Effect of casting speed and delay time on the residual stresses in centrifugal casting of aluminium rods

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Abstract

Longitudinal slitting technique has been employed to determine the residual stresses in centrifugal cast aluminium rods. Residual stresses were found to decrease with increase in casting speed in the centrifugal casting. The residual stresses of the aluminium rods cast at speeds of 100, 200, 300, 400 and 500rpm and at zero (0) second delay time have lower residual stresses as compared to those cast at the same varying casting speeds at ten (10) seconds delay time. At the different casting speeds, residual stress ratio (γ) was found to decrease with increase in the casting speeds with values of 40.91%, 31.82%, 22.73%, 13.64% and 9.09% at zero second delay time, while at ten seconds delay time the residual stress ratios were 68.18%, 59.09%, 54.55%, 50.00% and 36.36% respectively. Reduction in residual stress with increase in speed and delay time is attributed to the greater centrifugal forces created by the increasing casting speeds on the solidification of the molten aluminium.

Keywords

Residual stresses; Centrifugal casting; Aluminium; Longitudinal slitting; Delay time; Stress ratio; As-cast; Solidification

Introduction

Residual stresses are system of stresses existing in a workpiece when it is free from external forces. They are caused during metal forming processes in which strains occur in different or opposite directions within the workpiece. They are also generated as a result of inhomogeneous (non-uniform) plastic deformation, when a workpiece is subjected to cold and hot working processes as in rolling and cold drawing [1].

Thermally generated residual stresses are caused as a result of localised uneven cooling or heating processes as in welding, heat treatment and casting processes. The effects of residual stresses that are not controlled are dangerous to the reliability of the part performance.

In service, the associated residual stresses may combine with applied stresses to cause unexpected failure or to shorten the component life span. Therefore, it is important and essential to determine the residual stresses, so as to improve the design of engineering component, durability prediction and the prevention of failure when the parts are in service.

Residual stresses in cast parts occur due to inhomogeneous plastic deformations. While cooling to room temperature, elastic strains corresponding to the residual stresses are introduced. This is due to temperature gradients within the casting, contraction obstruction of the metallic die material and change of structure accompanying change of volume during solidification [2].

Casting is a process of melting of metal, pouring of molten metal into a mould cavity and allowing it to solidify so as to achieve the required shape [3]. Among the many casting processes, centrifugal casting is often used for large cylindrical parts because of its ability to produce the parts with a great degree of complexity, accuracy, and at the same time meeting the economies of scale. Centrifugal casting makes use of a permanent mould that is rotated about its axis at a known speed as the molten metal is poured [4].

Residual stresses are difficult to calculate with precision by analytical method, they are therefore determined by measurement. Various techniques have been developed for residual stress measurement [5], for different types of components these include: sectioning, longitudinal slitting, hole-drilling, Sach’s boring, deflection etching methods can be applied to determine residual stresses in cast parts and structural members as well as the use of ultrasonic, magnetic, electrical and X-ray or neutron diffraction methods [6].

Longitudinal slitting technique is one of the techniques employed in the determination of residual stresses in a cylindrical rod. This involves the making of longitudinal slit in a specimen, such as rod pieces. Under the influence of residual stresses the slit end closes or opens up. The slit opening is measured with micrometer gauge or vernier caliper.

The magnitude of the residual stresses as a result of bending moments in the pieces of the cast metal is directly proportional to the slit opening and can be calculated by direct substitution into a suitable formula [7, 8].

The technique was used to determine the longitudinal residual stress in solid rods from a single measurement of opening of a longitudinal slit [9]. In order to get the correct values of the longitudinal stresses, additional slit openings are created on the specimen. This additional slit opening is called corrected adjusted slit opening, it involves slit opening's correction due to local stress relief at the region beyond the slit length and due to frictional heat generated in the course of slitting operations.

The main objective of this research is to investigate the effect of centrifugal casting parameters of speed variation and delay time on the residual stresses retained in the castings of aluminium rods by Longitudinal Slitting Method.

