EFFECT OF COOLING RATE DURING CENTRIFUGAL CASTING ON THE CREEP RUPTURE STRENGTH OF 13 % Cr STEEL

A. R. EL-DESOUKY*

ABSTRACT:

It is known that 13 % Cr steel is one of the most economical stainless steels. It is, however, inferior to austenitic stainless steels in creep rupture strength above 600°C.

Therefore, attempt has been made to improve the creep rupture strength of 13 % Cr steel.
This work is principally concerned with the investigation of the influence of the cooling rate during centrifugal casting on the creep rupture strength of 13 % Cr steel.

The results obtained are as follows:

1. The creep rupture strength of 13 % Cr steel is improved by increasing cooling rate during centrifugal casting.

2. The higher cooling rate promotes: large sizes of columnar structures, fine dispersion of the precip- itates, and retardation of coalescence of precipitated particles. These are shown to have a beneficial effect on the creep rupture strength.

INTRODUCTION:

Pressure-containing components for power generating plant must operate for considerable periods at elevated

* Lecturer, Dept. of Design and Production Engineering, Faculty of Eng., and Tech., Menoufia University.

temperatures. Design approaches for these components
generally involve the application of an allowable stress
σ_a which permits calculation of a minimum wall thickness
(mwt) as:

$$mwt = PD / (2 \sigma_a E + P) \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

Where D is the outside diameter, P is the internal pressure,
and E is an efficiency factor.

Values of the allowable stress for creep applications
are determined from extrapolating the appropriate material's
uniaxial creep or creep-rupture data. However, safety
factors are applied due to uncertainties involved with
this approach.

Short-term uniaxial creep rupture data can, in general,
be described by a power-law dependence on stress. Simple
extrapolation of this information is known to overestimate
longterm lifetimes /1/.

The use of parametric techniques, e.g., the Larson-Miller
procedure /2/ allows data extrapolation of only approxi-
mately three times the longest rupture life /3/.

The application of finite element stress analysis technique
requires a more detailed material description.

To provide engineers with material information,
many methods of describing strain/time behaviour have
been suggested /4/.

Recentely, the θ projection concept has been suggested
which considers creep strain ε to be the sum of two
competing processes as follows /5/.

$$\varepsilon = \theta_1 (1 - e^{-\theta_2 t}) + \theta_3 (e^{\theta_4 t} - 1) \ldots \quad \ldots \quad \ldots (2)$$

Where θ_1 and θ_2 define the primary or decaying strain rate

component and θ_3 and θ_4 describe the tertiary or acc-
elerating strain rate component of the creep curve.

Extrapolation of θ parameters for long times has been
applied for 1/2 Cr- 1/2 Mo-1/4 V ferritic steel at 565°C/6/.

The factors affecting tube life operating under creep
conditions have been illustrated in Fig. 1.

Temparature-Dependent Material Properites	Tube Size	Operating Conditions
1. Thermal conductivity. 2. Thermal expansion. 3. Elastic modulus. 4. Poisson's ratio. 5. Stress-rupture life. 6. Creep response.	1. Diameter 2. Wall thick- ness.	1. Temperatures. 2. Pressures. 3. Type of working cycles: a- heating rate. b- duration. c- cooling rate. 4. Number of cycles.

Fig. (1): Factors affecting tube life under
creep conditions.

Creep deformation behaviour can be described by some
sets of equations so that the creep strain accumulated
during any time interval at a specific stress and temper-
ature can be readily calculated. This is one aspect of
developing constitutive equation for creep analysis.
A number of equations have been given in the literatures
/7 & 8/.

Creep damage leading to failure in ferritic steel at
service operating conditions results from /9/:
i) Structural coarsening leading to a continuous reduction
in creep strength during exposure.

ii) Intergranular creep cavitation.

Both processes normally occur simultaneously; the prevalence of either is determined by the initial state and purity in addition to conditions of stress and temperature.

In this work an attempt was made to improve the creep rupture strength of 13 % Cr steel.

The present work investigated the effect of cooling rate during centrifugal casting of 13 % Cr steel on the creep rupture strength. Variations in cooling rates during solidification were obtained by using a specially designed laboratory scale centrifugal casting machine, by changing the rotating speed, and by using different types of ingot moulds.

