PREDICTIONS OF RESIDUAL STRESSES CAUSED BY QUENCHING PROCESS IN ALUMINIUM 6351-T6 GAS CYLINDER.

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ABSTRACT

Finite element (FE) studies were conducted to simulate quenching process in aluminium 6351-T6 gas cylinders. The simulations aimed to evaluate the effect of quenching process on the stress state of the cylinder including through thickness residual stress distributions.

The gas cylinders are formed by a forging process whereby the open ended cylinder is forced into a forming die. The gas cylinders are then heat treated by using T6 heat treatment process to meet specifications for tensile strength and hardness. The forming and heat treatment processes introduce small folds and significant tensile residual stresses at the internal surface of the neck of the cylinder. When the effects of these folds and residual stresses arising from the quenching process are combined with the internal pressure of the cylinder, cracks may develop over time. The crack may result in the possibility of leakage or, more seriously, fracture of the cylinders.

Previous experimental studies confirmed that high level of tensile residual stresses is present at the internal surface of the neck of the aluminium gas cylinders. Finite element simulations were conducted to model the temperature distribution and thermo-mechanical effects accompanying the quenching of aluminium gas cylinders from 530 °C to room temperature. Using FE to model the quenching processes, thermal inelastic deformation were studied and a residual stress distribution through the thickness of the neck of the cylinder were obtained.

KEYWORDS

Residual stresses, quenching, thermal analysis, plastic strain, crack growth, aluminium, gas cylinder.

NOMENCLATURE

T - temperature
h - free convection heat transfer coefficient
k - thermal conductivity
c - heat capacity
ρ - density
q - thermal flux
T_o - sink temperature
t - time
σ^y - yield stress
σ^u - ultimate stress
E -Young's modulus
r, θ, z - coordinates
u_θ, u_r, u_z - displacements
ε - elongation

INTRODUCTION

Manufacture of aluminium gas cylinders consists of metal forming processes and heat treatment. Cylinders with one valve are back-extruded from a cast or extruded slug. The tube end is then sunk into a die which is shaped to the finished external form.

The formed cylinders are then heat treated in order to obtain the desired strength values. The heat treatment (T6) consists of heating to approximately 530 °C (close to the solidus of the aluminium alloy), quenching in a water bath. This is followed by aging at 170°C for 6 hours. Initial heating is used to reduce residual stresses introduced during forming processes. During quenching, the cylinder should be cooled down to 250 °C within 1 min to provide the desirable microstructure. The cylinder is subsequently cooled down to room temperature in air.

Metal forming processes introduce small folds (in the order of 2 mm deep and 20mm long) and surface scratches which are stress raisers [1]. Further, the quenching of the cylinders introduces significant tensile residual stresses at the internal surface of the neck of the cylinder [2,3]. When the effects of the flaws and residual stresses are combined with the internal pressure of the cylinders, cracks may develop over time.

The values of these residual stress are required to predict precisely the time to failure of the cylinders [3,4]. In this study FE algorithms were used to determine the residual stresses. The results of FE analysis are compared with the data obtained through destructive testing [3].

Residual stresses in the quenched cylinder arise from non-uniform plastic deformations due to temperature differences between the outer and inner surfaces .The level of residual stress depends on cooling rate which in turn depends on how the cylinder was exposed to the cooling media and thermal properties of the material.

As the amount of deformation of the cylinder depends on the thermal processes, residual stresses can be calculated only when the temperature distributions are known. The distributions must be determined at several time intervals for both stages of the cooling - first, in water bath, and then in air until the whole cylinder is cooled to room temperature. These distributions are a solution of non-linear transient heat conduction problem with surface convection boundary conditions specified. At the second step, by using the temperature distributions obtained throughout the thickness of the neck of the cylinder, residual stresses are obtained from the solution of thermal - elastic - plastic problem at specified time intervals.

