UDK 629.114.6:620.18 ISSN 1580-2949
Professional article/Strokovni članek MTAEC9, 40(2)73(2006)

MICROSTRUCTURE EVALUATION OF AN NRC-PROCESSED AUTOMOTIVE COMPONENT

OCENA MIKROSTRUKTURE AVTOMOBILSKE KOMPONENTE, IZDELANE PO POSTOPKU NRC

Matjaž Torkar[1], Bojan Breskvar[1], Matjaž Godec[1], Paola Giordano[2], Gianluigi Chiarmetta[2]

[1] Institute of Metals and Technology, Lepi pot 11, SI-1000 Ljubljana, Slovenia
[2] STAMPAL S.p.A., Via Lombardia 6, I-10071 Borgaro (TO), Italy
matjaz.torkar@imt.si

Prejem rokopisa – received: 2005-08-23; sprejem za objavo – accepted for publication: 2005-11-03

In this paper we present the theoretical background of the New Rheocasting (NRC) process, which is based on the thixotropic behavior of a melt with a globulitic primary phase. The NRC process represents an economic alternative to the forging process. The main goal of this study was an evaluation of the microstructure of this innovative and ecological production process. We present some characteristic microstructures observed during the evaluation of a slurry and a real automotive component. Some dendritic forms of the primary α_{Al} phase were observed in the component, which means there are possibilities for a further improvement of the temperature regime. An increased content of the eutectic phase near the surface was observed and inclusions with strontium were found in the eutectic phase.

Key words: rheocasting, thixotropic behavior, globulitic primary phase, microstructure, inclusions

Predstavljene so teoretske osnove novega postopka rheocasting (NRC), ki temelji na tiksotropnem vedenju taline z globulitno primarno fazo in je ekonomska alternativa kovanju. Glavni namen te študije je bila ocena mikrostrukture tega inovativnega in ekološkega proizvodnega procesa. Predstavljene so značilnosti mikrostrukture, ki so bile opažene med oceno surovca in realne komponente, izdelane po postopku NRC. Blizu površine je bila povečana vsebnost evtektika, v njem pa so bili vključki s stroncijem.

Ključne besede: rheocasting, tiksotropne lastnosti, globularna primarna faza, mikrostruktura, vključki

1 INTRODUCTION

The processing of semisolid metals is based on the production of slurries in which the primary phase exhibits a more or less spherical shape. Alloys with a dendritic microstructure in the two phase region are not suitable for the rheocasting process because a material with dendrites does not have isotropic properties. The discovery by Fleming, that a material with a globulitic microstructure in a two-phase region (L + α), behaves in a thixotropic way[1-5], enabled the development of semi-solid processing techniques such as thixocasting and the new rheocasting (NRC) process. The thixocasting process uses stirring of the melt during solidification and reheating into the freezing range in order to form a non-dendritic, globular structure of the primary phase. During the NRC process, the globular primary α_{Al} phase is obtained by rapid cooling, and after that there is controlled cooling to the temperature range of the hot working. At that point about 25% of the volume of the slurry is still in the liquid state. Research has confirmed[4] that the NRC process is suitable for Al- and Mg-alloys, and some attempts were also performed with steel on an ISC rheocaster[6].

The NRC process is schematically presented in **Figure 1**.

The NRC process demands a globular primary α_{Al} phase. The mechanisms of the evolution of the globular primary phase during the partial crystallization of metallic alloys are not yet well understood. The development of numerical modeling techniques and a modified cellular model[7] made it possible to analyze the mechanism of crystal growth in more detail. A modified cellular model was developed to predict microstructure evolution; this model includes solute redistribution in both the liquid and solid phases, and the curvature effect, i.e., the Gibbs Thompson effect of the curved solid/liquid interface. The simulation of the growth velocity at a certain supercooling in the melt is possible with the help of the Kurz-Giovanola-Trivedi model[8]. The supercooling at the interface, ΔT, is considered to be the sum of 3 contributions:

$$\Delta T = \Delta T_L + \Delta T_C + \Delta T_R \qquad (1)$$

where ΔT_L, ΔT_C and ΔT_R are the supercooling contributions associated with the local temperature (thermal supercooling) of the melt, the constitution (dependent on the local solute concentration) and the curvature, respectively. In a conventional casting process the local supercooling is responsible for the evolution of a dendritic microstructure. Lower total supercooling favors the evolution of globular microstructures. Therefore, the Gibbs-Thompson contribution, ΔT_R, is of special importance. It considers the "decrease" in the liquidus temperature due to the curved interface, and therefore counteracts the positive contributions resulting from temperature gradients and constitutional differences in the melt[8].

