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Quenching-rate determination for standard steel tensile specimens

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A vertical tube furnace and a four-channel digital storage oscilloscope have been used to determine quench rates for standard tensile specimens of a martensitic stainless steel. The quenching media examined were air, oil and water. Theoretical calculations were made, based on convection heat-transfer approaches, which quantify the heat flow from the specimen surfaces during cooling. Experimental data are in reasonable agreement with predicted values.

1. Introduction

The heat treatment of many engineering metals and alloys typically involves annealing at well-defined temperatures in the range ~ 500–1200 °C for the purposes of solution treatment, tempering, stress-relief, recrystallization, etc., followed by cooling at controlled rates, in order to achieve the desired combination of mechanical properties and microstructure. The magnitude of the cooling rate can be a crucial experimental parameter; for example, in ferrous systems it determines the nature of the transformation products in low-alloy steels [1], and the level of non-equilibrium solute segregation in austenitic [2, 3] and martensitic [4] stainless steels. Rarely, however, are precise cooling rates quoted in laboratory or small-scale component heat-treatment schedules; the principal reason is that the values are strongly dependent on test-piece geometry, alloy composition and the characteristics of the quench medium.

The present paper describes a simplified procedure for calculating cooling rates using the above input parameters. The predictions are compared with experimental measurements made during air, oil and water quenching of flat tensile specimens of a commercial stainless steel.

2. Experimental procedure

The dimensions of the sheet tensile specimens used in the present study are given in Fig. 1; this specimen geometry has been adopted as a standard for many research investigations at the Harwell Laboratory. Test pieces to this specification were die-stamped from an 0.75 mm thick strip of 1.4914 grade 12% Cr martensitic stainless steel of composition as given previously [4], and for which heat-treatment investigations were in progress.

A K-type thermocouple (NiCr–AlNi) was arc-welded to the mid-point of the gauge length using weld metal of melting point exceeding 1000 °C. The specimen was then suspended by a pure chromium wire in the hot zone of a vertical tube furnace located above a bath containing the quenching medium.

A schematic diagram of the experimental arrangement used for the measurement of quench rates is shown in Fig. 2. The thermocouple leads were attached to a Nicolet digital storage oscilloscope (DSO) with four memory channels, and also to a digital voltmeter to provide a direct indication of voltage changes during quenching. The DSO output was fed through a chart recorder to enable plots of thermocouple voltage as a function of time to be subsequently obtained. The DSO was set at 200 ms per signal point on a 100 mV full-scale range, whilst the chart recorder was operated at a chart speed of 1 s cm^{-1} and a voltage range of 0–4 V, to give a suitable amplification of plots.

The furnace was set to a controlled and measured temperature of 620 °C, representing a typical tempering condition for the steel, and the specimen allowed to equilibrate for 30 min. The specimen was then released into the quench bath and the oscilloscope simultaneously triggered, in order to capture the transient voltage signal versus time. Cooling curves were thus obtained for quenches into air, oil and water, and repeated five times per quench medium in order to obtain average data trends.

3. Results

Chart recorder outputs representing typical cooling curves (voltage–time traces) for quenches into air, oil and water are given in Figs 3–5, respectively. These traces were used to calculate mean cooling rate values,

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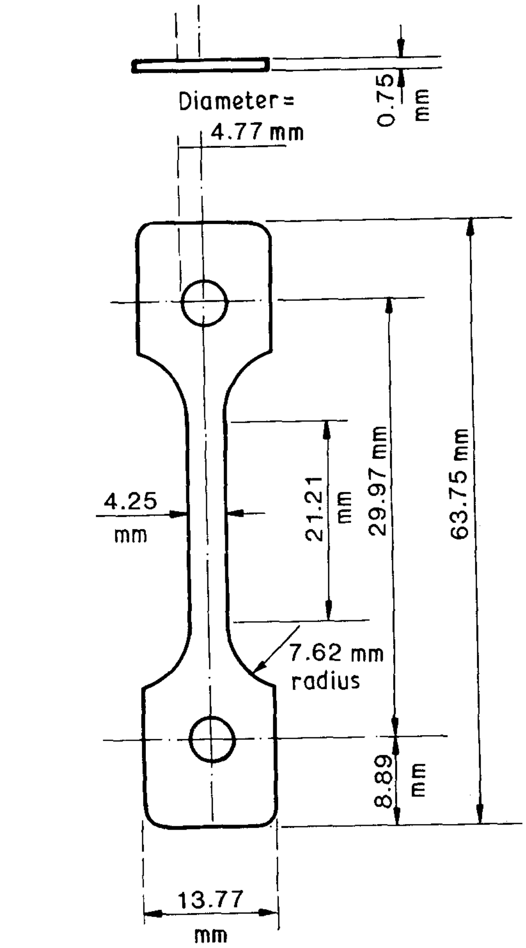