FINITE ELEMENT MODELS

Two FE models (for thermal and stress analysis) were designed to predict the residual stresses in the neck of the gas cylinder. The FE code ABAQUS version 5.4 [5] and preprocessor PATRAN were employed to evaluate the thermal processes in the cylinder during the quenching process, and calculate the residual stresses in the neck section after cooling to room temperature.

The problem is axisymmetrical and therefore only 5 degree sector was considered using cylindrical coordinate system r,θ,z. The FE model shown in Fig.1 consists of "20-node hexahedra" elements and has 870 and 1662 degrees of freedom for thermal and stress analyses respectively.

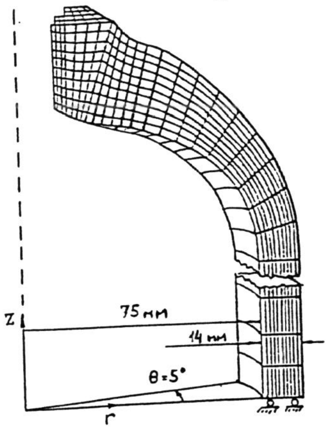


Fig. 1. Finite element idealisation of aluminium gas cylinder used to model temperature and stress distributions during quenching. Five degree sector was used for the axisymmetric problem.

The thermal properties of the aluminium alloy 6351T6 employed for the calculation were [6,7]: specific heat c=905 J/kg.°C, density ρ = 2700 kg/m^3; conductivity "k" was considered as a linear function of temperature 'T':

$$k=(175+0.0943\cdot T)\ \mathrm{W/m\ ^\circ C}. \qquad (1)$$

Boundary conditions were specified as

$$q = h\cdot(T - To)\ , \qquad (2)$$

where q - thermal flux, T_o - sink temperature, T - temperature of surface; h- free convection heat transfer coefficient. 'h' was determined using the data and approaches presented in [8,9] for various conditions of cooling at different surfaces. For outer surface of the cylinder while it was cooled in water, value of the heat transfer coefficient was h_w =716 W/m^2 °C, for the subsequent cooling in air the heat transfer coefficient h_a=16 W/m^2°C was used. For the inner surface h_i = 10 W/m^2 °C . The temperature of the coolant was T_o=15°C; inside the cylinder T_o is assumed to be 20% higher than the temperature of the surface to simulate lower cooling rate of air inside the cylinder in comparison with that of the inner surface.

A modified Newton's method for the solution of the equations of thermal conductivity was employed. Sufficient accuracy of the solution was provided by using self-adaptive time stepping algorithm to determine the time increment. Every time increment was calculated for a maximum temperature change of 10°C during the cooling process.

Temperature distributions obtained for these time intervals (approximately twenty in number) were used to calculate the thermal stresses. Thus, the size of time increments was adjusted according to the intensity of the thermal load applied to the gas cylinder. Quasi-Newton method was employed for the solution of equations at each increment.

Von Mises yield criterion and isotropic work hardening were assumed. The material properties were obtained from tensile tests of specimens manufactured from the neck of the gas cylinder. The results of the experiments at various temperatures are shown in the Table 1.

Table 1. Yield stresses, ultimate stresses and elongations obtained from tensile test at various temperatures.

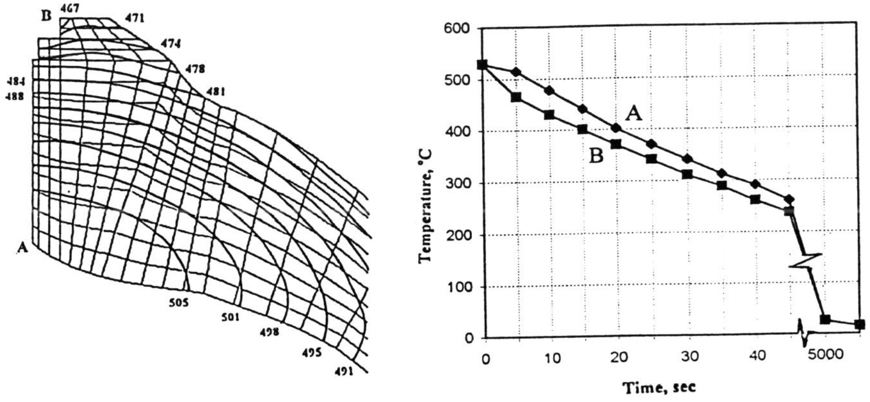
T °C	0	130	200	300	400	530
σ^y, MPa	291	262	105	20	5	2
σ^u, MPa	338	297	133	20	5	2
ε,% in 50 mm	11	12	18	-	-	-

