ANALYSIS OF THE REAL STRUCTURE AND RESIDUAL STRESSES OF THE TESTING CASTINGS FROM THE ALUMINUM ALLOY AlSiMg0.3 AFTER GRAVITY CASTING AND CONTROLLED COOLING BY THERMO-MECHANICAL SIMULATOR GLEEBLE

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Abstract

These days are more and more posing claims for the highest quality of castings from the aluminum alloys and for the lowest weight of these castings. These requirements force producers of such castings to utilize materials properties as much as possible. As one of such properties there is fatigue life which plays a crucial role at dynamically loaded parts. Dynamic working life depends on the many parameters such are loaded parts surface, structure and state of the residual stresses on the surface and so on. This paper deals with the utilization of the diffraction analysis at testing castings (specimens - rods) from the alloy AlSi7Mg0.3 that are poured into the metal mould after different thermal treatment methods. In this case was used diffraction analysis by means of the X-ray tensiometry and qualitative evaluation of structure by the Debye-Scherrer method (back-scattered). At the testing specimens was carried out analysis only on the surface by reason of the non-destructive determination of the residual stresses and real structure of specimens because testing specimens were subsequently tested by fatigue tests. One of the crucial parameters of fatigue life is the residual stress state on the loaded part surface and also its structure. Testing surface of all testing specimens was made by the same technology - turning by the CNC machine.

Keywords: Aluminum alloys castings, tensiometry analysis, Debye-Scherrer method

1. INTRODUCTION

Aluminum alloys have already found their application possibilities in the automotive industry. Mainly in the area of production car chassis and engine is still the highest portion of used materials taken by the casted materials whereas there is still competition between the alloys based on Fe and Al. These days there is very strong necessity to lower the production and operating costs which results as effort to decrease time for thermal treatment of castings while keeping, or even improve, some important properties as can be strength, ductility, dimensional stability and also fatigue properties. This is due to the fact that the better mechanical properties enable the better utilization of material characteristics [5, 6]. Better utilization of material results in the lowering weight of parts where own weight represents one of the very important parameters which influence the amount of CO_2 emissions. This lowering of construction parts weight (or just utilization the lightweight materials as are e.g. sandwiches, plastics or composites) is truly very important because on the other hand the better comfort and safety of passengers very often lead to the utilization of more parts.

Very important property of the chassis and engine is their service life (durability). This important property is surely closely related with the material fatigue properties which depend on many factors like is design shape, grain size of the material structure and last but not least there is also the magnitude and state of the residual stresses on the casting surface. Because fractures in majority of cases are created on the surface or right under it, they propagate in the material up to its failure. State of material real structure and magnitudes of the residual stresses on the surface is possible to non-destructive test and monitored by X-ray diffraction (XRD) [1]. This method was also used in this paper and for comparison real structure and state of residual stresses there were selected different thermal treatments used for castings.

2. PREPARATION OF THE TESTING RODS

The very important step before the own experimental part was a proper preparation of the testing rods. There was a strong requirement about the homogeneity of their mechanical properties through the whole testing set. Moreover, these testing rods were after production also subjected to the thermal treatments.

2.1. Shape of the testing rod

Measurements were carried out on the testing rods (see **Figure 1** - right). Shape of these testing rods was chosen with respect to the fatigue tests. On both ends of these rods were made threads to have possibility to clamp rods into the thermo-mechanical simulator GLLEBLE. Rods are made from the hardenable aluminum alloy AlSi7Mg0.3 and were casted at TUL (department of engineering technology) into the metal mould which was pre-heated at 300 °C. Melt was before casting modified and refinement by the refining salt T3 acc. to procedure described by the refining salt producer. Samples were produced within the cooperation with VUTS Liberec and producer warranted that all testing rods were produced under the same conditions and their audit department provided protocol about compliance of dimensions, accuracy and surface quality.