The additional molar energy of the system is represented by $\Delta G_\gamma = 2\ \gamma/R$, where R represents the radius of the curved interface and γ is the solid/liquid interfacial free energy. The equality with the classical nucleation theory is clear, where the free energy required for the formation of a nucleus with a critical radius of R^* is $\Delta G_\gamma = 2\ \gamma/R^*$. Thus, the additional free energy is equal to a temperature decrease of

$$\Delta T_R = \frac{2\gamma}{\Delta S}\frac{1}{R} \tag{2}$$

where ΔS is the solid/liquid entropy difference, R is the radius of the curved interface and γ is the solid/liquid interfacial free energy. The spherical nuclei are stable as long as $R > R^*$; however, the nuclei will dissolve if $R < R^*$.

During the first period of the growth of a small stable nucleus with $R > R^*$, only a protrusion with a very small radius can be assumed, with $r < R^*$. In this case $\Delta T_R > (\Delta T_L + \Delta T_C)$ and the protrusion will dissolve. This means that non-dendritic globular growth will take place as long as the ΔT_R is sufficiently high. When the solid globule becomes larger and larger, a protuberance with a larger radius can also be developed, and dendritic growth can occur.

When the primary phase continuous to grow in the semi-solid range, the importance of the contribution $(\Delta T_L + \Delta T_C)$ increases. For further globular growth, these two contributions must be limited to a minimum. This can be done either by forced convection of the melt or by slow cooling.

The NRC process uses slow cooling during the growth of the primary phase in the slurry. Due to possible convection and diffusion at a lower cooling rate the solute distribution in the liquid, close to the solid/liquid interface, is more uniform than the solute distribution in a quickly cooled melt. This leads to a lower constitutional supercooling, ΔT_C. At lower ΔT_C the Gibbs-Thompson effect has an influence on the increase of the interface stability. Thus, lower cooling rates support spherical growth[7,8].

Cellular or dendritic solidification is predominantly caused by the occurrence of constitutional supercooling, i.e., the liquid ahead of the solidification front exists below its equilibrium freezing temperature.

With respect to the microstructure evolution during freezing in the semisolid range, and in order to avoid dendrite formation, one has to provide a large number of small, solid nuclei to restrict the spacing between the nuclei and to cool the melt slowly.

Compared with the thixocasting process the NRC process has some additional benefits, i.e., the continuous casting of billets with electromagnetic stirring is not necessary, there is no cutting process for the billets and there is no reheating process for hot working in the semi-solid state. The rheocasting process starts from the liquidus phase and produces slurries that are directly transferred into a die or mould for further component shaping.

The main goal of this study was an evaluation of the microstructure of a real component produced by the NRC process.

2 EXPERIMENTAL

In the present work, slurries and components made by the NRC process were investigated. The NRC process was performed on an experimental device of the Japanese company UBE, installed in Stampal, Borgaro. The experimental device consists of a melting furnace, a casting device, a carrousel with controlled cooling

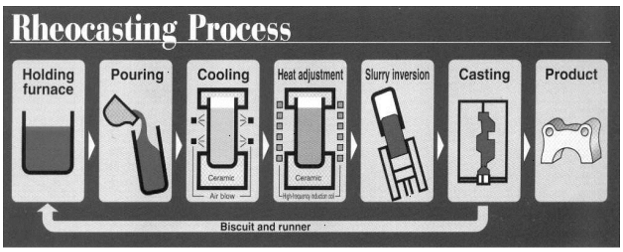

Figure 1: Schematic presentation of the new rheocasting (NRC) process with the possibility of the in-situ recycling of material (From project documentation GRD1-2002-40422)

Slika 1: Shema novega rheocasting postopka (NRC) z možnostjo "in situ" recikliranja materiala (Iz projektne dokumentacije GRD1-2002-40422)

Figure 2: Slurry from A 357 alloy, cut by a knife in the semisolid state

Slika 2: Surovec iz A 357 zlitine, prerezan z nožem v delno strjenem stanju

Table 1: Composition of A 357 alloy
Tabela 1: Sestava zlitine A 357

Alloy	Cu *w*/%	Mg *w*/%	Si *w*/%	Fe *w*/%	Mn *w*/%	Ti *w*/%	Zn *w*/%	Sr *w*/%	Al *w*/%
A 357	0.2	0.4 – 0.7	6.5 – 7.5	Max. 0.2	Max. 0.2	0.05 –0.2	Max. 0.2	0.03	Rest

devices, a robot for the slurry and a press for the squeeze casting.