EXPERIMENTAL PROCEDURE:

Four heats of 5 Kg each were air-melted in 20 KVA high frequency induction furnace; the chemical composition of the heats cast under different cooling rates is shown in Table 1.

Two types of moulds were employed (graphite & copper); in addition, the laboratory scale centrifugal casting machine was designed to give two different rotating speeds, 1400 and 1700 r.p.m corresponding to 50 g and 100 g respectively, where g is the gravity acceleration.

The dimensions of the centrifugally cast tubes were 120 mm length, 100 mm outside diameter and 60 mm inside diameter.

An alumel-chromel thermocouple was inserted in the mould wall to touch the outer surface of the cast tube and the cooling rate during centrifugal casting was measured.

Specimen	Casting Condition		Chemical Composition (wt. %)						Cooling rate °C/min
	Mould Type	Centr- ifugal force	C	Mn	Cu	Ni	Cr	Mo	
A	graph- ite	50 g	0.06	0.42	0.15	0.39	13.0	0.12	180
B	graphite	100g	0.08	0.67	0.12	0.42	13.4	0.22	370
C	Copper	50 g	0.07	0.53	0.20	0.53	13.6	0.10	400
D	Copper	100g	0.05	0.73	0.11	0.48	13.2	0.28	810

Table. (1):   Chemical composition of 13 % Cr steel
              with the cooling rate according to
              casting condition.

The creep rupture test specimens were machined long-
itudinally from the wall section of each centrifugally
cast tube.

Creep tests were conducted on simple lever-arm creep
machines accurate to within 0.05 % load.   The loading
system incorporated a series of universal joints in order
to reduce axial bending in the specimens due to non -
axiality of loading.   Tests were carried in air and
the specimens were heated in a resistance furnace cont-
rolled by proportional temperature controller to ± 1°C
along the gauge length.   Cylinderical specimens (6.6 mm
dia. x35 mm gauge length) had ridges at the ends of gauge
length for attaching the extensometry.   Extension was
determined by means of an electrical LVDT transducer
giving a strain sensitivity of 5×10^{-5}.

The creep rupture tests were conducted at 600°, 700°,
and 800°C for time periods extending up to 3000 hr.

RESULTS   AND   DISCUSSION:

The calculated results of the measured cooling rates during the solidififation of the centrifugally cast tubes are shown in Table 1.   The table shows a wide variation in the cooling rates depending upon the type of mould employed and the rotating speed of the centrifugal casting machine.   These variations are attributed mainly to the heat conductivity of the mould material as well as to the rate of cooling of the mould surface during rotation.

The macrostructure of the cross section of the cast tubes demonstrated the typical structure of an outer layer of chill crystals, then the columnar grains varying in their length and width (according to cooling rate) and the equiaxed grains along the inner side.

Fig. 2. shows the variations of the size of columnar grains in terms of L and D (where L is the length of column and D and is its width) with the respective cooling rate.
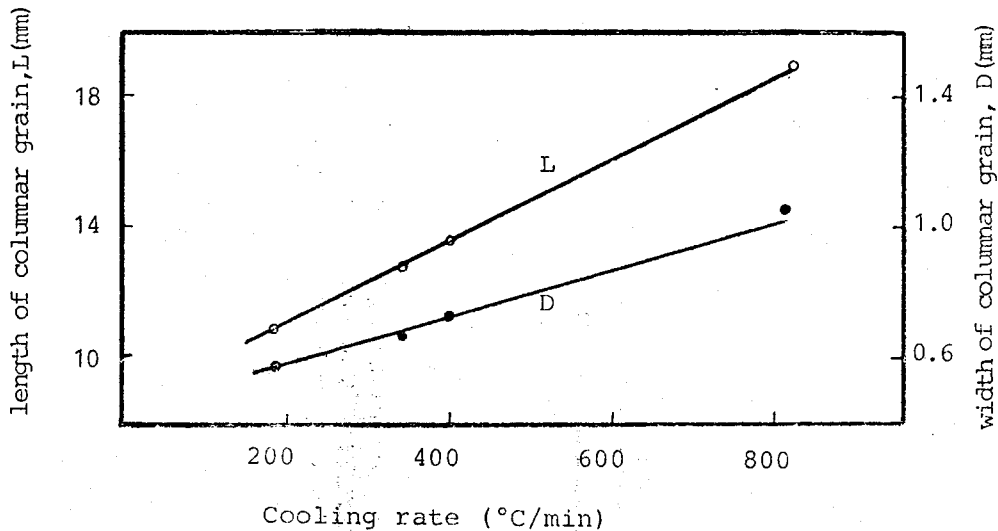

Fig. (2): The variation in length (L) and width (D) of the columnar structure with cooling rate.