Note that all the yield stress measurements were based on 0.1% proof stress. At room temperature and up to 130°C sharp yielding behaviour was observed followed by non-linear hardening; from 130°C to 200 °C linear strain hardening was prevailed, above this temperature the material behaves close to elastic-perfectly-plastic. Table 1 shows significant reduction of yield stress at elevated temperatures. Other mechanical properties of the material used in the calculation were Young's modulus E = 69GPa, and coefficient of thermal expansion $23 \cdot 10^{-6}$ °C^{-1}[7,10].

Boundary conditions are displacements u_θ=0 at $\theta = 0°$ and $\theta = 5°$,$u_\theta = u_r$ =0 at the axis of rotation, $u_z = 0$ at plane z=0.

RESULTS AND DISCUSSION

Figure 2a shows the temperature distribution in the neck area of the gas cylinder after 5 sec of water cooling from 530°C. Figures 2b and 2c show the change of temperature with respect to cooling time for the points marked in Fig. 2a at the outer and inner surfaces of the cylinders. From Fig.2c maximum temperature gradient of 50°C through the thickness of the neck arises during the first 15 sec and subsequently it drops to 20°C at the end of water cooling.

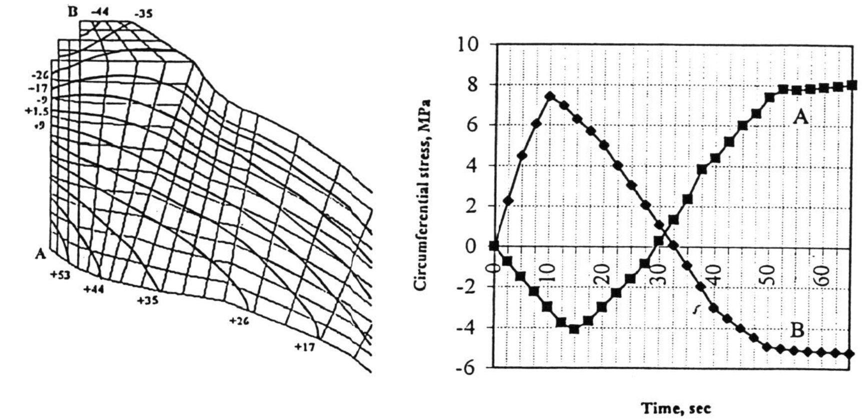


a) The temperature distribution in the neck area of the cylinder after 5 sec of water cooling.

b) The change of temperature with respect to cooling time at the inner surface (point A) and outer surface (point B).