Material and method

The materials and equipment used were aluminium scrap, vertical centrifugal casting machine, thermocouple, digital tachometer, silica sand, lateritic ant hill, water, micrometer gauge, v-block, and vernier caliper.

The analysis of composition of the aluminium scrap used for the study was carried out at National Geological Survey Agency, Kaduna, Nigeria and given in Table 1.

Table 1. Percentage composition of aluminium (Al) scrap

Al	Fe	Si	Zn	Mn	Ti	Cl	K	Ca	Cr	Ni	Cu	Ag	Pb
93.11	0.77	0.31	0.81	0.24	0.06	0.18	0.17	0.31	0.03	0.10	0.67	0.6	0.08

The vertical centrifugal machine used [10] has a torque of 21Nm; centrifugal force of 3.21 kN and a power of 854.7W (1.5hp) is shown in Figure 1.

Moulding sand was prepared using silica sand, lateritic ant hill mixed with 8% water to aid cohesiveness of the sand particles.

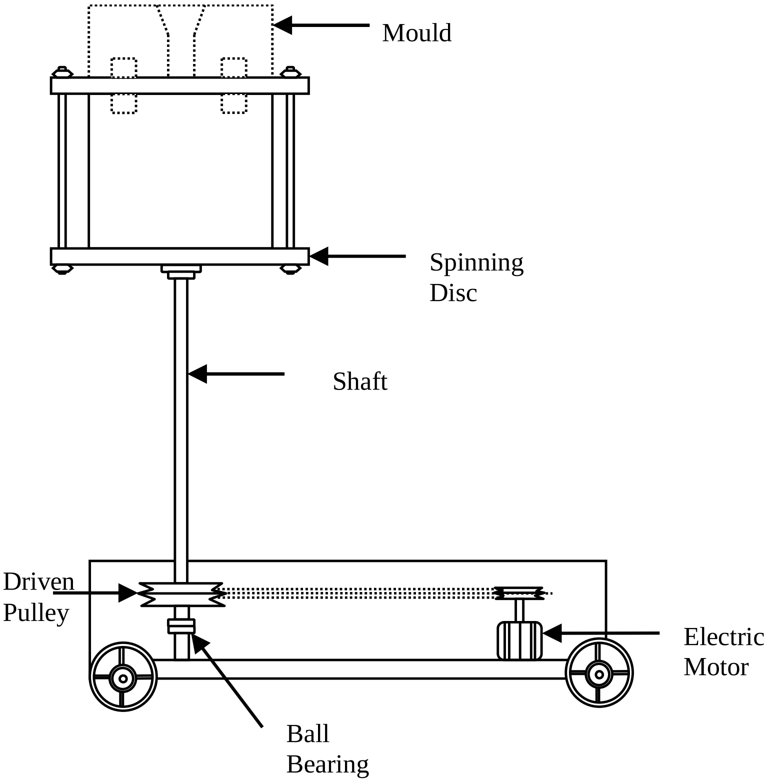

Figure 1. *Schematic diagram of vertical centrifugal casting machine*

Table 2 shows the percentage composition of mould material used.

Table 2. Percentage composition of the mould material

Material	**Composition (%)**
Lateritic ant hill	40
Water	8
Fine sieve silica sand	52

The operations involved in the study are shown in Figure 2. The patterns were made of solid cylindrical shape tapered from 15 to 20mm end diameters and 90±0.2mm length using seasoned wood with provision in the dimensions to take care of shrinkages and contractions of the solidifying metal melt. Sand moulds were made using the moulding sand, patterns and moulding boxes and allowed to dry before pouring of molten aluminium.

A coke-fired furnace was used for the melting of the aluminium scraps. The molten metal was poured at 710°C through the sprue into the mould using a ladle. The mould was rotated on the centrifugal machine after the required volume of aluminium has been poured into it for ten minutes depending on the required condition of the specimen of the cast needed (rotation speed and delay time).