2.2. Thermal treatment methods

Some of the testing rods as casted semi-products (selected randomly) were also annealed in the furnace at temperature 500 °C for time of 3.5 hours and subsequently were cooled in the water [2]. It was followed by the artificial ageing in two ways. The first procedure was to achieve maximal strength (TZ_MAX_P): annealing in the furnace for 7 hours at 165 °C and then the castings cooled on air. The second procedure was to achieve maximal ductility (TZ_MAX-Z): annealing in the furnace for 3 hours at 320 °C and then the castings cooled on air. From these castings were, after these thermal treatments, produced testing rods (**Figure 1** - right).

From the other casted semi-products were produced testing rods. Some of these rods stayed in this casted state (TZ_4) and at the other rods (TZ_1, TZ_2, TZ_3) were by the thermo-mechanical simulator GLEEBLE simulated very high cooling rate of these castings (**Figure 1** - left). Cooling rate was determined from the course of the maximal cooling rate for given dimension of part and for used copper clamping jaws. Temperature was recorded by means of the thermocouple fastened in the point 0 (**Figure 2**).

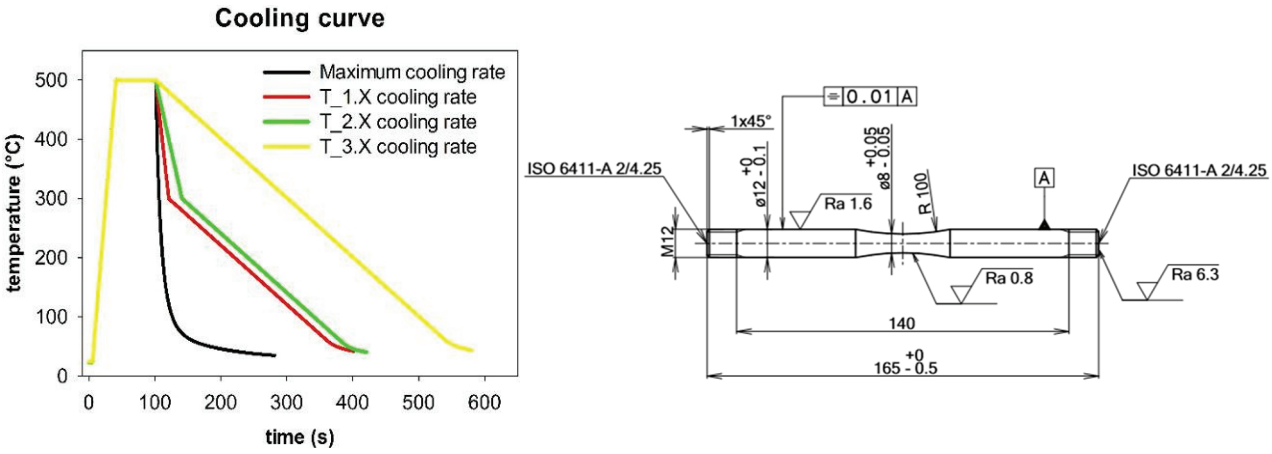


Figure 1 Cooliong curves for different types of the thermal treatment (left) and testing rod (right)

