subsequently filled with argon gas. A high power heating plate is used to heat the specimen to testing temperature. The temperature is controlled by thermocouples. An estimation of hardness values from tensile tests at the hot work tool steel at elevated temperatures reveals satisfying accordance with the results from dynamic hardness testing. Figure 2 shows a principle view of the hot hardness testing device (HHT) used in the experiments.

The hardness measurements were carried out over a time of 20 hours while keeping the temperature of the specimen constant.

MATERIAL INVESTIGATED

The nominal chemical composition and the heat treatment condition of the tool steel investigated are listed in Table 1 and 2. The hardness of the tested specimens is about 548 HV.



(a) View into the chamber. (b) Total view.

Figure 2. Hot hardness tester (HHT).

Table 1. Material investigated

Steel grade	Chemical compostion in wt%						
	C	Cr	Mo	V	Mn	Si	Fe
Böhler-W303 (X 38 CrMoV 5-3)	0,38	5,0	2,8	0,65	0,4	0,4	bal.

Table 2. Heat treatment conditions and hardness of the steel grade investigated

Steel grade	Austenitising	Tempering	Hardness [HV]
Böhler-W303 (X 38 CrMoV 5-3)	1050 $^{\circ}C$– 50 min	550 $^{\circ}C$– 1h / 610 $^{\circ}C$– 2h	548

RESULTS AND DISCUSSION

ANALYSIS OF THE CYCLIC THERMAL LOADING

The variation of the temperature at the surface of the irradiated specimen is shown in Fig. 3. Maximum temperatures of 475 $^{\circ}C$, 575 $^{\circ}C$ and 650 $^{\circ}C$ were chosen, the resulting temperature ranges are related to the time of the break between the laser pulses. In the present experiments, the temperature ranges were between 300 and 400 K. These loading conditions are characteristic for various fields of application of hot work tool steels. To investigate the

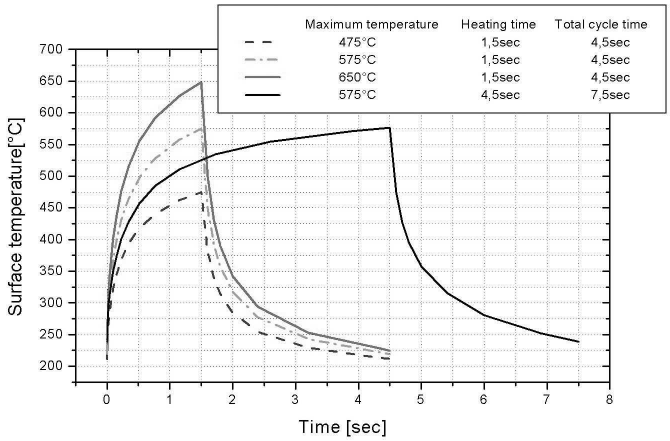


Figure 3. Surface temperature cycles of the chosen thermal cycling experiments.

influence of the heating time irradiation durations of 1,5 and 4,5 s were chosen. ε_{ik} FEM calculations were performed for analysing the thermal cycles and the resulting thermo-mechanical loading situation (strains and stresses) of the irradiated specimen.

The total strain ε_{ik} at each point of a heated body comprises of two components. In an elastic body the total strain can be described by equation (1) [11, 12]. $\alpha\Delta T$ is the uniform thermal expansion, the second part comprises the strains (stresses) required to restrain the distortions of neighbouring elements to maintain the continuity of the body. If the stresses exceed the yield stress of the material, plastic strains occur too.

$$\varepsilon_{ik} = \frac{1}{2G}\left[\sigma_{ik} - \frac{\nu}{1+\nu}(\sigma_{xx}+\sigma_{yy}+\sigma_{zz})\delta_{ik}\right] + \alpha\Delta T\delta_{ik} \qquad (1)$$

ε_{ik} is the total strain, G the shear modulus, α the thermal expansion coefficient, σ the stress, ν the Poisson's ration, ΔT the temperature difference and δ_{ik} a factor which is 0 for $i \neq k$ and 1 for $i = k$.

The calculated equivalent elastic and plastic strain ranges are shown in Fig. 4. For maximum surface temperature of 475, 575 and 650 $\mathcal{C}$and a pulse duration of 1,5 s the equivalent plastic strain ranges $\varepsilon_{e,p}$ are 0,172%, 0243% and 0,39% respectively. For a maximum surface temperature of 575 $\mathcal{C}$and a pulse duration of 4,5 s the equivalent strain range $\varepsilon_{e,p}$ is calculated to be

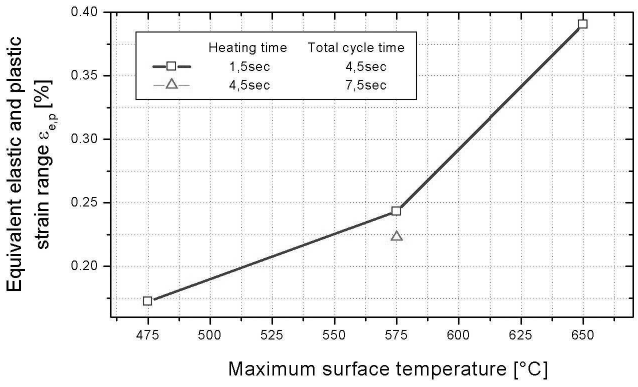


Figure 4. Resultant equivalent elastic and plastic strain ranges for.