Cast specimens were produced at zero (0) second delay time and ten (10) seconds delay times for varying speeds of 100, 200, 300, 400 and 500 rpm including as-cast specimen

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as shown in Table 3. Each cast specimen was allowed to cool for thirty minutes before removal from the machine.

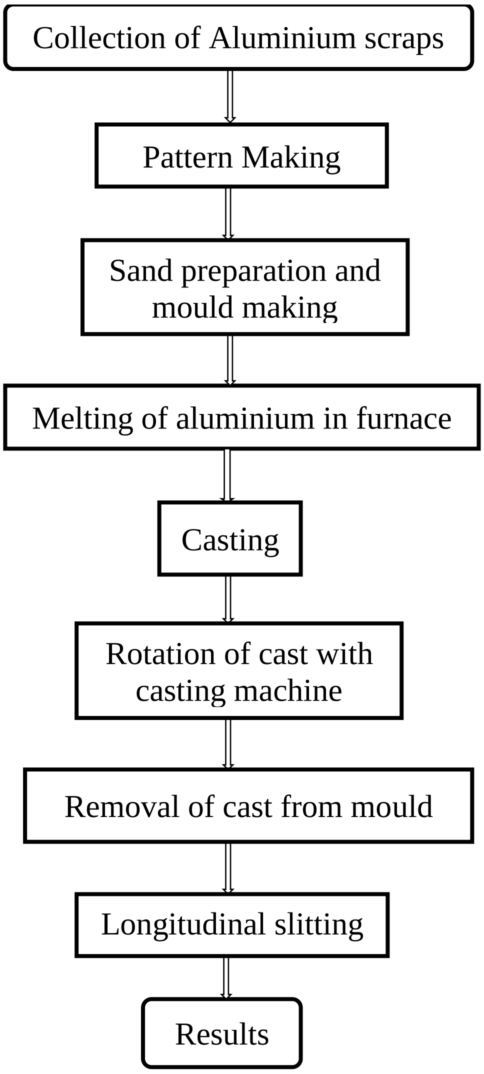

Figure 2. *Sequence of experimental operations*

The specimens produced were prepared for longitudinal slitting technique test. Annealing of the as-cast specimen was carried out by heating the specimen in an electrical resistance furnace to a temperature of 350°C and soaked for 30 minutes.

The annealed specimens were allowed to cool in the furnace. The purpose of annealing the specimen from as-cast specimen was to account for residual stress introduce by sawing effect as annealed specimens were taken to be residual stress free.

The tapered cylindrical aluminium specimens were initially marked longitudinally through the mid-planes with the aid of a height gauge at suitable intervals along its length. Using the vernier caliper, the diameters at different points along the length were measured and recorded.

Table 3. Identification of cast specimens

Specimen	Speed of Castings (rpm)	Delay time (seconds)
A	100	0
B	200	0
C	300	0
D	400	0
E	500	0
F	100	10
G	200	10
H	300	10
I	400	10
J	500	10
K	As Cast	
L	Annealed Specimen	

The specimens were slit longitudinally through the mid-axis as shown in Figure 3 over a length of 65mm using a hand hack saw with a blade of 0.5mm thick and the slit openings at each marked length was carefully measured using micrometer gauge and recorded. During the slitting operations, lubricating oil was applied on the sawing blade at an interval in other to minimize friction and excessive heat.