We investigated the slurry (**Figure 2**), and the component (**Figure 3**), all made of a hypoeutectic silumin A 357 alloy. A typical composition of the A 357 alloy is presented in **Table 1**. The slurry was cut in a semi-solid state. The component was heat treated (T5, 6 h at 170 °C, hardness HB 5/250 92-96).

Table 2: Control of temperature in the slurry of A 357 alloy, Φ 116 mm, at three positions
Tabela 2: Kontrola temperature v surovcu zlitine A 357, Φ 116 mm, na treh pozicijah

	Temperature (°C)		
	T_A	T_B	T_C
Temperature (°C)	579	582	587
Distance from the bottom (mm)	40	95	170

A visual inspection of the surface of the components was performed. The internal soundness was checked with an industrial x-ray device (YXLON SMART 225 kV (Andrex)).

The samples for the light-microscopy investigation were cut from the slurry and from the components and prepared by standard methods used in metallography.

The metallographic investigation of the microstructures was performed with a Nikon Microphot FXA light microscope, equipped with a Hitachi HV-C20A 3CCD video camera and analySIS software for analyzing the metallographic figures. The hardness was measured by Brinell.

The EDS analysis of the inclusions was performed with a field-emission gun (FEG) JSM-6500F scanning microscope with an INCA ENERGY Oxford Instruments EDS.

3 RESULTS AND DISCUSSION

The slurry was cut in the positions where the temperatures T_A, T_B and T_C were measured (**Table 2**). **Figure 4** presents the microstructure in the middle of the slurry (Position T_B). The microstructure of the slurry shows the primary α_{Al} phase and the eutectic distributed among the globular grains of primary phase.

The visual inspection and the non-destructive x-ray examination of the component did not reveal any surface failures or internal defects, like porosity or big inclusions.

The microstructure of the component consists of globular grains of primary α_{Al} phase and a eutectic among the globular grains. The eutectic is more or less uniformly distributed among the grains of the primary phase (**Figure 5**). The share of the eutectic phase was increased near the surface of the component (**Figure 6**) to 85 %; compared to 23 % in the middle of the component. The reason is in the deformation process that caused, during the pressing of the slurry into the die cavity, the movement of the liquid eutectic toward the surface of the component, before the solidification was complete.

In the thin section of the component a finger-like protuberance (the start of a dendrite's growth) on some globular grains was observed (**Figure 7**). There are two possible origins of protuberances: either a change in the local supercooling during the process of deformation,

Figure 3: Component 1 (heat treated T5), A 357 alloy
Slika 3: Komponenta 1 (toplotno obdelana T5), zlitina A 357

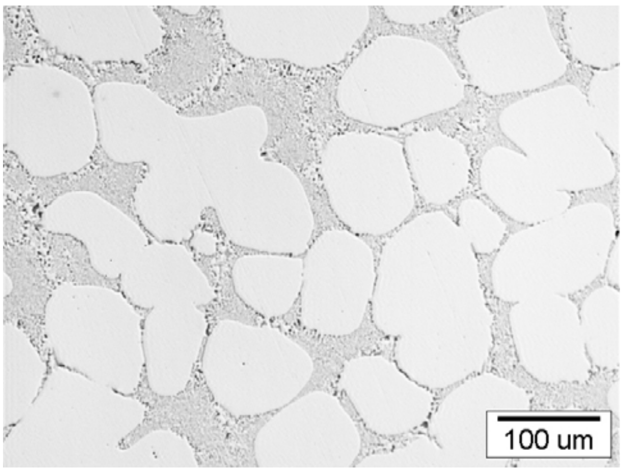

Figure 4: Microstructure of slurry of A 357 alloy, at position T_B
Slika 4: Mikrostruktura surovca zlitine A 357 na poziciji T_B

