

Effects of Pressure, Die, and Stress-Relief Temperatures on the Residual Stresses and Mechanical Properties of Squeeze-Cast Aluminum Rods

J.A. Aniyi, F.L. Bello-Ochende, and M.B. Adeyemi

The effects of die heating and stress-relief temperatures in reducing residual stresses of squeeze-cast aluminum alloy rods are experimentally determined by the longitudinal slitting method, and their reduction effects on the mechanical properties of the squeeze-cast alloy rods are investigated. Stress relief is much more effective than die heating in reducing residual stresses of the squeeze-cast alloy. Stress relief is substantially completed at 350 °C in 1 h, but at the expense of reduction in strength and hardness. Appreciable reduction in strength and hardness is avoided by using a stress-relief temperature of 250 °C for residual stress reduction of squeeze-cast aluminum alloy. Die heating to a maximum of 200 °C is considered adequate to substantially reduce the chilling effect of the metal mold on the solidifying molten metal and to avoid appreciable reduction of strength and hardness resulting from die heating effects.

Keywords

die heating, longitudinal slitting method, residual stresses, squeeze cast, stress-relief

1. Introduction

THE SQUEEZE casting process combines permanent mold casting and die forging operations (Ref 1-3). It utilizes punch pressures (Ref 4) applied on the metal metered into a permanent mold to consolidate the metal during solidification; this eliminates defects due to shrinkage cavities and/or gas porosity (Ref 1-4). Application of pressure (Ref 2) improves mechanical properties of squeeze-cast products provided the applied pressure exceeds a certain critical value (Ref 1, 2). Some of the advantages of this process are higher casting yield, higher mechanical properties, reduction in tooling cost, and higher dimensional accuracy.

Several experimental investigations on squeeze-cast products have centered mainly on the variations (Ref 2, 4) of their mechanical properties as a result of varying production parameters, such as pressure application, pouring temperatures, die temperatures, and lapse time between pouring and pressure application, etc. The improved mechanical properties are due to modification of the microstructure of the squeeze-cast product by pressure applications.

Many investigations have been undertaken on the effects of production parameters on the mechanical properties of squeeze-cast products. However, published research work on the effects of production parameters on the residual stresses of squeeze-cast products have not been fully undertaken. The exception is the experimental evaluations (Ref 5) of residual stress ratios of the squeeze-cast rods determination at various applied punch pressures under instantaneous and long-time pressure applications with the die maintained at a room temperature of 30 °C.

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Residual stresses are known to be reduced by thermal treatment (Ref 6-9) at temperatures that do not result in an unacceptable loss of strength and hardness. The present work, therefore, aims to provide more detailed information on the residual stress levels, die, and residual stress-relief temperature effects on squeeze-cast products prepared at different levels of pressure applications. The mechanical properties of the squeeze-cast products at different pressure applications with die and stress-relief temperatures are also determined experimentally.

2. Experimental Procedure

2.1 *Specimen Preparation*

The material used is commercially pure aluminum: 99+% Al with (approximate) impurities 0.1% Cu, 0.4% Si, 0.4% Fe, and 0.1% Mn.

Cylindrical test specimens were cast in a graphite lubricated tapered die steel chamber with electric heaters incorporated for heating purposes. The die temperatures were controlled to an accuracy of ±1 °C within the investigated range of 30 to 300 °C. A metered quantity of the aluminum melt, maintained at 750 °C, was poured into the die chamber maintained at various constant temperatures. A preselected load was applied via a punch on the melt at a constant approximate time of 16 s after pouring. The aluminum test specimens were cast at atmospheric (no pressure application) and at 80 MN/m^2 and 110 MN/m^2 pressures with the die maintained at temperatures ranging from 30 to 300 °C.

