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SPRAY COOLING OF ALUMINUM CHASSIS FRAMES

By means of thermographical measurements of one-side spray cooled discs heat transfer coefficients for varied cooling conditions were determined. These were used to calculate cooling and thermal distortion of chassis frames by means of the finite element software ANSYS. Simulation results reveal that cooling using a water air spray is almost as fast as usual water quenching. Besides, thermal distortion can be reduced using spray cooling where distortion is within the range of common gas cooling.

Spray cooling, gas cooling, aluminium, ANSYS, simulation.

Путем термографического анализа водо-воздушного охлаждения тонких дисков определены значения коэффициентов теплоотдачи для различных условий закалки. Эти данные использованы при моделировании температурных полей и термической деформации подрамника автомобиля в ходе его термической обработки при помощи конечно-элементной программы ANSYS. Показано, что скорость водо-воздушного охлаждения близка по интенсивности к чистому водяному. С другой стороны, применение двухкомпонентного способа охлаждения позволяет уменьшить искажение формы изделия от действия термических напряжений до величин деформации, характерных для принудительного охлаждения воздухом.

Шляхом термографічного аналізу водо-повітряного охолоджування тонких дисків визначені значення коефіцієнтів тепловіддачі для різних умов гартування. Ці дані використані при моделюванні температурних полів і термічної деформації підрамника автомобіля в ході його термічної обробки за допомогою кінцево-елементної програми ANSYS. Показано, що швидкість водо-повітряного охолоджування близька по інтенсивності до чистого водяного. З іншого боку, вживання двокомпонентного способу охолоджування дозволяє зменшити зміну форми виробу від дії термічних напружень до величин деформації, характерних для примусового охолоджування повітрям.

Introduction

Heat treatment of light metals respectively steel is of a particular interest for the controlled adjustment of material properties. Regarding aluminum alloys properties such as material strength, sensitivity to corrosion or electric conductivity can be adjusted by heat treatment based on precipitation-hardening.

Aluminum casts such as chassis frames with complex geometries, e.g. the alloy AlSi11Mg, are heat treated by applying at first a solution-annealing for 6 h at 525 °C, then a quenching in a water-bath tempered to 80 °C, followed by an artificial aging treatment for 3 h at 155 °C. In this "T6" heat treatment an inhomogeneous cooling of the components occurs while immersion cooling in water due to the so-called Leidenfrost effect. This causes thermal induced residual stresses, which overlap with residual stresses of prior stages of production released by the heat treatment. Distortion occurs requiring time consuming and cost-intensive reworking. Thus, an alternative processing characterized by low-distortion during heat treatment is necessary.

Objectives

Objective of the presented work is the process design of a controlled T6 heat treatment of aluminum parts using spray cooling based on water and compressed air as an alternative to the conventional quenching by immersion cooling. Based on previous works [1, 2, 3] a numerical model of the heat treatment process is to be realized for a component cooling with low-distortion. Reducing distortion is notably accompanied by a reduction of reworking, which will lead to substantial saving of production costs.

Heat transfer during spray cooling of aluminum alloys

Determination of heat transfer coefficients.

In order to determine temperature-dependant heat transfer coefficients in the spray-cooling process an approach was used that is based on the *Lumped Heat Capacitance Method*. For this purpose discs of the alloy AlSi11Mg (s. table 1) with a thickness of 1 mm and a diameter of 70 mm are impinged on one side by spray-cooling.

Table 1

Chemical analysis (mass %) of the investigated alloy AlSi11Mg

Al	Si	Mg	Zn	Fe	Cu
89,472	8,999	0,373	0,145	0,579	0,086

On the back side of the discs the temperature progression is measured by a thermographic camera. With the temperature T of the component, it's temporal changes dT/dt, the water temperature T_w, alloy density ρ, volume V and surface A of the disc and the heat capacity c_p subsequently the heat transfer coefficient h can be evaluated using equation 1 [4]:

$$h = -c_P \cdot \rho \cdot \frac{V}{A} \cdot \frac{1}{T - T_W} \cdot \frac{dT}{dt} \quad . \tag{1}$$