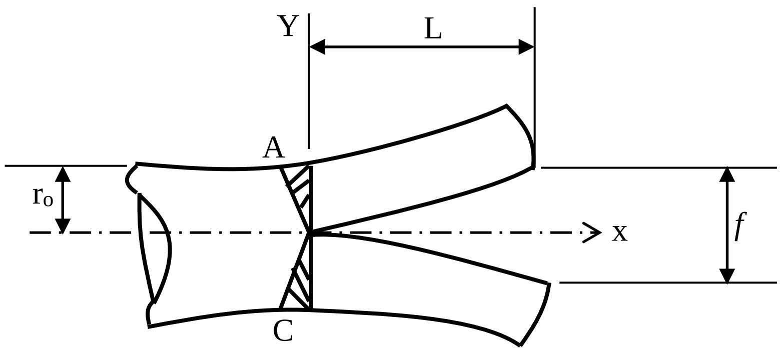

Figure 3. *Slit specimen sketch*

The slitting operation was carried out on the as-cast aluminium rods produced using centrifugal casting machine. To find the corrected slit opening for a given length L, of the as-cast product, the specimen was clamped at the end not slitted, and another slit was made transversely relative to the initial slit at 3 mm distance behind it from position x = 0 as seen in Figure 3. This produced a region of local stress-relief, so that the slit portion of the rod undergoes a rotation, giving the corrected slit opening (f_{1}), of a slit length (L), of the as-cast aluminium specimen. The same process was performed on the other centrifugally cast specimens as to obtain their corrected slit openings.

Additional corrections were needed to be made to the corrected slit openings readings obtained for the various cast specimens. For the as-cast aluminium rods the additional corrections to corrected slit opening was obtained by annealing the specimen and recording the residual stresses introduced during the slitting operation.

The residual stresses due to slitting effects were obtained by measuring the slit openings (f_2) of the annealed specimen. The values of the slit openings (f_2) were subtracted from corresponding values of the corrected slit openings (f_1), as to obtain the adjusted corrected slit opening (f') using equation (1).

$$f' = f_1 - f_2 \tag{1}$$

where f' = adjusted corrected slit opening; f_1 = corrected slit opening of as-cast specimen; f_2 = slit opening of annealed specimen.

The percentage of residual stress (γ) remaining in the specimen as a result of stress relief was calculated by taking the ratios of the adjusted slit openings of the as-cast specimens (f'_{cc}) to corrected adjusted slit opening of centrifugal cast specimen (f'_{ac}), over a given length, L, which was kept constant for all slitting operations carried out as given by equation (2).

$$\gamma = \frac{f_{cc}}{f_{ac}} \tag{2}$$

where γ = percentage residual stress; f_{ac} = as-cast specimen corrected adjusted slit opening; f_{cc} = centrifugally cast specimen corrected adjusted slit opening.

Results and discussion

Figures 4 and 5 present the results of the effect of slit lengths on slit openings of the centrifugal cast and as-cast for zero and ten seconds delay times. While Figure 6 shows the effect of casting speeds on the residual stress ratio for zero and ten seconds delay times. The results of slit openings and percentage residual stress ratio of the cast specimens are presented in Table 4.

Figure 4 and 5 shows the variation of uncorrected slit openings with slit lengths for as-cast and centrifugally-cast aluminium rods produced under various conditions.

For the as-cast aluminium (produced under no conditions), the slit openings increase from 1.28mm to 1.40mm with increase of slit lengths from 15mm to 65mm, while for centrifugally castings under different speeds and delay times (zero and ten seconds), the slit openings increased with increase in slit length up to a maximum slit opening length of 45mm (mid-length of the specimen). Beyond this, the slit openings started to reduce with increase in slit lengths for centrifugally-cast aluminium rods. At the mid slit length, high values of slit openings were obtained for as-cast aluminium specimen than the mid slit length for all the centrifugal castings, except for the casting at 100 rpm and ten seconds delay time, where the value of the slit opening are equal.