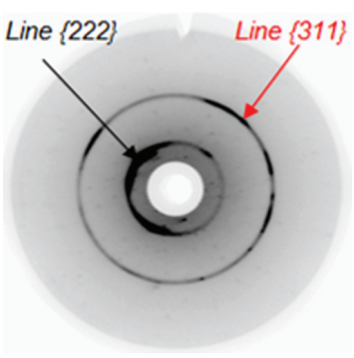
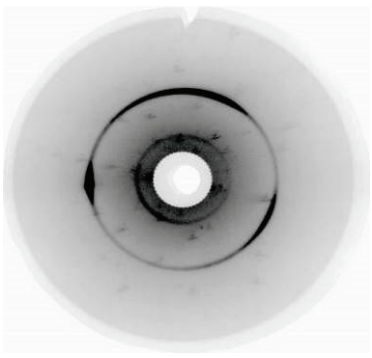
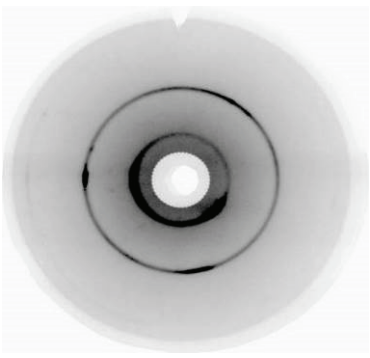
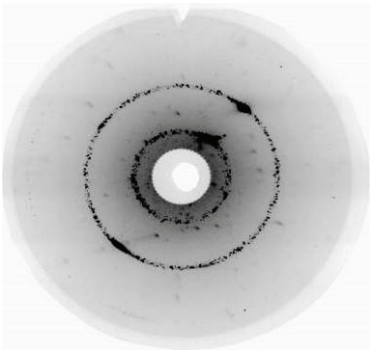
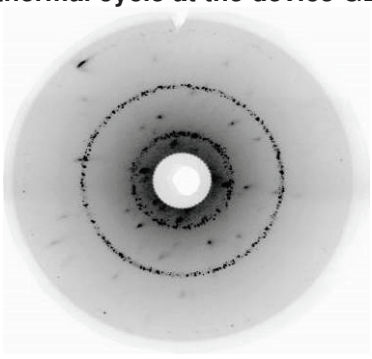
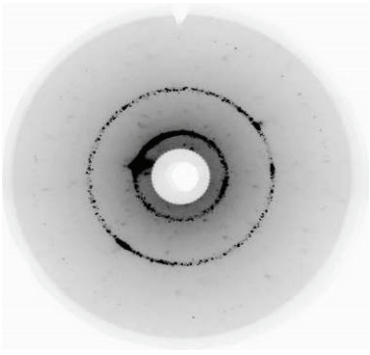
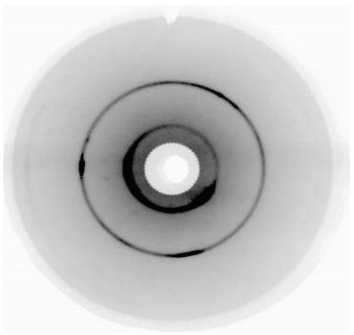
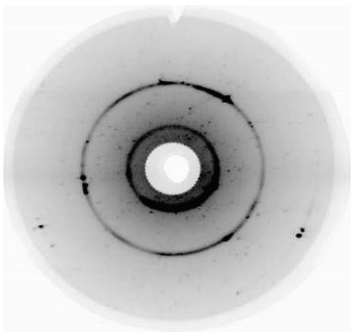
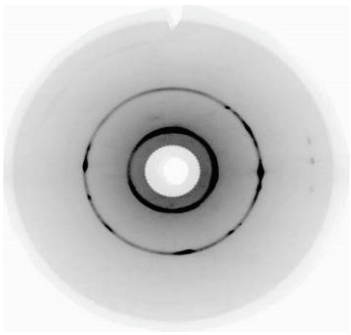
3. X-RAY DIFFRACTION ANALYIS OF THE TESTING RODS

As it was already mentioned before, X-ray diffraction (XRD) is widely used for the non-destructive testing of materials. In this paper it was used both for qualitative evaluation of structure by the Debye-Scherrer method (back reflection) and for quantitative evaluation of residual stresses.

3.1. Qualitative evaluation of structure by the back-reflection Debye-Scherrer method

For the quantitative evaluation of testing rods surface structure there was used the Debye-Scherrer method. In the experimental part was for determination the back-reflection X-ray diffraction patterns used a device with the high-voltage generator ISO DEBYEFLEX 3003 and X-ray tube with Cr anode. X-ray beam passed through the collimator of 1 mm^2 cross-section [1]. For measurement were adjusted the following parameters: current 20 mA, voltage 30 kV and exposure time 2.5 min. Distance between the sample and image plate was 30 mm. Diffractograms were recorded on the image plate and after scanning they were modified with the help of the software D-tech. A symbol that looks as “notch” in the upper part of X-ray diffraction patterns (see **Table 1**) serves for their orientation - it is orientation in the major axis **A** direction of testing rod. Structure analysis was carried out in the point 0 of testing rod (**Figure 2**).