Figure 1 Tensile test-piece geometry.

taken as the slope of the straight line drawn from initiation of quench to the point at which room temperature was reached, as illustrated; these were converted into units of $K\ s^{-1}$ by reference to international standard tables for K-type thermocouples.

The cooling rates thus estimated by this procedure were: (i) air, $47\ K\ s^{-1}$; (ii) oil, $116\ K\ s^{-1}$; (iii) water, $\sim 347.5\ K\ s^{-1}$. Instabilities were noted in the water quench curve particularly during approach to room temperature, implying potential errors in the estimation of this cooling rate.

4. Prediction of cooling rates

Simplified heat-transfer theory can be used to predict the heat loss from plate-shaped objects, where convective heat flow under either turbulent or laminar conditions is dominant [5]. This approach has been adapted in the present studies for the specific situation of quenching of a tensile specimen of the above geometry [6].

The heat flow of the convected medium (i.e. air, oil or water) is characterized by the Prandtl number (Pr), given by

$$\mathrm{Pr} = \mu c_f / k_f \quad (1)$$

where μ, c_f and k_f represent the viscosity, specific heat and thermal conductivity, respectively, of the convected fluid. (Throughout, the subscript f is used to denote materials properties of the fluid and s for that of the solid specimen material.)

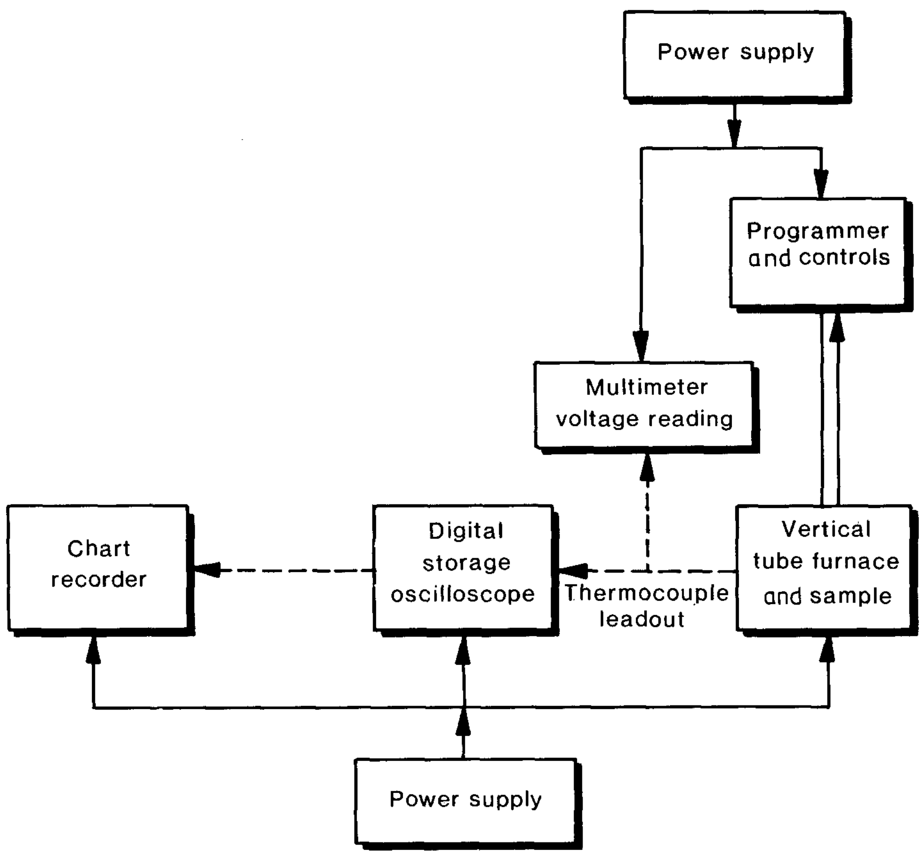

Figure 2 Schematic diagram of equipment layout for quenching rate determinations.