A precondition is that the thermal conduction in the disc, compared to the heat transfer on the surface, is comparatively high. A criterion is a Biot-number less than about 0.1 [5]. According to equation 2, the Biot-number Bi is calculated by the ratio of volume V to surface A, multiplied with the heat transfer coefficient h and the thermal conductivity k:

$$Bi = \frac{h}{k} \cdot \frac{V}{A} < 0.1 \quad . \tag{2}$$

The examined aluminum discs were coated with graphite on one side prior to heating, in order to increase the emission ratio to 0.95. Subsequently they were heated in a resistance furnace to a temperature of about 550 °C. The quenching occurred through the impingement by spray cooling for 10 s in the experimental set-up depicted in fig. 1, where the graphite coated side faced the thermographic camera. The tests were carried out with a round spray nozzle type SUJ12, 1/8JJAU manufactured by the company Spraying System Co. Experiments were taken within the range of 0.1 MPa to 0.4 MPa of the air pressure (L) and of 0 MPa to 0.5 MPa of water pressure (W). A thermographic camera, type ThermaCam SC 3000 manufactured by FLIR Systems Inc., that enables measurement frequencies within 50 Hz to 750 Hz was used to measure the time-temperature-progression. Distance between the camera and the disc was chosen to be 380 mm and between disc and nozzle 150 mm. The measuring range of the camera was 50 °C to 600 °C. For each parameter setting 3 measurements were taken and averaged. The dependency of the heat transfer coefficient on the air respectively water pressure of the round spray nozzle is depicted in fig. 2.

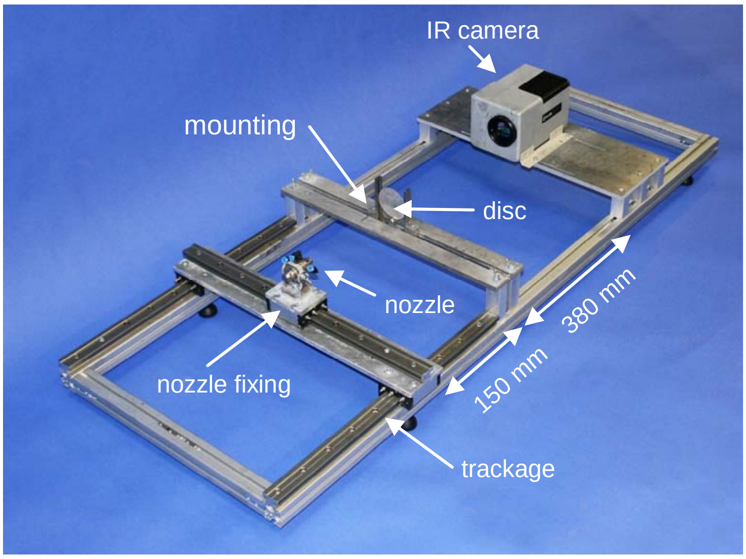

Fig. 1 – Experimental set-up for determination of the heat transfer coefficients by means of thermographical measurements of one-side spray cooled discs

The maximum value, approximately 60 kW/(mI·K), was reached with the parameter combination 0.1L-0.3W. One can see that the heat transfer coefficient increases when the water pressure is higher than the air pressure.

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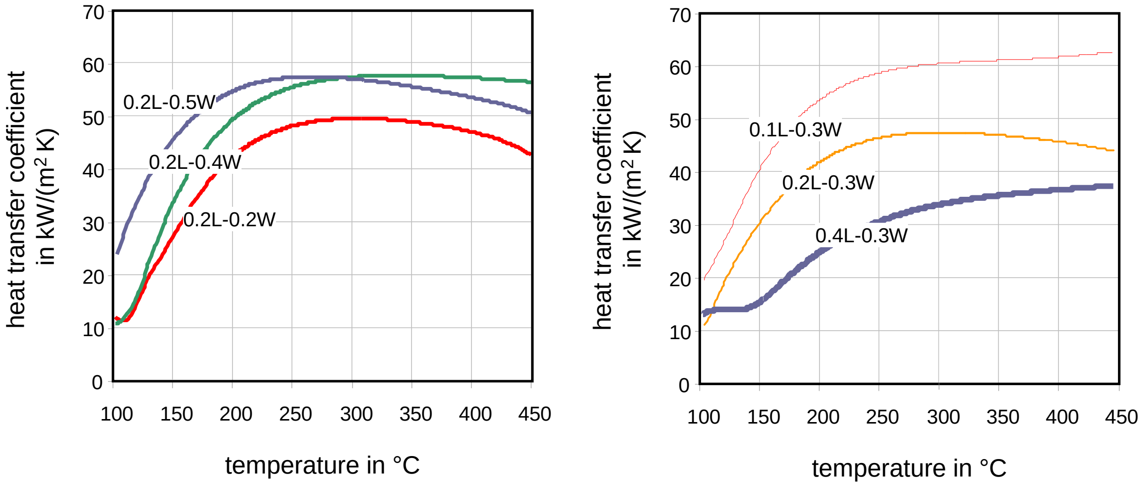