Table 1 Back-reflection X-ray diffraction patterns of line {311} α_2-Al and line {222} α_1-Al measured in point 0

X-ray diffraction pattern (Debye-Scherrer method)	**Machined surface**		
			
Rod	TZ_1.1	TZ_2.1	TZ_3.1
X-ray diffraction pattern (Debye-Scherrer method)	**After thermal cycle at the device GLLEBLE**		
			
Rod	TZ_1.1	TZ_2.1	TZ_3.1
X-ray diffraction pattern (Debye-Scherrer method)	**Machined surface**		
			
Rod	TZ_4.1	TZ_MAX_P1	TZ_MAX_T1

3.2. Quantitative evaluation of residual stresses by the X-ray diffraction method "chi-modified" at the diffractometer PROTO iXRD COMBO

X-ray diffraction measurements were made at the diffractometer PROTO iXRD COMBO in "chi-modified" layout of the goniometer by X-ray tube with Cr anode (**Figure 2**) under the voltage 25 kV and current 4 mA. There were analyzed diffraction planes {311} of phase α_2-Al to which, under the used radiation, corresponds the diffraction maximum $2\theta \approx 139°$.

Magnitudes of the residual stresses were computed from the lattice deformation which were determined on the basic of the experimental dependences $2\theta^{311\alpha 2}$ ($\sin^2\psi$) on condition of the bi-axial stress state for residual stresses where: θ - diffraction angle (°),
Ψ - angle between sample and the diffracting lattice plane (°).

Dependences $2\theta^{311\alpha 2}(\sin^2\psi)$ were measured under the azimuth A [3, 4]. Diffracted radiation was recorded by two linear detectors which were located on the both sides of collimator and was processed with the help of the software WRD Win 2000. The same software was used also for determination the magnitudes of macroscopic residual stresses.

For areas 1 till 5 was the change of diffraction angle $2\theta^{311}$ CrKα diffracted on the lattice planes {311} of phase α_2-Al determined by the autocorrelation method. At stress computation there were used X-ray elastic constants as following: $\frac{1}{2}s_2 = 19.54$ TPa^{-1}, $s_1 = -5.11$ TPa^{-1}. Experimental error written for the individual measured values represents the standard deviation acc. to algorithm for computation the residual stresses by the method termed as "sin²ψ". Parameters of the measurement were following: exposure time 1 s, 15 repetitions of every measured diffraction maximum, cylindrical collimator with diameter 1 mm, oscillation of the radiation source around axis within ± 3°, sample performs rotation motion and translation ± 2mm in the direction of major axis X, macroscopic residual stresses were measured under 15 inclinations of ψ - totally there were obtained 30 diffraction maxims.[7]