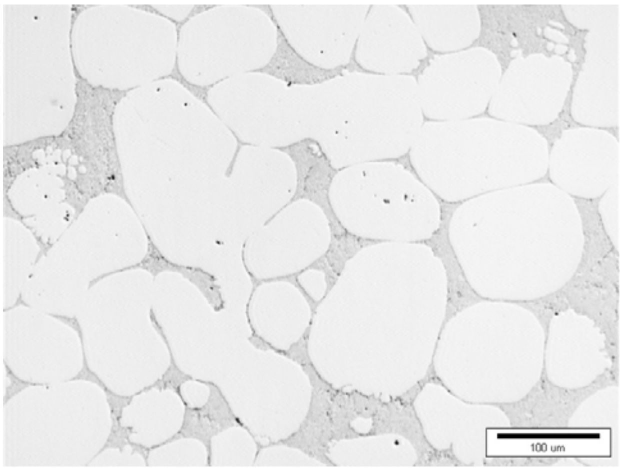

Figure 5: Microstructure of the component, A 357 alloy, heat treated T5, 6 h at 170 °C
Slika 5: Mikrostruktura komponente iz zlitine A 357, toplotno obdelana T5, 6h pri 170 °C

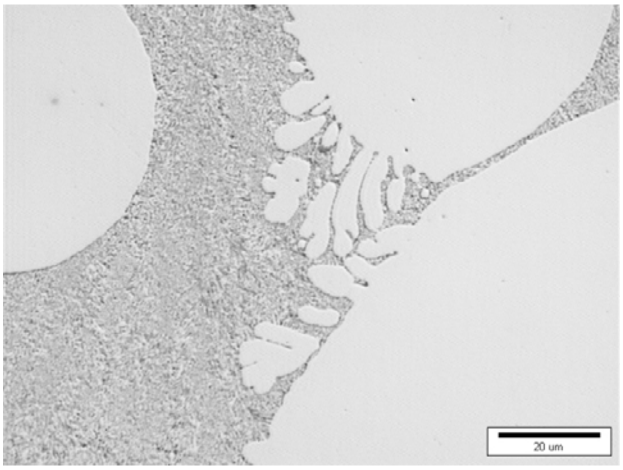

Figure 7: Protuberances, growing from the globular primary phase of α_{Al} in the component
Slika 7: Izrastki, ki rastejo iz globularne primarne faze α_{Al} v komponenti

which enabled the evolution of dendrites on the surface of the primary phase grains; or an unfinished globularization process of the primary α_{Al} phase in the slurry. The more likely is the local change in undercooling and solution partitioning during the deformation process in the tool, because increased undercooling and solution partitioning favors the evolution of dendrites. In addition to that, the protuberances were not observed in the microstructure of the slurry (Figure 4) as it solidifies in a more controlled temperature regime.

The explanation for the appearance of protuberances, observed in the microstructure of the component, can also be found in theory. As long as ΔT_R is sufficiently high, the interface of the growing nucleus is stable, and globular growth will take place. The solid globule becomes larger and larger, and it is possible that a protuberance with a larger radius can be developed and dendritic degeneracy can occur.

Besides that, a study[7] of solute concentration profiles in the liquid during the evolution of the primary phase for various cooling rates showed that under high cooling rates the solute is rapidly enriched in the liquid phase near the S/L interface because of the solution partitioning at the interface and the short time available for the solute diffusion. Therefore, the interface stability is quickly destroyed, leading to the appearance of protuberances and dendritic growth on the surface of the primary phase.

A lower pouring temperature, combined with lower cooling rates enhances the formation of a globular structure. In addition, inoculation favors the formation of a globular structure.

The microstructure of the component revealed, in addition to a globular primary α_{Al} phase, some dendritic forms of primary phase, which means the temperature regime of the NRC process was not optimized.

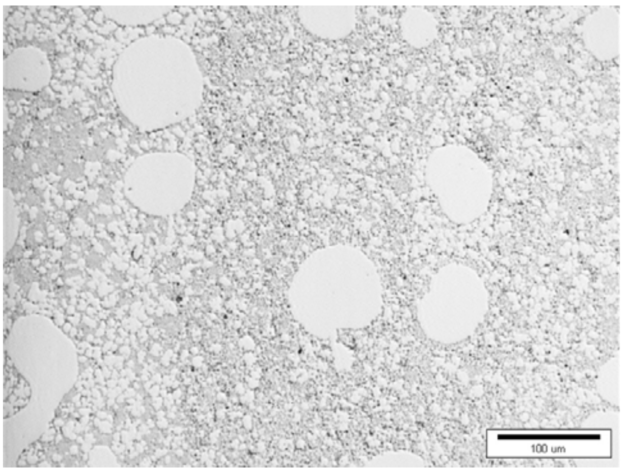

Figure 6: Increased quantity of eutectic near the surface of the component
Slika 6: Povečana količina evtektika ob površini komponente