2.2 *Stress Relief and Residual Stress Determination*

The cast aluminum rods were isothermally stress relieved in an electrical furnace at 100 to 350 °C at an interval of 50 °C for 1 h. They were later allowed to cool in the furnace. The temperature of each specimen was continuously measured by a Chromel/Alumel (BICC Thermocheat, BICC Pyrotenax Limited, Hebburn, Tyne & Wear, NE31 1XR, England) type thermocouple in contact with it to enable adequate corrections to be made for the heating-up period. Because an appreciable amount of time was required for the specimen to reach the stress-relief temperature, an appropriate heating-up time correction obtained from the temperature versus time curves was introduced to account for residual stress relief occurring at this period and to maintain equal stress relief time of 1 h for all stress-relief temperatures.

The longitudinal slitting method (Ref 7, 10) was used to measure the maximum, longitudinal residual stress in the squeeze-cast products. The longitudinal slitting method involves making a longitudinal slit in the specimen; the slit end then opens up or closes in under the effect of the residual stresses (Ref 10). In this investigation, the slit end was measured with a micrometer and was reproducible to an accuracy of a few percent.

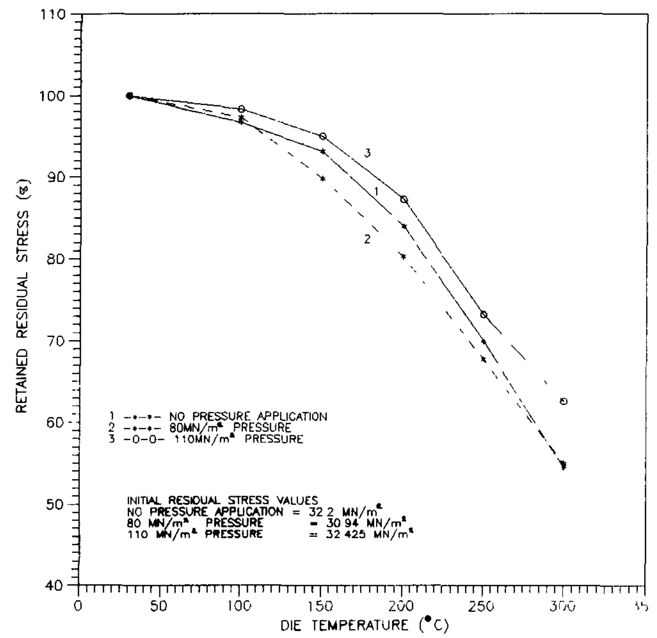


Fig. 1 Effect of die temperature on the residual stresses of squeeze-cast aluminum alloy rods

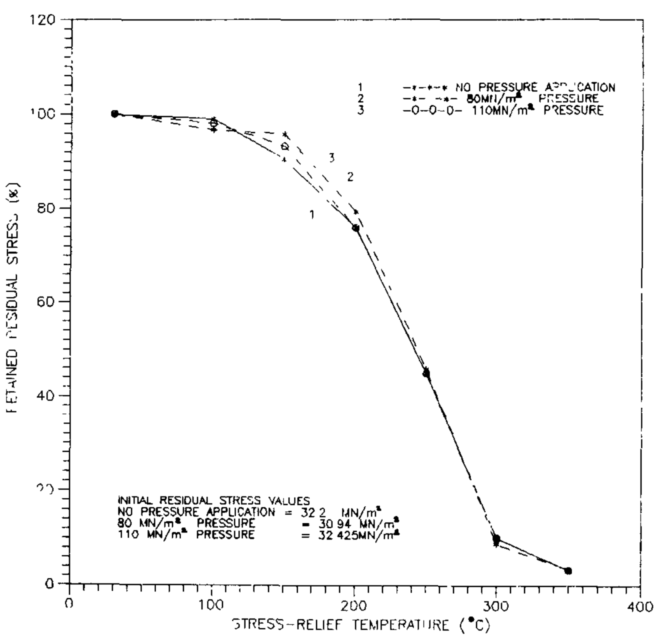


Fig. 2 Effect of stress-relief temperature on the residual stresses of squeeze-cast aluminum alloy rods

Equation 1 was used to determine (Ref 5) the residual stresses in the as-cast products, from which the residual stresses in squeeze-cast products prepared under various conditions could be deduced by Eq 2. The percentage of residual stress remaining in the products either as a result of die heating or stress relief was determined using Eq 2 based on the ratios of the slit openings, f and f^*, over a given slit length, L, which were kept constant for all slitting operations conducted for all the experimental investigations.