Fig. 2 – Heat transfer coefficients determined for the centre of a spray cooled disc of the alloy AlSi11Mg for various spray types; nozzle type SUJ12, 1/8JJAU (Spraying Systems Co.); left: influence of rising water pressure; right: influence of rising air pressure

Numerical Model.

Purpose of the developed model is to determine suited spray cooling parameters to reduce distortion for a given minimum cooling rate. The chosen model geometry of the aluminum chassis frames is about 410 mm broadness, 130 mm height and 30 mm thickness. Calculations are realized using the finite-element-software ANSYS. User specific subroutines were implemented on behalf of the macro language APDL. Thus, the non-linear heat transfer due to spray cooling can be considered and critical cooling rates be observed. Instead of modelling the parts’ cooling by separate nozzles a homogenous temperature depended heat transfer coefficient on the surface was initially chosen. Beyond the above presented results heat transfer coefficients from previous investigations were implemented as well [6]. Fig. 3 depicts the overall scheme of the approach used to calculate optimized cooling conditions.

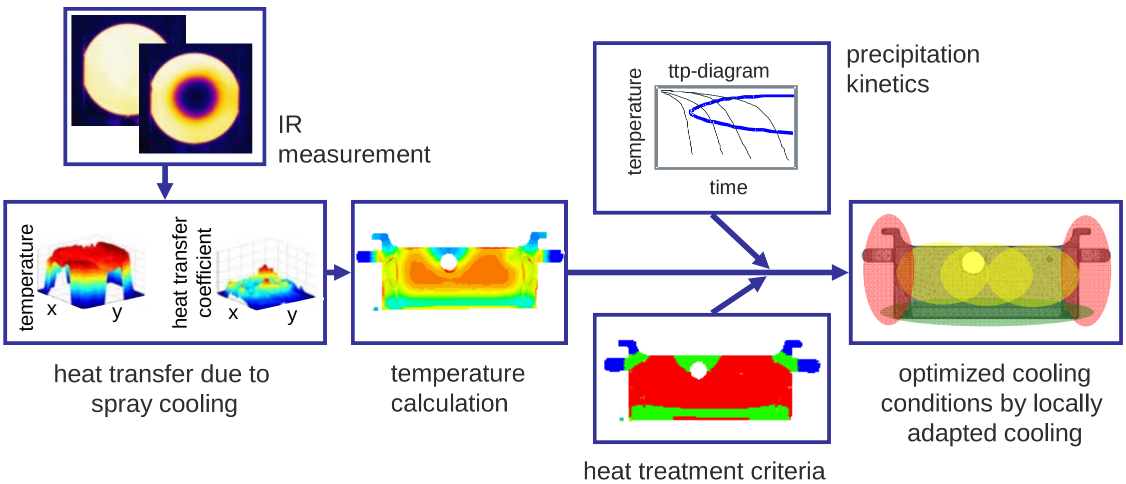

Fig. 3 - Scheme of the approach used to calculate optimized cooling conditions for minimized thermal distortion considering determined heat transfer coefficients, critical cooling rates and possible spray field configurations

Fig. 4 depicts a scheme of the implemented APDL subroutines used for the calculations by means of a flow diagram. During program start the part's geometry as well as material properties are initiated. Furthermore, the spray cooling conditions can be determined. Materials properties like density, heat capacity, thermal conductivity and so on are (s. table 2) based on the *Magmasoft* materials database.