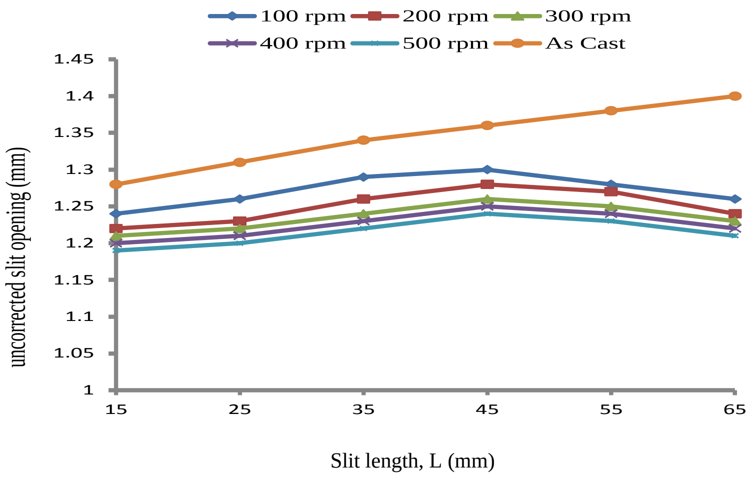

Figure 4. *Effect of slit lengths on slit openings of the centrifugally-cast and as-cast aluminium alloy at zero (0) second delay time*

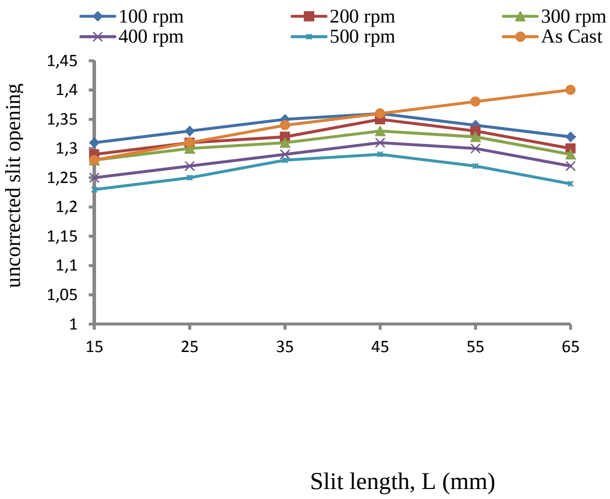

Figure 5. *Effect of slit lengths on slit openings of the centrifugally-cast and as-cast aluminium alloy at ten (10) seconds delay time*

Figure 5 also shows that aluminium alloy cast at ten seconds delay time has a higher slit openings for various speed considered given rise to higher residual stress when compared to the those cast at zero second delay time because the molten metal solidifies slowly in a stationary mould during the delay period but as the rotation of the mould increases cooling of the molten metal is rapid, resulting into faster solidification and hence slit opening decreases giving rise to lower residual stress.

The higher slit openings of the as-cast may be attributed to possible high shrinkage variation due to thermal gradients within the castings, leading to high residual stresses. In centrifugal castings, thermal gradients are eliminated by effect of centrifugal force during solidification. The higher slit openings value in as-cast corresponds to higher maximum residual stress value than in centrifugal cast aluminium products. The maximum slit opening occurred at mid-length of the specimen produced from centrifugal castings, but are not present in the as-cast products possibly due to residual stresses redistribution under the rotational speed of the mould. The residual stresses redistribution under this situation results in smaller inner tensile residual stresses that solidified last in the castings.

Table 4. The slit openings and percentage residual stress ratio of the cast specimens

Specimen	**Uncorrected slit openings, f (mm)**	**Corrected slit openings, f_1 (mm)**	**Corrected adjusted slit openings, f' (mm)**	**% Residual stress ratio, γ**
A	1.26	1.24	0.09	40.91
B	1.24	1.22	0.07	31.82
C	1.23	1.20	0.05	22.73
D	1.22	1.18	0.03	13.64
E	1.21	1.17	0.02	9.09
F	1.32	1.30	0.15	68.18
G	1.30	1.28	0.13	59.09
H	1.29	1.27	0.12	54.55
I	1.27	1.26	0.11	50.00
J	1.24	1.23	0.08	36.36
K	1.40	1.37	0.22	100.00
L	1.17	1.15 (f_2)		

Table 4 shows the slit openings for uncorrected, corrected, corrected adjusted and the corresponding percentages of residual stress ratios at various casting speeds for both zero and ten seconds delay time.