$$\sigma_{zm*} = \frac{0.6604 E^* R_m^4 f^*}{R_*^3 L^2 \left(1 + \frac{4.8D}{L}\right)} \quad \text{(Eq 1)}$$

$$E^* = \frac{E}{1 - \mu^2}$$

$$F = \frac{f}{f^*} \times 100 \quad \text{(Eq 2)}$$

where L is slit length; f^* is slit opening of the cast product at room temperature; f is slit opening of the squeeze-cast product at any die heating or stress-relief temperature; E is Young's modulus of elasticity and is assumed constant over the temperature range investigated; μ is Poisson's ratio; R_m is mean radius over the slit length L; R^* is radius at slit length L; σ_{zm*} is maximum longitudinal residual stress at the die temperature of 30 °C under as-cast condition (no pressure application); F is percentage of fractional residual stress remaining; and D is diameter of product at slit length L.

2.3 *Hardness and Tensile Properties Measurements*

Hardness measurements were carried out both longitudinally and transversely on samples using a Rockwell hardness tester. Hardness impressions were taken transversely in approximately two perpendicular directions across the cross section of the prepared sample to obtain the average hardness values.

Tensile tests were conducted on the Monsanto tensiometer to determine ultimate tensile strength (UTS) for various stress-relieved and squeeze-cast products.

Percentage of ultimate tensile strength remaining (Ref 13) in the squeeze-cast product after each thermal treatment was calculated using Eq 3 whereas the percentage of change in hardness was calculated using Eq 4.

$$F_\sigma = \frac{\sigma_u}{\sigma_1} \times 100\% \quad \text{(Eq 3)}$$

$$F_H = \frac{H - H_1}{H_i} \times 100\% \quad \text{(Eq 4)}$$

where F_σ is percent of fractional UTS retained; F_H is percentage of fractional hardness retained; σ_u is ultimate tensile strength after die heating or stress relief; σ_i is initial ultimate tensile strength of either as-cast or squeeze-cast rod at the die temperature of 30 °C; H is hardness (HRB) after stress relief or die heating; and H_i is initial hardness of either as-cast or squeeze-cast rod at the die temperature of 30 °C.

3. Experimental Results and Discussion

3.1 *Die Heating and Stress-Relief Temperature Effects on Residual Stresses*

3.1.1 Die Temperature Effect on Residual Stresses

Figure 1 shows the variation of the percentage of fractional residual stress remaining, F, with increase in die heating temperatures. The percentage of fractional residual stress remaining decreases with increase in the die heating temperature over the die temperatures and the three pressures investigated. For the three pressure levels tested, the residual stresses decrease with an average reduction rate of 0.061% per °C within the die temperature range of 30 to 150 °C. This is followed by a higher average residual stress reduction rate of 0.26% per °C between the die temperature range of 150 to 300 °C.

Also found experimentally, the initial residual stress of 30.94 MN/m^2 for squeeze casting made at a pressure level of 80 MN/m^2 is lower than that obtained for casting at atmospheric and a pressure level of 110 MN/m^2. The initial residual stress of 32.425 MN/m^2 at a pressure level of 110 MN/m^2 is slightly higher in value than the initial residual stress of 32.2 MN/m^2 for as-cast at atmospheric pressure. The results agree with those of Abifarin and Adeyemi (Ref 5). Within the investigated die heating temperature range of 30 to 300 °C, the residual stress reduction rates reduce as the initial residual stresses increase. The average residual stress reduction rates within 30 to 150 °C of castings at atmospheric and 80 MN/m^2 pressures are 0.057% per °C and 0.085% per °C, respectively. Squeeze casting at 110 MN/m^2 gives a least stress reduction rate of 0.042% per °C with the highest residual stress. At a higher temperature range of 150 to 300 °C, the residual stress reduction rates are approximately close in values, but the reduction rates are still higher in castings produced at lower pressure levels application.