Fig.2. Temperature distributions obtained from the thermal analysis

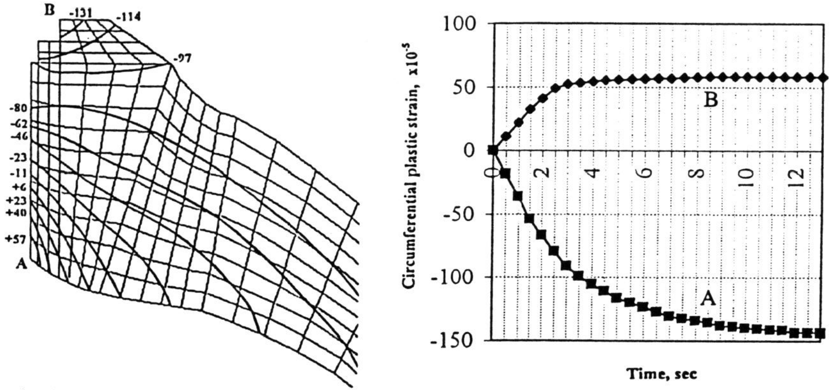
Results of stress analysis are presented in Fig.3 and 4. Fig. 3b, 4b show the stress contour during the quenching process. At the beginning of cooling high tensile stresses on the cooled surface arise due to the shrinking of material, and high compressive stresses in the inner region are produced as a balance to the outer surface tensile stresses. These stresses are of sufficient magnitude to cause plastic flow of the material on both surfaces of the cylinder. Plastic strains have developed within a short time (6-8 sec) and reached a maximum when the stresses rise to their peak values. Further cooling, the temperature gradient decreases on both surfaces and the stresses change their sign due to the mismatch



a) The circumferential residual stress distribution.

b) The change of the circumferential stress at the initial stage of quenching on the inner (point A) and outer (point B) surfaces of the cylinder.

Fig. 3. Stress distributions in the neck area of the cylinder.



a) The circumferential plastic strain distribution after quenching.

b) The change of the plastic strains at the inner (point A) and outer (point B) surfaces of the cylinder.

Fig .4. Plastic strains distributions in the neck area of the cylinder

of strain. Negative plastic strain at the inner surface leads to tensile residual stress, and positive plastic strain at the outer surface yields compressive residual stress.

The FE results show that the maximum of tensile residual stresses of 61 MPa caused by quenching process occur in the region which is susceptible to cracking. These values of residual stresses and those obtained by using strain gauges from destructive testing [3] are given in Table 2 and 3 for comparison.

Table 2. Residual stresses obtained from destructive testing using strain gauges and FEA.

Conditions	Experiment	FE analysis
As headed	+27	-
Heat treated, not quenched	- 39	-
Heat treated and quenched	+56	+61
Machined and aged	+63	-
Machined, aged and hydrotested	+72	-

As it can be observed, the FE results have good agreement to the values obtained experimentally. The 8 % difference can be attributed to the experimental factors such as inhomogeneous heating and cooling, and the assumptions used in the formulation of the boundary conditions for thermal problems, and the assumptions of the material behaviour at high temperature in the FE analysis.

Table 3. Residual stresses for four machined, aged and hydrotested cylinders obtained from destructive testing using strain gauges.

Cylinder	1	2	3	4
Circumferential residual stress, MPa	49	164	43	83

Table 3 indicates significant variations in residual stresses obtained experimentally for four cylinders. These variations may be due to non-axisymmetric cooling conditions. Therefore, it is anticipated that an extension of the present investigation is to consider the sensitivity of non-axisymmetric temperature distribution using a solid finite elements employed in this study.

Cooling rate plays a main role in the development of residual stresses of the cylinder. Therefore the cooling rate should be determined carefully and accurately by considering both the final strengths required for the specifications of the cylinder and the level of residual stresses which can cause crack growth and propagation. The numerical model provides quantitative estimates of the relationship between cooling rate and residual stresses.

To investigate the sensitivity of cooling rate, the thermal problem was repeated with heat transfer coefficient h_{aw} = 2749.1 W/m$^{2\cdot}$s which provides a cooling rate of approximately 6 times higher than that considered before. In this case, a maximum residual stress of 115 MPa was obtained. The significant difference between these two results suggesting that the procedure might be used to obtain an optimum thermal treatment which provides both the desirable structure of alloy and a minimum level of residual stress.

CONCLUSION

Finite elements models were created to calculate the residual stresses in aluminium gas cylinders after quenching in water. The FE results show that the maximum tensile residual stresses of 61 MPa occurs in the region which is susceptible to cracking. The FE results have good agreement to the values obtained through destructive testing.

The FE results suggesting that the established model and procedures might be used to obtain an optimum thermal treatment which provides both desirable microstructure of the alloy and a minimum level of residual stresses.

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