0,223%, which is smaller than that for the shorter pulse duration. This is caused by a smaller temperature gradient due to a lower heat flux in case of the longer pulse duration.

To investigate the influence of the thermal cycling conditions on the material properties hardness measurements were carried out at the surface of irradiated specimens after various numbers of cycles. The results of these hardness measurements are presented in Fig. 5. No hardness change is observable in case of a maximum surface temperature of 475 $^{\circ}C$whereas softening occurs for the maximum surface temperatures of 575 and 650 $^{\circ}C$. The hardness loss increases significantly with increasing maximum surface temperature. The results for a maximum temperature of 575 $^{\circ}C$indicate that the hardness loss is more pronounced for the longer pulse duration despite the equivalent strain range $\varepsilon_{e,p}$ is slightly lower than in case of the shorter pulse duration. This suggests that rate dependent deformation processes play a role in the damage process.

ANALYSIS OF THE SOFTENING BEHAVIOUR

Isothermal softening Hardness and strength of hot work tool steels is significantly affected by nano-scale precipitates. These precipitates coarsen

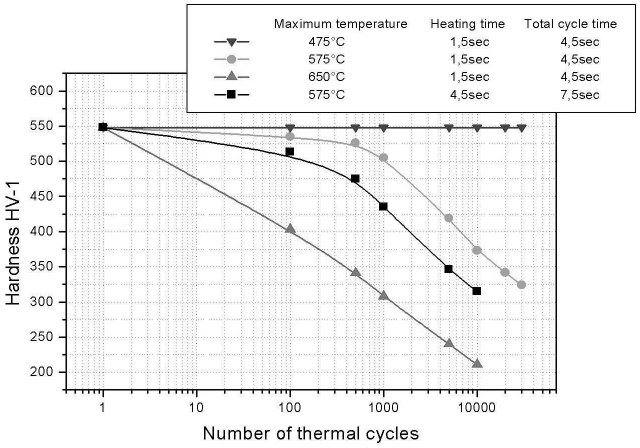


Figure 5. Variation of the surface hardness of the irradiated specimens.

during exposure to elevated temperature. Assuming that the dominating deformation mechanism is the so called "Orowan" mechanism, the yield strength of the tool steel can be described by equation (2) [6]:

$$\sigma_y(T,t) = \sigma_0^*(T) + \Delta\sigma_p(T,t) = \sigma_0^*(T) + \frac{2G(T)bf(f_v,\text{shape})}{\sqrt[3]{r_{p0}^3 + \alpha(T)t}} = \sigma_0^*(T) + \frac{K_p(T)}{\sqrt[3]{r_{p0}^3 + \alpha(T)t}} \quad (2)$$

$\sigma_0^*(T)$ is the strength of the tempered martensite and $\Delta\sigma_p$ is the strength contribution caused by precipitation hardening. G is the shear modulus, b the burgers vector, $f(f_v, \text{shape})$ a function depending on the volume fraction and the shape of the particles, r_{p_0} is the average particle radius prior coarsening, $\alpha(T)$ a material constant depending on the microstructure and t the time. An analytical solution for α in case of binary alloys was first published by Lifshitz, Slyozov [13] and by Wagner [14]. For α-phase particles in a β-matrix their analysis yields:

$$\alpha(T) = \alpha_{LSW}(T) = \frac{8}{9}\frac{\sigma(V_m^\alpha)^2 D^\beta x^{\frac{\beta}{\alpha}}}{V_m^\beta RT(x^\alpha - x^\beta)^2} \quad (3)$$

σ is the interfacial energy, V_m^α the molar volume of the α-phase, D^β is the diffusion coefficient in the β-phase, $x^{\frac{\beta}{\alpha}}$ the composition of the β-phase at the boundary to the α-phase, V_m^β the molar volume of the β-phase, R the gas constant, T the temperature and x^α and x^β the chemical compositions of the α and β-phase.