In other to determine corrected adjusted slit opening for each product, value of the slit openings resulting from the slit opening of the annealed aluminium alloy specimen (L) which was taken to be residual-stress free, was then deducted from corresponding value of the corrected slit openings obtained to finally find the adjusted corrected slit opening for each specimen.

Also, in other to determine the percentage of residual stress (γ) remaining in the products as a result of stress relief was based on the ratios of the slit openings of corrected adjusted slit opening for each centrifugal cast specimen A to J to the corrected adjusted slit opening of the as-cast product (specimen K).

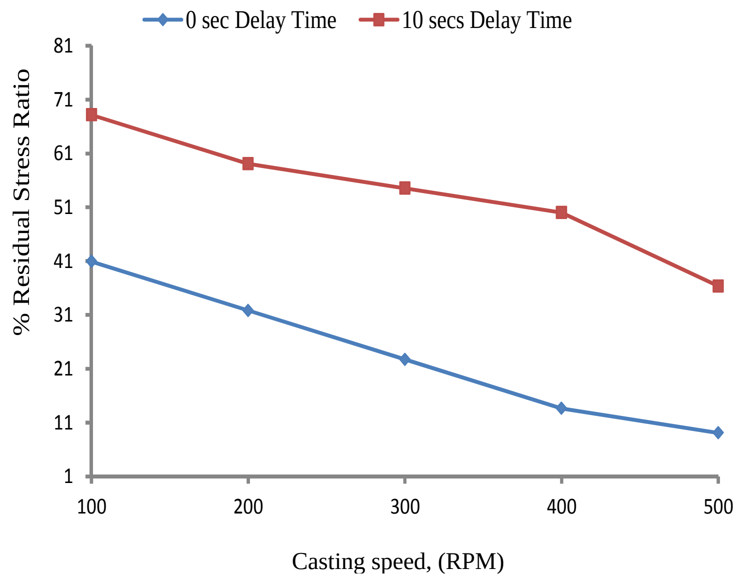

Figure 6. *Effect of various casting speeds on the residual stress ratio,γ, of centrifugally-cast at zero and ten seconds delay time*

Figure 6 shows effect of casting speed on the residual-stress ratios (percentage of the residual stress remaining) of centrifugal-cast to as-cast at zero and ten seconds delay time.

For the various casting speeds, it can be seen that the residual stress ratios, γ, decrease with increase in the casting speed and higher residual stress ratios are obtained at 100rpm for both zero and ten seconds delay times investigated. Reduction in residual stress with increase in casting speed may be attributed to the fact that in centrifugal casting, rotation speed of the mould plays an important role.

The residual stress ratio for various castings speed 100rpm to 500rpm at zero delay time gives 40.91%, 31.82%, 22.73%, 13.64% and 9.09% while at ten seconds delay time gives 68.18%, 59.09%, 54.55%, 50.00% and 36.36% .

As the speed increases, it affects rates of solidification of the molten metal, the centrifugal force acting on the casts is increased by a squared proportion, which may results to promote better grain refinement and improved mechanical properties [11].

Conclusions

The investigation has revealed that proper combinations of delay time and casting speed are required to achieve lower residual stresses in centrifugal-cast products. The results shows that residual stresses of centrifugal cast aluminium rods increased with slit length up to a mid-length of 45mm before further decrease, while for the as-cast products, the residual stress increased with increase in slit length. Higher residual stresses occurred in the as-cast aluminium rods than that of centrifugal-cast aluminium rods, except at 100rpm 10 seconds delay time. This gives centrifugal casting operation an additional advantage of lower value of residual stresses to improved mechanical properties of centrifugal cast aluminium rods. The residual stresses of the aluminium casts at speed of 100, 200, 300, 400 and 500rpm at zero (0) second delay time are lower as compared to those cast with the same casting speed at ten (10) seconds delay time. For the various casting speeds, residual stress ratios,γ, decrease with increase in the rotational casting speed. Reduction in residual stress with increase in casting speed may be attributed to the greater centrifugal forces on the solidifying molten aluminium with casting speed increase.

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