Table 2

Implemented material properties

property	**value**	**unit**
density	2680	kg/m3
heat capacity	963	J/(kg·K)
thermal conductivity	113	W(m·K)
Poisson's ratio	0.333	-
Young's modulus	71	GPa
thermal expansion	22.9	μm /(m·K)

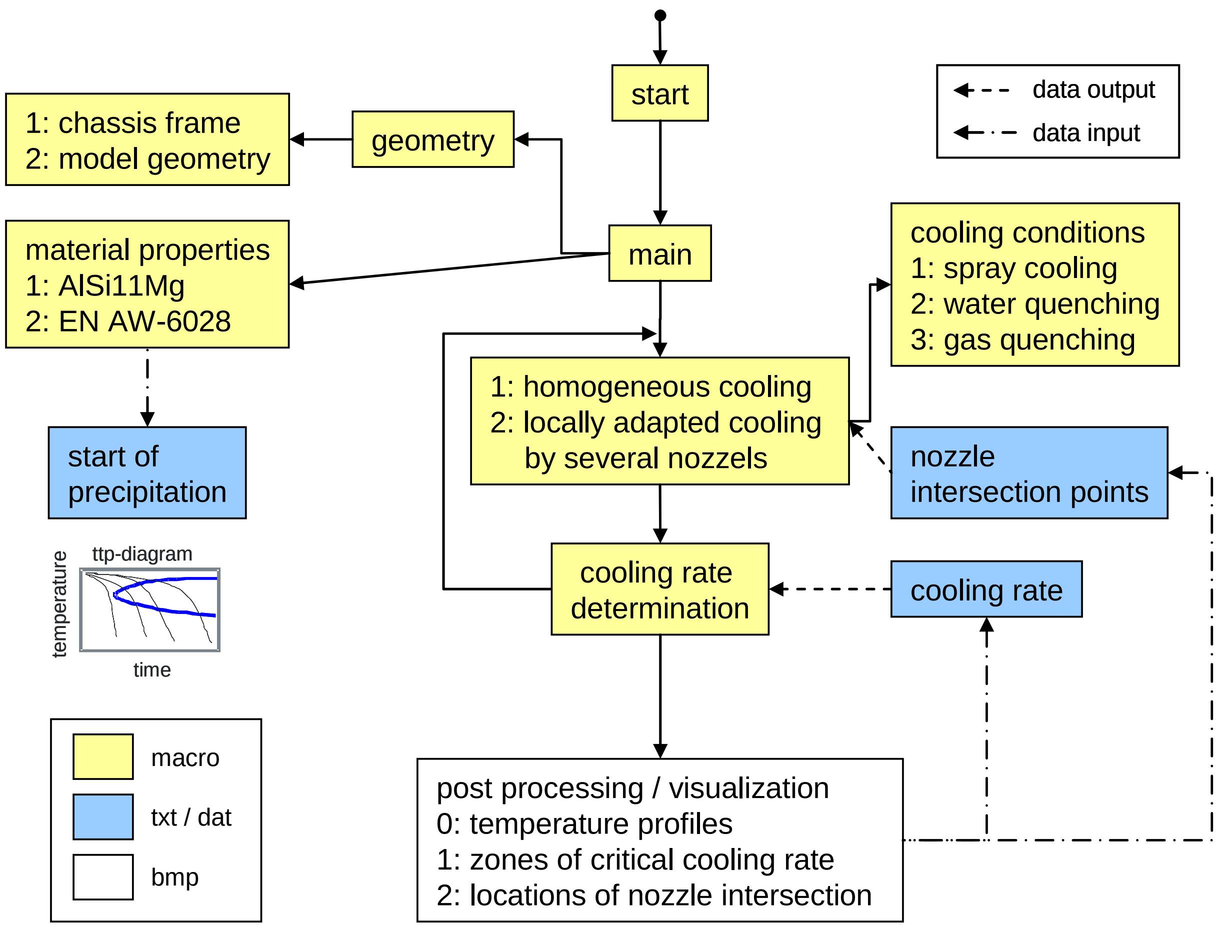

Fig. 4 - Scheme of the implemented APDL subroutines used for the carried out calculations

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Since no flow curves for the investigated alloy AlSi11Mg were available, materials characteristics according to table 3 were assumed. Such material characteristics are typically for aluminum alloys of the type Al-Mg-Si [7]. Multilinear kinematic hardening plasticity was chosen to consider the materials plasticity in ANSYS.