Assuming that the hardness (HV) is proportional to the yield strength, the temperature and time dependence of the hardness can be described by equation (4):

$$HV(T,t) = HV_0^*(T) + \frac{K_p^*}{\sqrt[3]{r_{p0}^3 + \alpha(T)t}} \tag{4}$$

The effect of isothermal annealing at 600 $^\circ C$ and 650 $^\circ C$ on the hot hardness of the steel X 38 CrMoV 5-3 is shown in Fig. 6. The results indicate

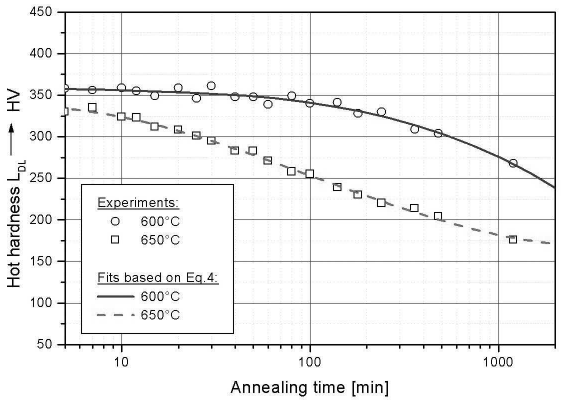


Figure 6. Hot hardness change during isothermal annealing at 600 and 650 $^\circ C$.

that the experimentally determined data can be well described with equation (4). Further the hardness curves show the important role of the annealing temperature on the softening rate. The hardness loss is about one order of magnitude faster in case of the higher annealing temperature. Hot hardness change during isothermal annealing at 600 and 650 $^\circ C$.

Softening due to thermal cycling The irradiated specimen surfaces are subjected to thermal cycling. To evaluate the effect of the thermal cycles on the softening, the influence of temperature and time have to be analysed in detail.

From all parameters which affect α in equation (4) the diffusion coefficient D^{β} shows the strongest temperature dependency. The temperature influence on α can be thus simplified to:

$$\alpha(T) \cong \frac{C D^{\beta}(T)}{T} \tag{5}$$

The effect of the temperature cycle on the softening behaviour due to particle coarsening can be estimated by equation (6):

$$HV(T,t) = HV_0^*(T) + \frac{K_p^*}{\sqrt[3]{r_{p_0}^3 + C \int_0^t \frac{D^{\beta}(T)}{T(t)}\, dt}} \tag{6}$$

The integral in this equation represents the kinetic strength [15] of the thermal cycle and can be calculated with numerical methods based on the temperature cycle and the diffusion coefficient of the rate controlling element.

In the present paper the chemical compositions of the matrix, the metastable secondary hardening carbides and the diffusion coefficients were predicted based on the software packages THERMOCALC and DICTRA. Molybdenum was assumed to be the rate controlling element of the material investigated. The thermal strength for each temperature cycle was calculated using the tracer diffusion coefficient of molybdenum for the tempered martensitic matrix. The variation of $D^{Mo}(T)/T$ for the thermal cycles from Fig. 3 and the resulting kinetic strength is shown in Fig. 7.

The effect of the thermal cycles can be expressed by an equivalent annealing (time and temperature). Figure 7 also contains the estimated equivalent isothermal tempering times at 650 $^{\circ}C$ which lead to a comparable coarsening as the considered complete thermal cycle. Based on these considerations the calculated hardness loss caused by particle coarsening during thermal cycling is shown in Fig. 8.

A comparison of the results in Fig. 5 and Fig. 8 suggests that the softening in the thermal cycling experiments is significantly higher than it would be

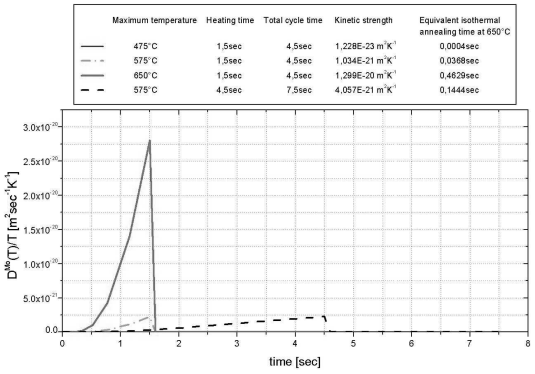


Figure 7. Variation of $D^{Mo}(T)/T$ for the thermal cycles shown in Fig. 3 and the resulting kinetic strength.