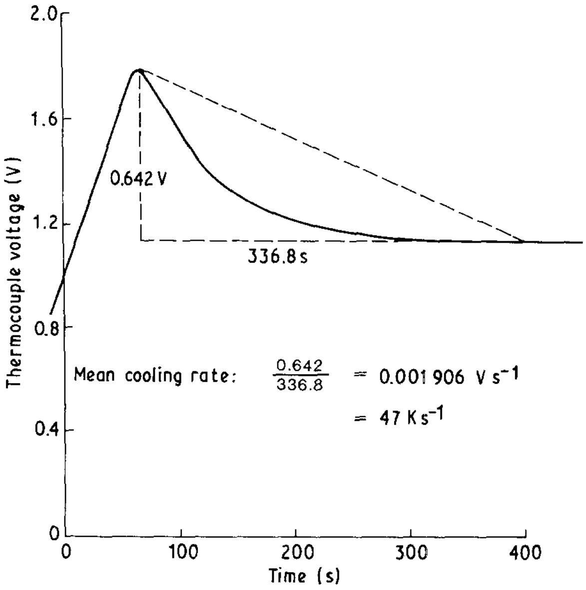

Figure 3 Voltage–time output during air cooling.

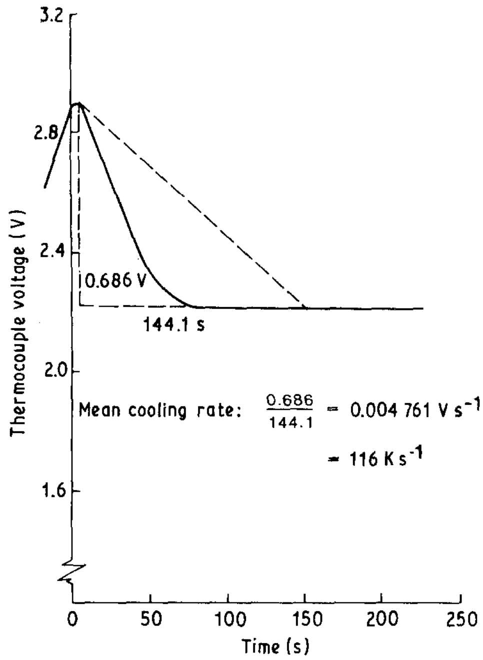

Figure 4 Voltage–time output during oil quenching.

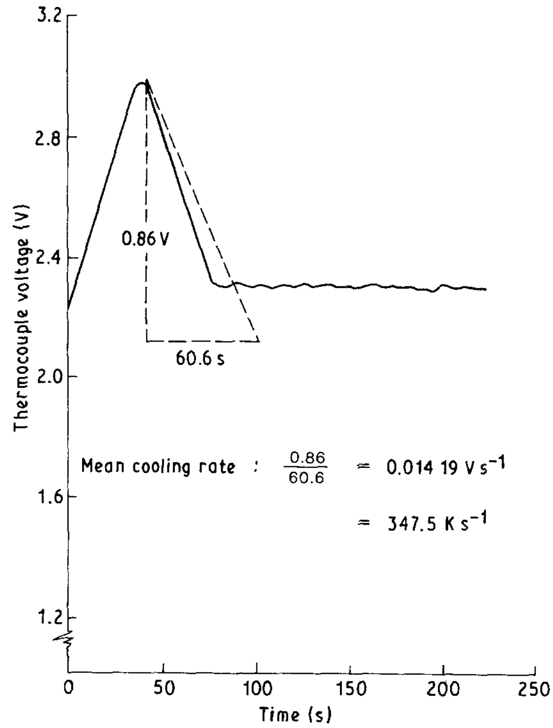

Figure 5 Voltage–time output during water quenching.