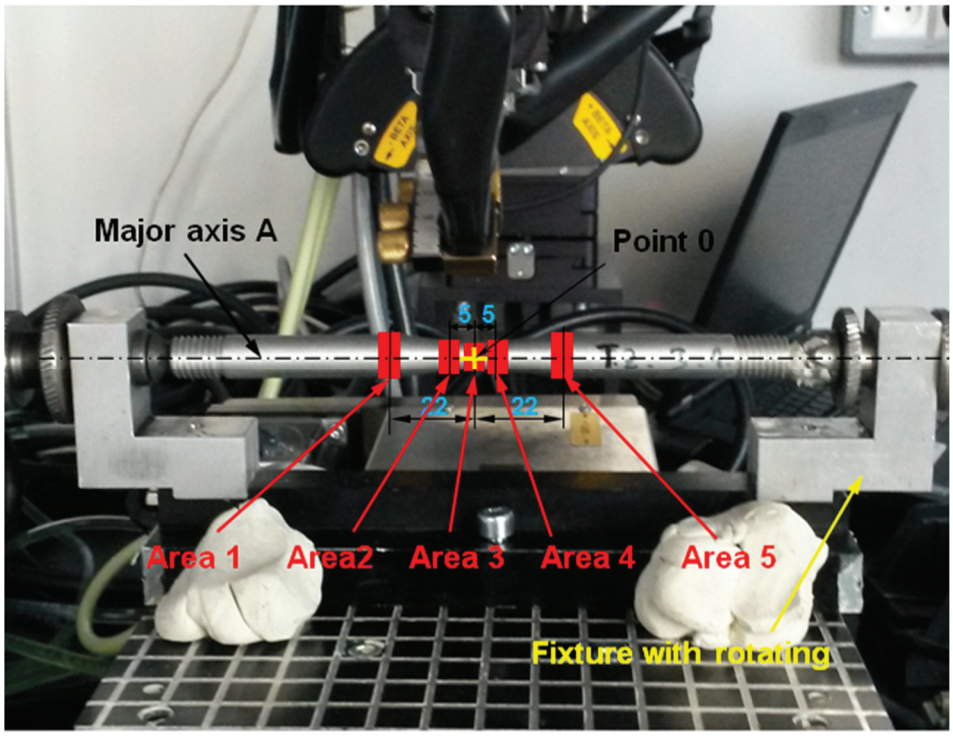


Figure 2 Testing rod clamped in the jig with rotary motion during measurement the residual stresses (utilization of diffractometer PROTO iXRD COMBO, chi-modified lay-out of the goniometer)

Table 2 Residual stresses for chosen samples in areas 1 till 5, different operations and with / without rotation

	$\sigma_A \pm \Delta\sigma$									
	With sample rotation					*Without sample rotation*				
	area 1	area 2	area 3	area 4	area 5	area 1	area 2	area 3	area 4	area 5
TZ_1.6 - after machining	-24 ± 7	10 ± 6	5 ± 5	29 ± 5	5 ± 4	-65 ± 16	3 ± 13	4 ± 9	3 ± 25	-18 ± 13
TZ_1.9 - after GLEEBLE	-37 ± 5	-2 ± 5	-13 ± 7	11 ± 5	8 ± 4	-12 ± 8	-20 ± 18	-15 ± 18	8 ± 18	-12 ± 11
TZ_2.3 - after GLEEBLE	-44 ± 6	-14 ± 4	-13 ± 5	-14 ± 7	-55 ± 4	-18 ± 11	45 ± 24	-45 ± 23	20 ± 15	3 ± 11
TZ_MAX_P 1 - after machining	-46 ± 6	26 ± 11	16 ± 5	29 ± 6	-36 ± 8	-58 ± 11	7 ± 13	18 ± 12	37 ± 13	-39 ± 8
TZ_MAX_T 3 - after machining	-65 ± 6	-9 ± 4	-12 ± 4	8 ± 6	-16 ± 4	-69 ± 14	-43 ± 8	3 ± 11	-2 ± 9	-27± 6