The reduction effects of residual stress during die heating can be attributed to thermal conditions that reduce the die chilling effect on the molten liquid metal, thus resulting in less thermal gradient during molten metal solidification and finally reduced residual stresses. The decreases of the reduction rates of residual stress with increases of initial residual stress values are due to greater obstacles to be overcome in more dense product resulting form greater, nonuniform deformation occurring with increased pressure application and/or higher thermal cooling gradients.

3.1.2 Stress-Relief Temperature Effects on Residual Stresses

Figure 2 shows the effectiveness of stress-relief heat treatment in reducing residual stresses in squeeze-cast aluminum alloy rods. The residual stress remaining in the rods, expressed as a percentage of initial values prior to heat treatment, decreases with increase in stress-relief temperature. For the three pressure levels used, the rate of residual stress reduction is low initially; that is, an average of 0.073% per °C for increase in the stress-relief temperature between 30 and 150 °C. There is a remarkable increase in reduction rate of approximately 0.53% per °C between 150 and 300 °C. Above 300 °C, there is a decrease in the stress reduction rate of an average value of about 0.137% per °C. In addition to various reduction rates in residual stress in the castings prepared at various pressure levels, the average reduction rate appears to be independent of pressure levels at temperatures above 200 °C (see Fig. 2). The residual stress is virtually eliminated (i.e., reduced to about 3.3%) when stress relieved at 350 °C for 1 h. The decrease in residual stress with increase in stress-relief temperature may result from the increase in activation energy with increase of stress-relief temperature, resulting in greater induced strain relaxation and, hence, greater residual stress reduction (Ref 7).

3.1.3 Comparison of Die and Stress-Relief Temperature Effects on the Residual Stress and Mechanism of Operation

Figure 3 compares die heating with stress-relief temperatures on the residual stress remaining in the as-cast aluminum alloy rods. Die heating to 300 °C reduces the residual stress by about 45.5% whereas stress relieving to the same temperature reduces the residual stress by about 90%. Stress-relief heat treatment is, therefore, more effective in reducing residual stress of squeeze-cast aluminum rods than die heating above 100 °C. Notice that the reductions of residual stresses for both die heating and stress-relief heat treatment become noticeable above 100 °C.

Since the die heating and stress-relief processes can be regarded as thermally activated processes, then using the exponential law model (Ref 12), the fractional residual stress remaining, F, in the cast aluminum rods is:

$$F = \frac{\sigma_{zm}}{\sigma_o} = C\, e^{-\Delta H/RT} \qquad \text{(Eq 5)}$$

where ΔH is activation energy; T is absolute temperature; R is gas constant; σ_{zm} is residual stress after die heating or stress relief at any temperature, T; and σ_o is residual stress in either as-cast or squeeze-cast rod at 30 °C.

For the 30 to 300 °C temperature range for both the die heating and stress-relief processes, a plot of $\ln(\sigma_{zm}/\sigma_o)$ versus the increase of absolute temperature ($1/T$ in K) shows straight lines at temperatures above 150 °C.

For die heating in the 150 to 300 °C temperature range,

$$\frac{\sigma_{zm}}{\sigma_o} = 18.0e^{-6254/RT} \qquad \text{(Eq 6)}$$

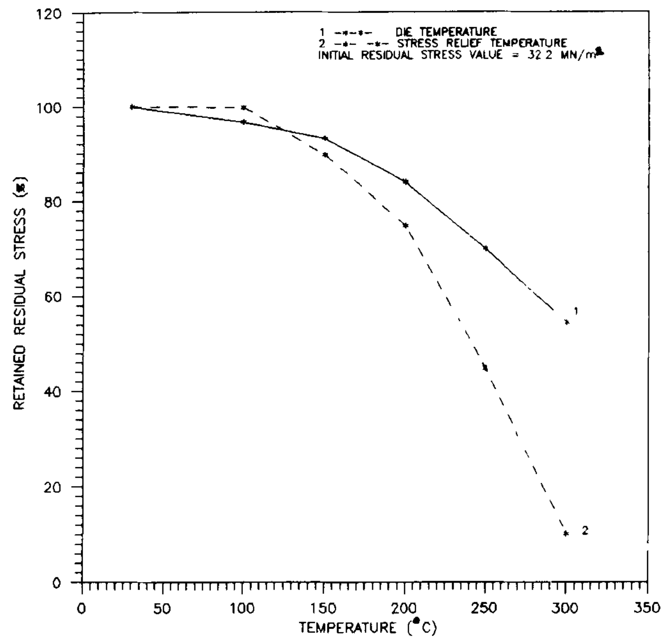
(castings at atmospheric pressure)