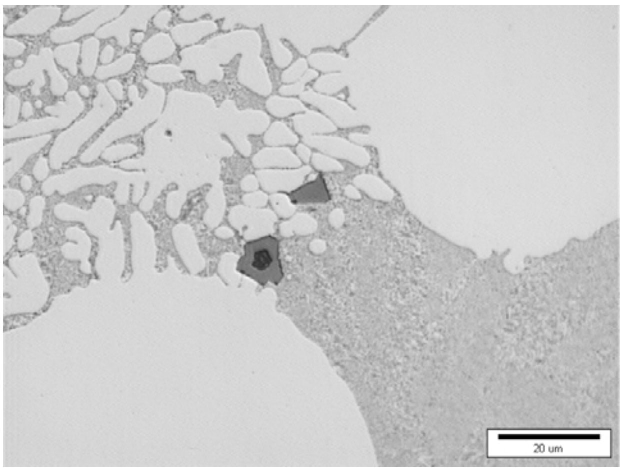

Figure 8: Inclusion with dark center, rich in Sr, surrounded by α_{Al} grains and eutectic
Slika 8: Vključek s črno sredino, bogat s Sr ter obdan z α_{Al} zrni in evtektikom

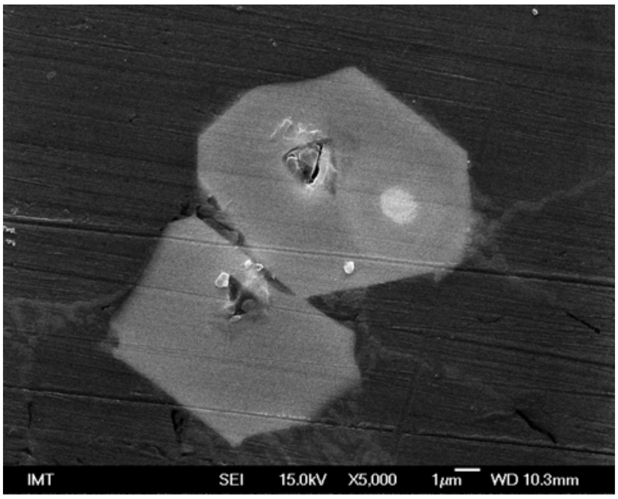

Figure 9: Combined inclusion in the component, A357, T5 alloy (SEM)
Slika 9: Kombiniran vključek v komponenti, zlitina A 357, T5 (SEM)

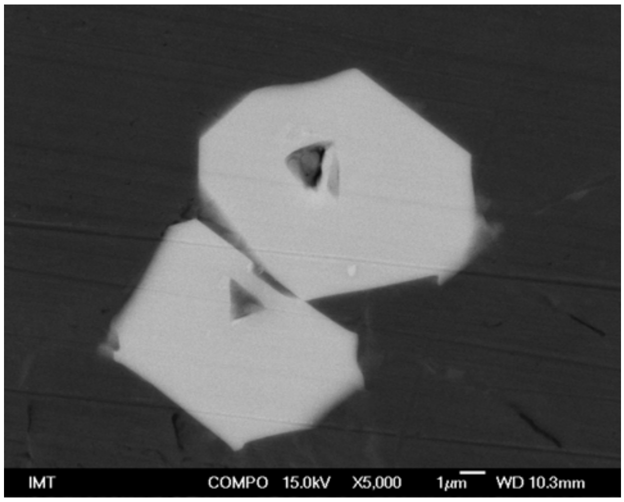

Figure 10: Combined inclusion in the component, A357, T5 alloy (BSE)
Slika 10: Kombiniran vključek v komponenti, zlitina A 357, T5 (BSE)

Inclusions with a dark area in the middle, as shown in **Figure 8**, were observed in the component. Point analyses with EDS were performed in a combined inclusion (**Figure 9** and **10**). The results of the EDS analyses are presented in **Table 3**. The analyses were performed on both parts of the combined inclusion: in the dark areas inside the inclusion and near the dark areas.