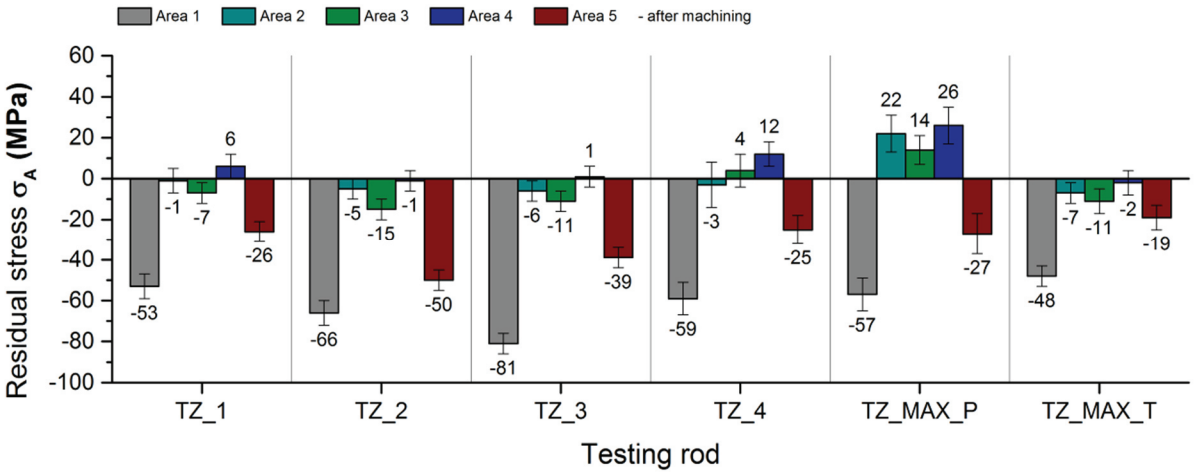


Figure 3 Average magnitudes of the residual stress for samples after machining

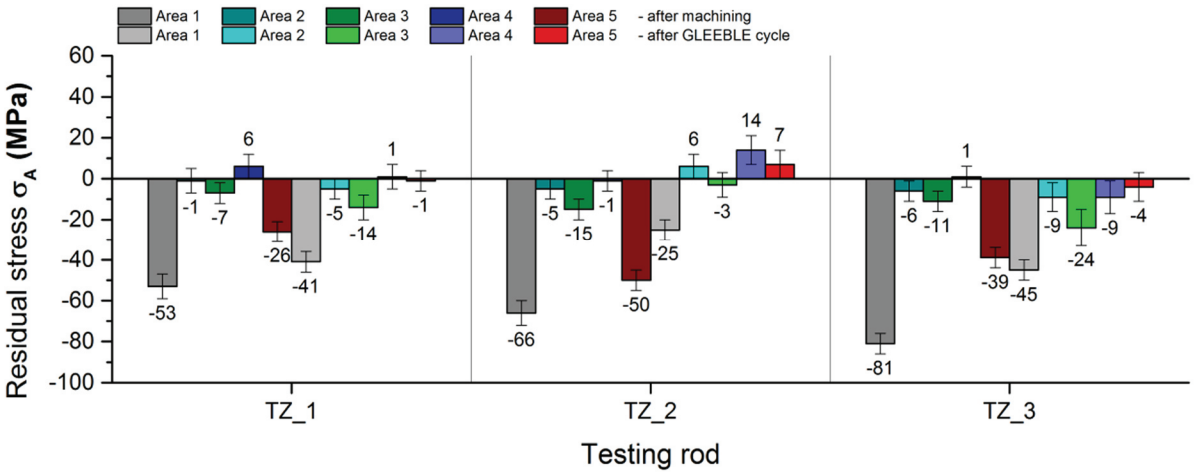


Figure 4 Average magnitudes of the residual stress for samples after machining and after GLEEBLE cycle

4. CONCLUSION

From the diffraction patterns can be made the following conclusions. Due to the influence of the thermal cycle at the device GLLEBLE there is discretization of the surface layer which was created after machining. There is also partial decrease in the crystals preferred orientation that is observed as area of the diffraction line having higher intensity. In the most of measured patterns revels the plane {222} α_1-Al higher preferred orientation than plane {311} α_2-Al. For analysis of the residual stresses is suitable to select the plane {311} α_2-Al. To eliminate preferred orientation and local non-homogeneities there was selected the sample rotation along the major axis A and translation in the direction of the major axis A.

Analysis of the residual stresses proves the presumption determined from the diffraction patters where after elimination local non-homogeneities in the structure and preferred crystals orientation resulted translation and mainly the sample rotation in lowering magnitudes of measurement uncertainties - namely for the samples after the thermal cycle at the GLEEBLE (see **Table 2**). From such analysis of the residual stresses it is obvious that after machining is achieved the highest magnitudes of the compressive residual stresses in area 1. At samples which were refined on the maximal ultimate strength are achieved the highest tensile residual stresses (**Figure 3**) in areas 2, 3 and 4 (**Figure 2**). Samples after the thermal cycle at device GLEEBLE revealed the decrease in tensile values of achieved residual stresses in areas 1 and 5 and in some cases the tensile stresses transformed in the residual stresses. In the other areas of samples after the thermal cycle was not observed the strong changes in magnitudes of achieved residual stresses (**Figure 4**).

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