$$\frac{\sigma_{zm}}{\sigma_o} = 21.0e^{-5478/RT} \quad \text{(Eq 7)}$$

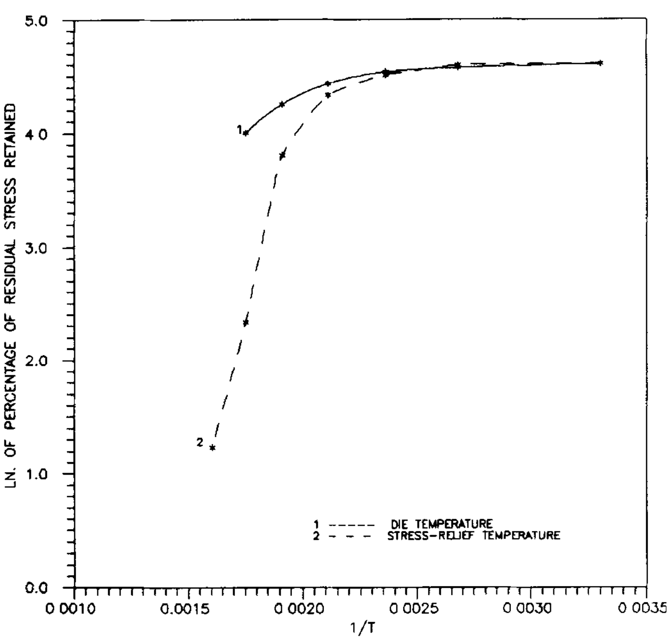
(castings at 80 MN/m² pressure)

$$\frac{\sigma_{zm}}{\sigma_o} = 10.0e^{-8938/RT} \quad \text{(Eq 8)}$$

(castings at 110 MN/m² pressure).



(a)



(b)

Fig. 3 (a) Effects of die and stress-relief temperatures on the residual stress of squeeze-cast aluminum alloy rods (stress relief time = 1 h). (b) Typical graph of ln (σ_{zm}/σ_o) versus $1/T$ for both die and stress-relief temperatures (initial die temperature of 30 °C and no pressure application)

For the stress-relief process, since there is no noticeable casting pressure effect on the residual stress in the 150 to 300 °C temperature range, the exponential law formula for stress-relief process from 150 to 300 °C can be approximated to:

$$\frac{\sigma_{zm}}{\sigma_o} = 2.0 \times 10^{-5}e^{-62{,}967/RT} \quad \text{(Eq 9)}$$

Using the straight portion of the plot of ln(σ_{zm}/σ_o) versus $1/T$ (K), (see Fig. 3b), the average activation energies, ΔH, for die heating and stress-relief processes within the temperature range above 150 °C are, respectively, 6.87 and 63.0 kJ/mol based on Eq 6 to 9. The apparent activation energy of 63.0 kJ/mol for stress-relief processes over the test temperature range of 150 to 300 °C suggests that the dislocation glide-point defect interaction mechanism is operative for the stress-relief process because the activation energy (Ref 11, 12) of about 67.0 to 79.0 kJ/mol for aluminum supports this mechanism within this temperature range. The lower activation energy of 6.87 kJ/mol for the die heating process suggests that migration of vacancies is the operative mechanism. The exponential law model thus supports the earlier explanation given in section 3.1.2 that increase in the activation energy is responsible for decrease in residual stresses as the stress-relief temperature increases.