From which, L and D increase with increasing cooling rate. These results seem to be inconsistent with the well known studies on: 0.6 % C steel /10/, Al-alloys /11/, and Cu-alloys /12/ which say that the lower the cooling rate, the larger the grain size.

However, the latter is concerned with "static" casting conditions while in centrifugal casting many other factors interact together and naturally the result might be different. Quantifying the latter indicator remains for future work /13/.

The X-ray diffraction analysis of the electrolitically extracted residues shows that the fast colling rate tube (D) contained $(Cr, Fe)_{23} C_6$ and $Cr_2 N$, while the residues of the slow colling rate tube (A) contained a considrable amount of $(Cr, Fe)_7 C_3$ /13/.

The creep rupture tests of each tube at 600°, 700°, and 800°C are shown in Fig. 3. Examination of the data presented in the figure reveals a number of items of interest regarding the effect of different cooling rates. For example, at 600°C, the creep rupture strength does not show any remarkable change with increasing cooling rate, while at higher temperature, 700°C, the creep rupture strength gradually increased with the increase in cooling rate.

With a further increase in the test temperature to 800°C, the creep rupture strength of the high cooling rate tube (D) is approximately twice the creep rupture strength of the low cooling rate tube (A).

The creep rupture data are plotted to give the Larson-Miller parameter master curves for A and D specimens as in Fig. 4.
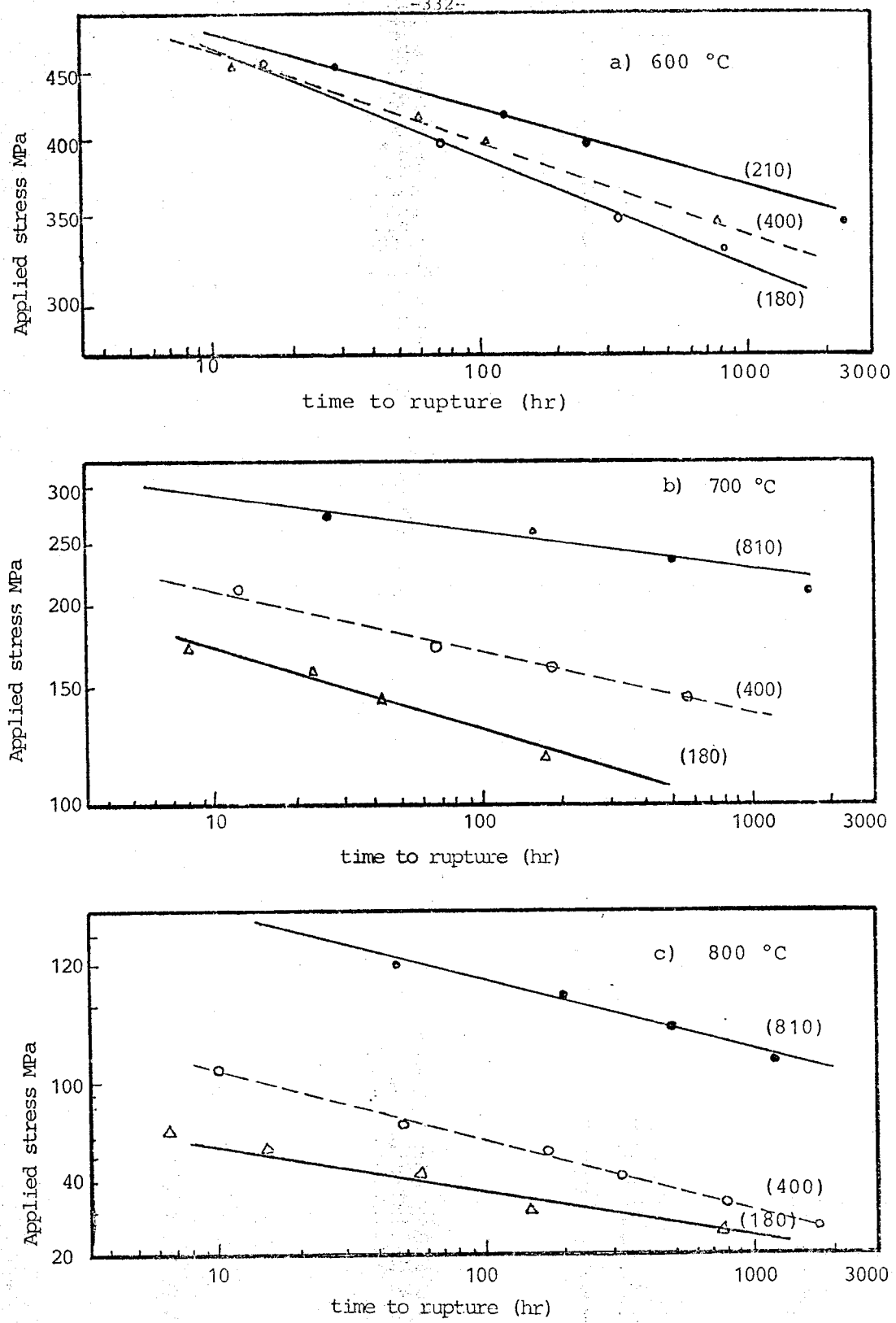
Fig. (3): Creep rupture tests at 600°C, a) 700°C ,
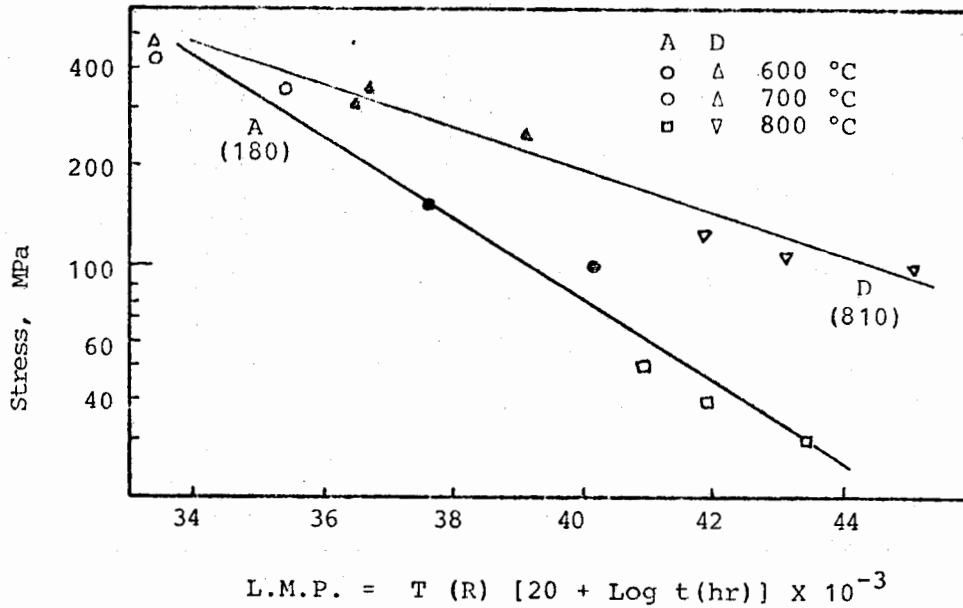b) and 800°C c)-(Cooling rate during casting
in °C/min).

Fig. (4): The Larson-Miller Parameter (L.M.P) master
curves. (Cooling rate during casting in
°C/min).

Again this confirms that with higher temperatures and
prolonged times, the creep rupture strength increases
with the increase of cooling rate during centrifugal
castings.

Several microstructural variables can influence the
creep rupture strength of 13 % Cr steel. The most imp-
ortant of these which improve the creep strength with
increasing cooling rate are:
i)   Solid solution strengthening,
ii) Dispertion hardening,
iii) Dislocation density, and
iv) Grain size & grain morphology.