From the EDS point analysis it is evident that in the whole inclusion the content of Sr, Al and Si prevails. In the darker areas the increased quantity of O, Mg and P and slightly lower quantities of Al, Si and Sr were detected. It appears that the mixture of oxides in the darker areas represented the basis for inclusion growth.

The strontium was added to the A357 alloy to lower the surface tension, to accelerate the globularisation process of the α_{Al} primary phase and to change the morphology of the silicon in the eutectic[9].

4 CONCLUSIONS

A visual check and the x-ray analysis of the component made by the New Rheocasting (NRC) process did not reveal any surface or internal defects.

Observations of the macro- and microstructure of the slurry showed good homogeneity and a uniform size of the globular grains of the primary solidified phase.

Some dendritic forms of the primary α_{Al} phase and an increased content of the eutectic near the surface of the component were observed. This means that there are possibilities for a further improvement of the temperature regime.

The NRC process seems to be a promising semi-solid manufacturing technology for the production of automotive and other structural components.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the EC 5th Framework program for financial support under grant G1RD-CT-2002-03012

5 REFERENCES

[1] Giordano P., Chiarmetta G. L., Thixo and Rheo Casting: Comparison on a High Production Volume Component, Proceedings of the 7th S2P Advanced Semi-solid Processing of Alloys and Composites, ed. Tsutsui, Kiuchi, Ichikawa, Tsukuba, Japan, (**2002**), 665–670

Table 3: Point analysis in dark and light areas of inclusion from **Figure 10**
Tabela 3: Točkasta analiza na temnih in svetlih mestih vključka na **sliki 10**

Element	Dark area 1		Dark area 2		Light area 3		Light area 4	
	w/%	*x*/%	*w*/%	*x*/%	*w*/%	*x*/%	*w*/%	*x*/%
O Kα	19.60	36.99	12.60	25.94	1.06	2.60	0.97	2.36
Mg Kα	2.72	3.38	1.57	2.12	0.37	0,60	0.27	0.43
Al Kα	21.85	24.45	24.32	29.68	27.14	39.46	27.83	40.18
Si Kα	18.27	19.64	21.00	24.62	25.00	34.92	25.83	35.82
P Kα	3.80	3.71	3.20	3.40	1.63	2.06	1.11	1.40
Ca Kα	0.51	0.38	0.45	0.37	0.54	0.53	0.49	0.47
Sr Lα	33.25	11.46	36.87	13.86	44.26	19.82	43.,50	19.33

[2] Müller-Späth H., Sahm P. R., Razvojni dosežki na področju "Thixocasting"-postopka na livarskem inštitutu RWTH Aachen, Livarski vestnik, 44 (**1997**) 2, 33–42

[3] Wabusseg H., Kaufmann H., Wahlen A., Uggowitzer P. J., Theoretische Grundlagen und praktische Umsetzung von New Rheocasting von Al-Legierungen, Druckguss-Praxis, 1 (**2002**),16–19

[4] Kaufmann H., Uggowitzer P. J., The Fundamentals of the New Rheocasting – Process for Magnesium Alloys, Advanced Engineering Materials, 3 (**2001**) 12, 963–967

[5] Hall K., Kaufmann H., Mundl A., Detailed Processing and Cost Consideration for New Rheocasting of Light Metal Alloys, Proceedings 6 th International Conference on Semi-Solid Processing of Alloys and Composites, ed. G. L. Chiarmetta, M. Rosso, Torino, (**2000**), 23–28

[6] Blazek K. E., Kelly J. E., Pottore N. S., The Development of a Continuous Rheocaster for Ferrous and High Melting Point Alloys, ISIJ International, 35 (**1995**) 6, 813–818

[7] Zhu M. F., Kim J. M., Hong C. P., Modeling of Globular and Dendritic Structure Evolution in Solidification of an Al-7 mass % Si Alloy, ISIJ Intern., 41 (**2001**) 9, 992–998

[8] Uggowitzer P. J., Kaufmann H., Evolution of Globular Microstructure in New Rheocasting and Super Rheocasting Semi-Solid Slurries, Steel Research Int. 75 (**2004**) 8/9, 525–530

[9] Dahle A. K, Nogita K., Zindel J. W., McDonald S. D., Hogan L. M., Eutectic Nucleation and growth in Hypoeutectic Al-Si Alloys at Different Strontium Levels, Metallurgical and Materials Transaction A, 32A, (**2001**), 949