3.2 *Mechanical Properties*

3.2.1 Die Temperature Effects on Mechanical Properties

Figure 4 shows the effect of die temperature on the ultimate tensile strength, whereas Fig. 5 shows the change in hardness of squeeze-cast aluminum alloy rods. Die temperatures reduce the values of UTS and hardness of castings made under no pressure application and applied pressures, but at varying rates. The re-

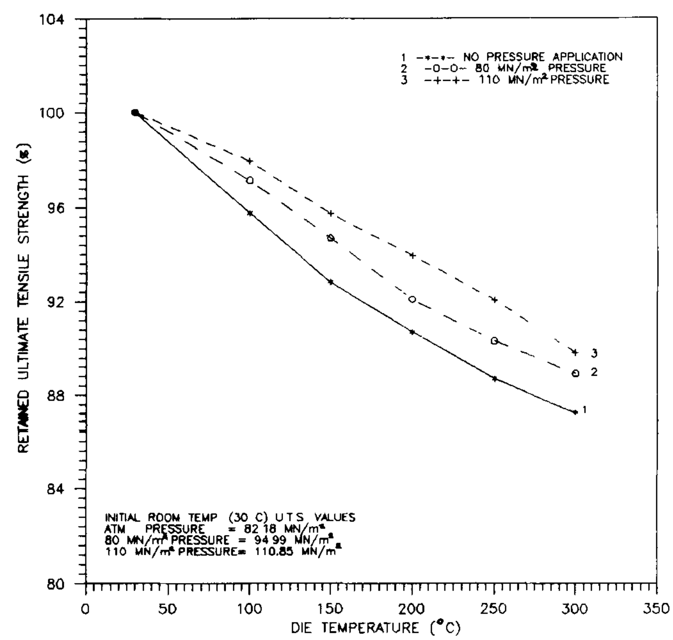


Fig. 4 Effect of die temperature on the ultimate tensile strength of squeeze-cast aluminum alloy rods at the indicated pressures

duction in values decreases with increase in pressure level applications. The general trend of the die heating effect is a reduction in hardness as the die temperature increases (see Fig. 5); the maximum reduction occurs in the castings made without pressure application. The reduction rates are lower at temperatures between 30 and 200 °C, but faster at temperatures between 200 and 300 °C. The reduction in hardness change rate is lowest in castings prepared at 110 MN/m^2 but highest in castings with no pressure application, although in all cases an abrupt change (increase) in hardness reduction rates occurs above 200 °C. The reduction in hardness rate is about twice as much within the range of 200 to 300 °C when compared to the reduction rate between the temperatures of 30 and 200 °C for all three pressure application levels investigated. This suggests that die heating should be limited to a maximum of 200 °C for the alloy investigated to avoid excessive hardness reduction. Figure 6 shows the die heating effect on elongation of squeeze-cast aluminum rods. Elongation increases with increase in die temperature for all the pressures investigated. The highest effect is observed in castings made without pressure application whereas the lowest effect is in castings made with 110 MN/m^2 pressure application. The increase rates are lower at die temperatures between 30 and 200 °C and faster at temperatures above 200 °C. The reduction in strength and hardness is characterized by increase in ductility.

3.2.2 Stress-Relief Temperature Effects on Mechanical Properties

Figure 7 shows the variation of ultimate tensile strength with increase in stress-relief temperature whereas Fig. 8 shows that of change in hardness with stress-relief temperatures. Stress-relief heat treatment reduces the two properties at various rates from stress-relief temperatures of 100 to 350 °C for castings made with or without pressure application. For the three pressure levels used, the rates of reduction in UTS are low initially, between 100 and approximately 200 °C, but they increase sharply, by as much as ten times, above 250 °C. A sharp increase in the reduction rate in UTS above 250 °C suggests that 250 °C is adequate for stress relieving the alloy tested if strength and hardness are not to be seriously impaired.