Table 3

Implemented true stress values as a function of temperature

strain	strain rate in 1 s^{-1}	temperature in °C				
		300	350	400	450	500
0	0.001	98	47	28	18	12
0.1	0.001	99	48	29	19	13
0.3	0.001	100	49	30	20	14
0.4	0.001	101	50	31	21	15
0.5	0.001	102	51	32	21	16

Calculation Results.

Temperature sequences for three different cooling conditions are given in fig. 5. Within 10 s the chassis frame is cooled down both for water quenching and spray cooling of the type 0.3L-0.3W. In comparison, the water quenching occurs slightly faster. In this case water quenching is modelled using heat transfer coefficients according to *Besserdich* [8]. Gas cooling (0.5L) to room temperature takes place in approximately 40 s.

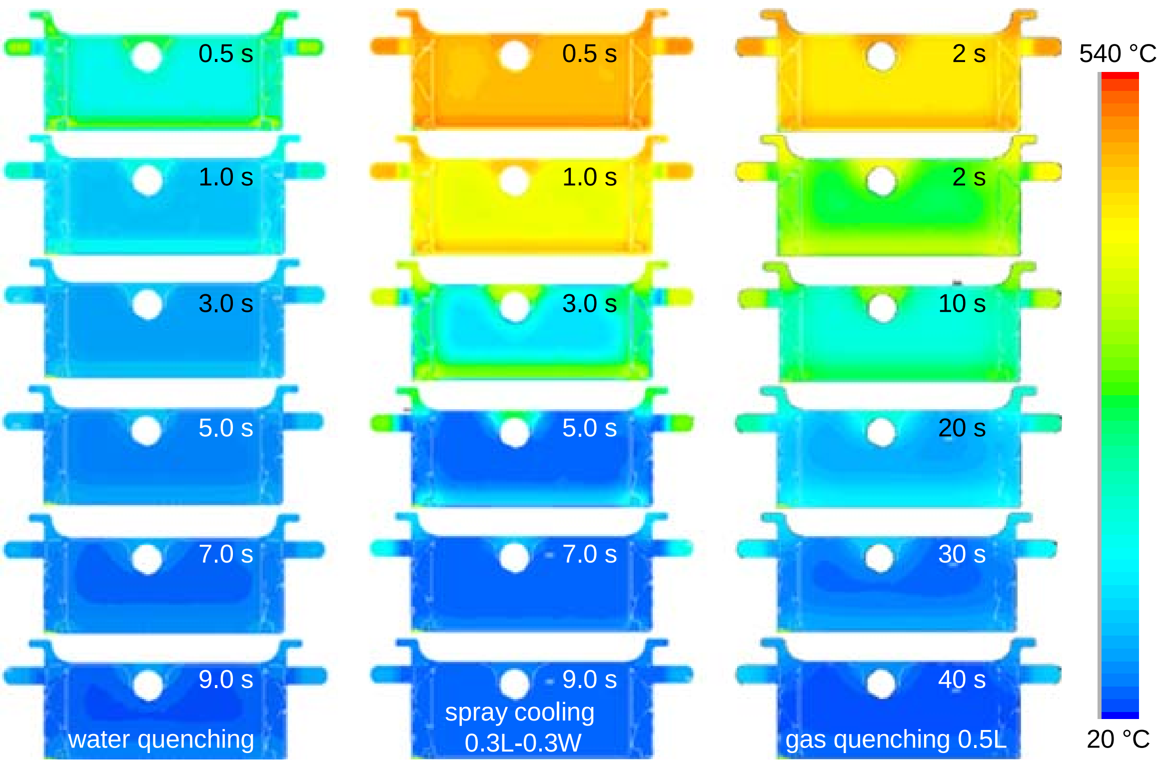

Fig. 5 - Temperature sequences for water quenching (left), spray cooling (0.3L-0.3W) and gas cooling (0.5L)

The influence of the three varied cooling conditions on the distortion of the chassis frame is depictured in fig. 6. For three different positions strains in x-, y- and z-direction are shown during the parts’ heating and cooling. Distortion due to spray cooling is clearly reduced compared to water quenching. Both the range within which distortion occurs as well as the accumulated distortion values of all positions are lowered. Besides, distortion values due to spray cooling are similar to distortion values due to gas cooling.