Regarding the first factor, it was found /14/ that steel with a higher cooling rate of solidification, contained in its ferritic matrix dissolved carbon about 0.06 wt. % higher than that in steel with a low cooling rate. This is in agreement with that quoted for Al-Fe alloys /11/.

Increasing cooling rate during centrifugal casting led to a fine dispertion of $(Cr, Fe)_{23} C_6$ and $Cr_2 N$ precipitates. Strong interactions between dislocations and these precipitates are quite possible indicating that dispertion hardening was prominent in determining creep strength.

Honeycombe /15/ has reviewed the direct evidence for the nucleation of alloy carbide and nitride particles at the $\gamma - \alpha$ interfaces during transformation of austenite.

The particles formed during interphase precipitation, or in ferrite after the phase transformation, can be very small, on the order of 5 nm, and are therefore very effective as strengthening agents /16/. The spacing of the precipitate planes decreases as the cooling rate increases /17/.

In addition, Sidey /18/ has shown that the secondary creep behaviour of 1 Cr-Mo-V steel with a microstructural consisting of 10 % bainite and 90 % ferrite can be explained in terms of recovery controlled creep. The rate could be expressed in terms of the following equation:

$$\varepsilon^{\circ} = A (\sigma_a - \sigma_o)^{3.5} \exp (- 240000/RT) \ldots (3)$$

Where A is a constant, σ_a is the applied stress, and σ_o is the friction stress introduced by the VC particle dispertion, which opposes dislocation motion, and which is additive to the normal resistance of the matrix to dislocation flow.

There is no reason to suspect that the above equation does not apply to the creep of 13 % Cr steel studied in the present work.   Thus, increasing cooling rate during centrifugal casting should result in a higher friction stress, σ_o, due to the finer dispertions of alloy carbides and nitrides.

In the examined range of test temperatures, no coalescence of the precipitated particles has been observed. Thus, fine dispertions of the precipitates, resulting from higher cooling rates during solidification (together with solid solution strengthening) are considered as affective means for improving the creep rupture strength of 13 % Cr steel.   The retardation of coalescence of precipitated carbides and nitrides can be an important factor for ensuring high temperature creep rupture strength.

In addition, the observed difference for the high creep rupture strength can be attributed to the variation in the as-cast structure (grain size and grain morphology) as a result of employing different cooling rates. However, the reason why the larger size of columnar grains displays much better creep rupture strength (specimen D) can be interpreted to the interparticle spacing of the precipitates.   The latter was found to be smaller for the tubes with a large columnar size, which would prevent deformation and fracture by creep more effectively than those in the smaller columnar size structure (specimen A).

CONCLUSIONS:
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Attempt has been made to improve the creep rupture strength of 13 % Cr steel. Four heats of 13 % Cr steel, 5 kg each, were centrifugally cast under different cooling rates.

The results obtained are summarised as follows:

1) The creep rupture strength is generally improved by accelerating the rate of cooling during casting.

2) Variation in the cooling rate during centrifugal casting, by employing two different types of moulds and different centrifugal forces, resulted in a considrable change of the size of precipitated particles and of the as-cast structure.

3) In the examined range of test temperatures (600°, 700°, and 800°C) no coalescence of the precipitated carbides and nitrides has been observed. The fine dispertion of precipitated particles as well as solid solution strengthening, resulting from higher rates of cooling, can be an important factor for ensuring high creep rupture strength.

4) The higher cooling rate promotes a large size of columnar structure which has a beneficial effect on the creep rupture strength. This effect can be attributed to the smaller interparticle spacing of the precipitates formed at the boundaries of the large grains and will be effective in preventing deformation and fracture by creep. In addition, cavities will have less chance to be condensed at grain boundaries. Consequently, microcracks formation and their linking up to form macrocracks will be highly reduced.

5) It is proposed to study the effect of Mo and V additions on long-term creep rupture strength of 13 % Cr steel under rapid rates of solidification.

Saudi Arabia and was performed at the Main Thanks
Workshop, Taif.

   With profound gratitude and deep-felt respect
I thank Major General: Murshed A, El-Ammari for his
generous assistance.

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