The reduction in hardness rate also is low initially and increases abruptly at the stress-relief temperatures above 250 °C (see Fig. 8). Strength and hardness are reduced by an average of 8 and 11%, respectively. This observation further supports the recommendation for stress relief of squeeze-cast aluminum alloy rods at 250 °C because there are no appreciable reductions of strength and hardness at these relief temperatures, and the residual stress is substantially reduced. Figure 9 shows the effect

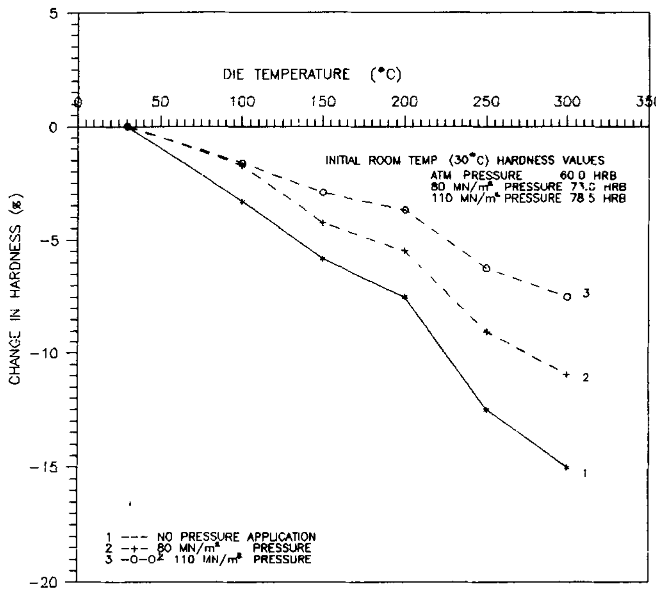


Fig. 5 Effect of die temperature on hardness of squeeze-cast aluminum alloy rods

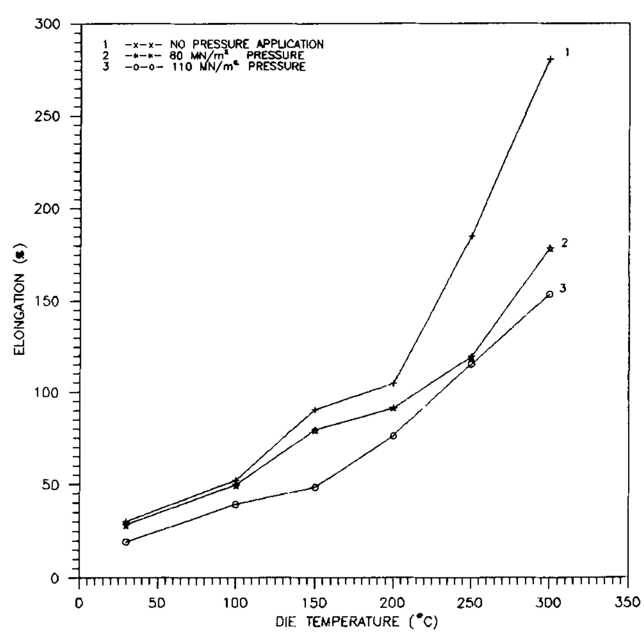


Fig. 6 Effect of die temperature on the elongation of squeeze-cast aluminum alloy rods

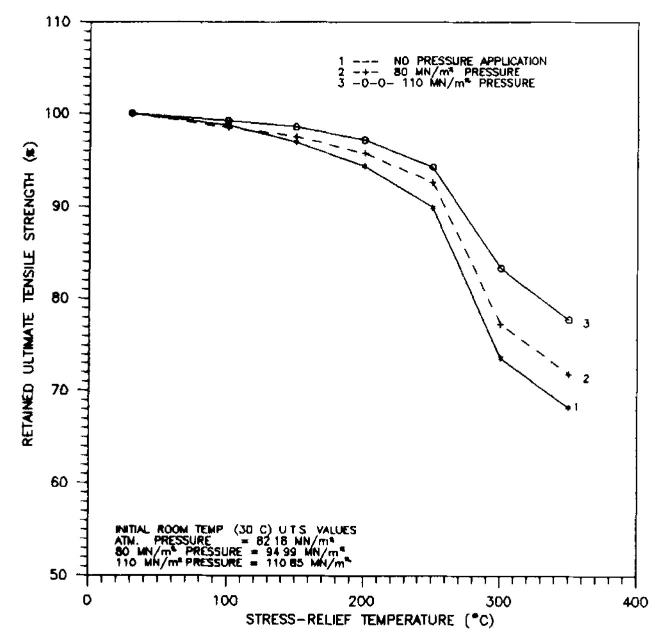


Fig. 7 Effect of stress-relief temperature on the ultimate tensile strength of squeeze-cast aluminum alloy rods at indicated casting pressures