Discussion and conclusions

The presented method was applied to calculate the cooling of aluminum chassis frames as well resulting thermal distortion. The following sub-steps were used:

i) thermograpical measurement of the cooling of one-side spray cooled discs of the alloy AlSi11Mg,

ii) calculation of the heat transfer coefficients by means of the lumped heat capacitance method,

iii) implementation of the heat transfer coefficients into the finite element software ANSYS,

iv) calculation of cooling, thermal stresses and thermal strains, respectively.

Realized subroutines written in APDL code can be changed with few expenses. Thus, e.g., modified geometries or varied heat transfer coefficients can easily be implemented. Calculation results reveal that spray cooling can be used for a fast cooling of aluminum parts of the alloy AlSi11Mg and is suited to accomplish a precipitation hardening.

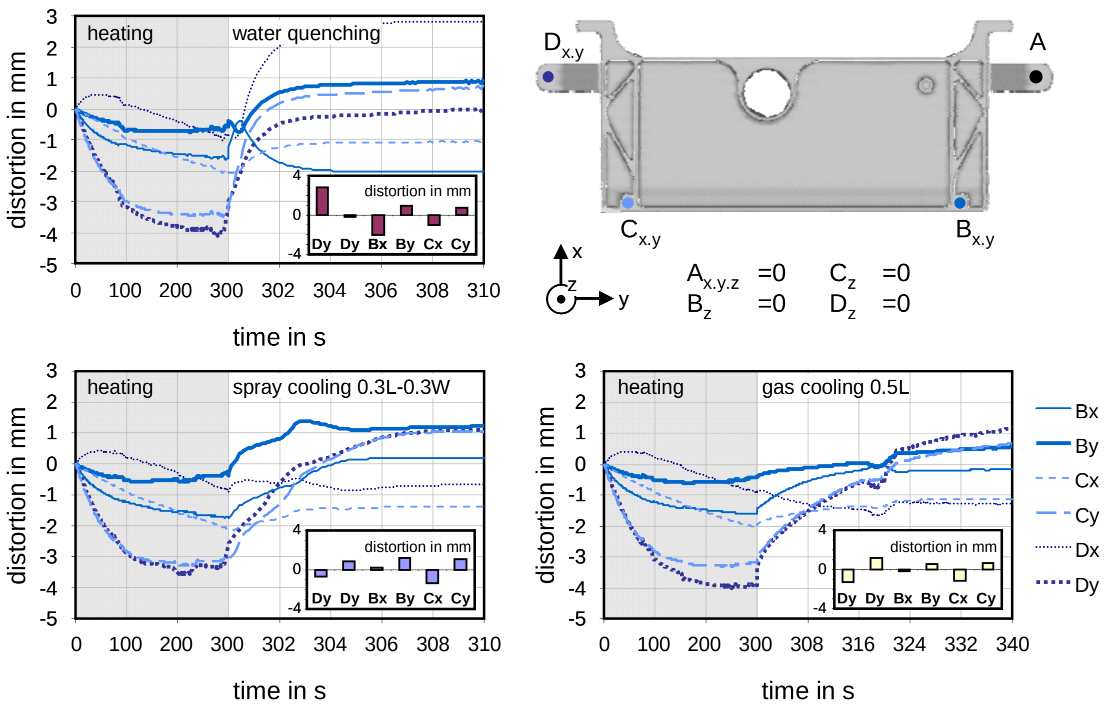

Fig. 6 - Strains in x-, y- and z-direction during the parts’ heating and cooling at three different positions (B, C and D).

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Thermal distortion during spray cooling is less than during water quenching. Distortion due to spray cooling is similar to distortion due to a comparatively slow gas cooling. Further work will be dedicated to validate the numerical simulation results by means of physical cooling experiments.

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