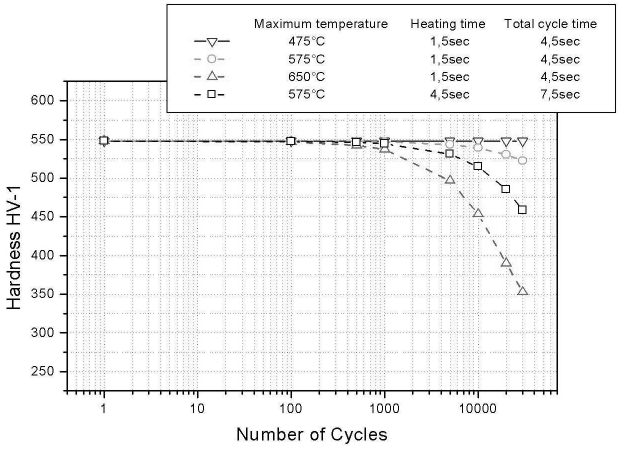


Figure 8. Estimated hardness loss for the thermal cycling experiments due to particle coarsening.

expected from particle coarsening due to volume diffusion. This leads to the conclusion, that also other effects contribute to softening. Most probable are softening due to cyclic plastic straining and time dependent deformation processes.

CONCLUSION

Isothermal annealing and cyclic thermal experiments were performed on the hot work tool steel X 38 CrMoV 5-3 in order to study the damage mechanisms.

Thermal cycling experiments were performed under conditions which are typical for many manufacturing processes (maximum surface temperatures: 475, 575 and 650 $^{\circ}C$; heating time: 1,5 and 4,5 sec). The material changes are characterised by hardness changes as a result of the number of the thermal cycles. FEM simulations were employed to predict the thermal fatigue loading (temperature cycle, thermal stresses and strains).

In-situ hot hardness tests during isothermal annealing experiments at 600 and 650 $^{\circ}C$ were done to characterise the softening behaviour of the tool steel. A comparison of the experimentally determined hardness changes and the results of microstructural modelling leads to the conclusion that the softening occurs more rapid than it would be expected from particle coarsening by volume diffusion. This indicates that softening due to cyclic plastic straining plays an important role in the damage process. The experimentally determined effect of the heating time on the hardness changes further suggests that rate dependent process play an important role in the damage process.

ACKNOWLEDGMENTS

Financial support for this work by the Technologie Impulse G.m.b.H in the frame of the Kplus Competence Center Programme is highly acknowledged.

REFERENCES

[1] G. SPUR, D. SCHMOECKEL, Handbuch der Fertigungstechnik Band 2/2, Carl Hanser Verlag München Wien 1984, Beanspruchung der Werkzeuge p.667.

[2] W. BERGMANN, Werkstofftechnik, Teil 2 Anwendungen, Carl Hanser Verlag München Wien 1987, p.377.

[3] S. KARAGÖZ and H.-O. ANDREN: Z. Metallkd. 83 (1992) 6, 386.

[4] S. KARAGÖZ, H.F. FISCHMEISTER, H.-O.ANDREN and CAI GUNANG- JUN: Met. Trans. A Vol.23A (1992) 1631.

[5] P. FRATZL, O. PENROSE and J.L. LEBOWITZ: Journal of Statistical Physics, Vol. 95, Nos. 5/6, 1999.

[6] R. EBNER, H. LEITNER, F. JEGLITSCH and D. CALISKANOGLU, Methods of property oriented tool steel design, Proc. of the 5th International Conference on Tooling, Leoben, 29th Sept. to 1st Oct. 1999, 3.

[7] R. EBNER, H. LEITNER, D. CALISKANOGLU, S. MARSONER and F. JEGLITSCH, Methods for Characterising the Precipitation of Nanometer- Sized Secondary Hardening Carbides and Related Effects in Tool Steels , Carl Hanser Verlag München, Z.Metallkd 92 (2001), p.820.

[8] M. BILY, Cyclic Deformation and Fatigue of Materials, Institute of Materials and Machine Mechanics of the Slovak Academy of Sciences, Czechoslovakia, Elsevier, 1993.

[9] I. SILLER, W. WALDHAUSER, R. EBNER and T. ANTRETTER, Investigation and simulation of the thermal fatigue behaviour of a hot working tool steel employing pulsed laser radiation, 8th International Fatigue Congress, FATIGUE 2002, Stockholm, 2nd to 7th June 2002

[10] D. CALISKANOGLU, H. LEITNER, R. EBNER and F. JEGLITSCH, A new testing device for investigation of the thermal stability and modelling of the material behaviour, EUROMAT 2001,Conference Proceedings Rimini, 10-14 July 2001.

[11] E. MELAN and H. PARKUS, Wärmespannungen, Springer-Verlag, Wien, Austria, 1953.

[12] B. BOLEY, Theory of Thermal Stresses, Columbia Institute of Flight Structures, U.S.A., Krieger, 1985.

[13] C. WAGNER, Zeitschrift für Elektrochemie 65 (7/8) (1961) 581-591.

[14] I. M. LIFSHITZ and V. V. SLYOZOV: J. Phys. Chem. Solids Pergamon Press 1961, Vol. 19, Nos 1/2, 35-50.

[15] O. GRONG, Metallurgical modelling of weldings, sec. ed., University Press Cambridge, 1997