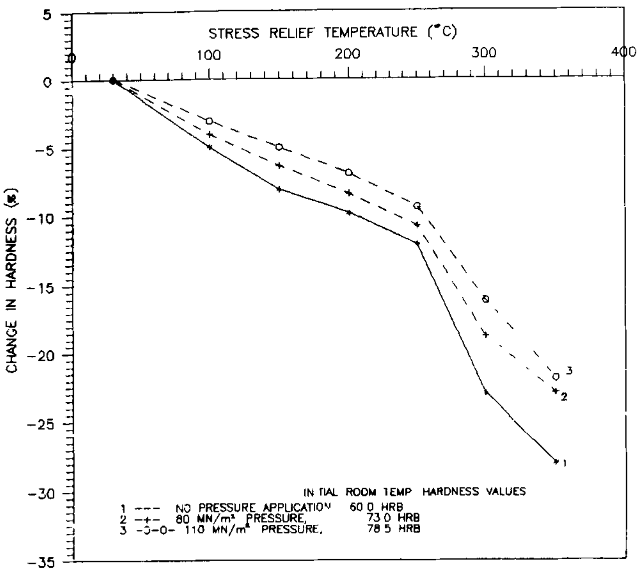


Fig. 8 Effect of stress-relief temperature on hardness of squeeze-cast aluminum alloy rods at indicated casting pressures

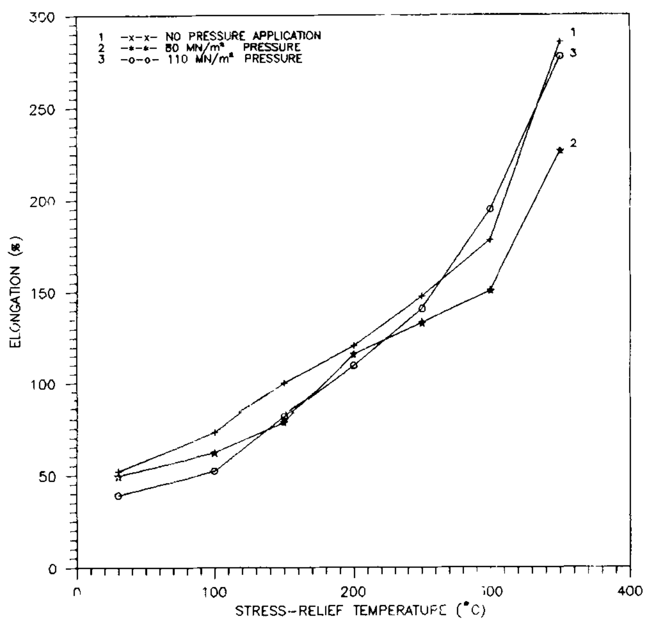


Fig. 9 Effect of stress-relief temperature on the elongation of squeeze-cast aluminum alloy rods

of stress-relief temperature on the squeeze-cast aluminum rods. Elongation increases with increase in stress-relief temperature as expected, but to varying degrees at different pressure applications. A higher increase in the rate of increase in ductility (elongation) is observed at temperatures above 250 °C.

4. Conclusions

Die heating, like stress-relief heat treatment, reduces the residual stresses, mechanical properties, UTS, and hardness, of squeeze-cast aluminum alloy rods, but to different reduction values. Stress-relief heat treatment is much more effective than die heating in reducing the residual stress. The residual stress of squeeze-cast aluminum alloy rods is virtually eliminated when they are stress relieved at 350 °C for 1 h with considerable reduction in strength and hardness. To avoid substantial reduction in strength and hardness, a stress-relief temperature of about 250 °C is recommended, which reduces the residual stress level by more than half of the initial value with a tolerable reduction level in strength and hardness. Die heating to a maximum of 200 °C is also recommended; it is considered sufficient to strike a balance between the need for heat to prevent premature solidification, thermal fatigue, and cold lapse and reduction in strength and hardness resulting from die heating.

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