The fluid flow around a predefined object with a temperature difference (a) between solid and surrounding convected fluid is described by the Grashof number (Gr) in the equation

$$\mathrm{Gr} = \rho_f^2 a L^3 g\alpha/\mu^2 \quad (2)$$

where ρ_f and α are the density and cubic expansivity of the convected fluid, respectively, g is the gravitational constant and L is the length of the solid from which heat loss is occurring.

The boundary conditions for laminar flow during convection are $10^4 < (\mathrm{PrGr}) < 10^9$, and the flow behaviour is governed by the Nusselt number (Nu), where

$$\mathrm{Nu} = 0.69\,(\mathrm{PrGr})^{1/4} \quad (3)$$

Turbulent flow conditions exist when $10^9 < (\mathrm{PrGr}) < 10^{12}$, and the Nusselt number is then

TABLE I Properties and heat-transfer data for solid (steel) specimen

Density, ρ_s (kg m^{-3})	7833
Thermal conductivity, k_s (W m^{-1} K^{-1})	37.2
Specific heat, c_s (J kg^{-1}K^{-1})	323.4
Gravitational constant, g (m s^{-1})	9.8
Solid/fluid temperature difference, a (K)	600
Gauge length, L (m)	0.021 2
Gauge thickness, x (m)	0.000 75
Surface area of gauge section, A (m^2)	212×10^{-6}
Volume of gauge section, V_g (m^3)	67.6×10^{-9}
Heat capacity of gauge section, C_g (J K^{-1})	0.171

given by

$$\mathrm{Nu} = 0.129\,(\mathrm{PrGr})^{1/3} \quad (4)$$

The convection coefficient (h) can be calculated from:

$$\mathrm{Nu} = hL/k_f \quad (5)$$

and hence the fluid flow rate (U) resulting from convective flow obtained as

$$\frac{1}{U} = \frac{x}{k_s} + \frac{1}{h} \quad (6)$$

where x is the thickness of the solid body and k_s the thermal conductivity.

The rate of heat transfer (Q) is given by

$$Q = UAa \quad (7)$$

where A is the surface area of the solid body.

Finally, the cooling rate (R) is obtained simply as

$$R = Q/C_g \quad (8)$$

where C_g denotes the heat capacity of the solid body (i.e. of the gauge section of the tensile specimen), and is

TABLE II Properties and heat-transfer data for cooling fluids

	Air	Oil (SAE 59 Grade)	Water	
Viscosity, μ (kg m^{-1} s^{-1})	27.34×10^{-6}	0.799	9.58×10^{-4}	
Specific heat, c_f (J kg^{-1} K^{-1})	1054	1880	4189	
Thermal conductivity, k_f (W m^{-1} K^{-1})	41.74×10^{-3}	0.145	0.603	
Density, ρ_f (kg m^{-3})	1.162	88.23	997.8	
Cubic expansivity, α	36×10^{-4}	63×10^{-4}	21×10^{-5}	
PrGr	25.0×10^{4}	4.55×10^{4}	8.67×10^{7}	
	(laminar flow)	(laminar flow)	(laminar flow)	(turbulent flow)
Nu	15.5	10.08	66.6	57.1
Convection coefficient, h (W m^{-2} K^{-1})	30.5	69.0	1893.7	1624
Fluid flow rate, U (W m^{-2} K^{-1})	30.5	69.0	1824.0	1572
Heat-transfer rate, Q (W)	3.88	8.78	232	200
Cooling rate, R (K s^{-1})	22.6	51.3	1356.8	1170

calculated from:

$$C_g = \rho_s c_s V_g \qquad (9)$$

where, ρ_s and c_s are the density and specific heat, respectively, of the solid and V_g the volume of the solid body.

The above analysis was used to calculate values of R induced in the gauge length of the tensile specimen by quenching into air, oil and water. The dimensional parameters L, x, A and V_g required in the equations were taken as the tensile gauge length, specimen thickness, gauge length surface area and volume of the specimen within the gauge length, respectively. Relevant materials properties (at 20 °C) and calculated heat-transfer parameters for the solid (steel) are listed in Table I, together with the specimen dimensions used, whilst materials properties (at 20 °C) and convection parameters for the three quench media are given in Table II [7]. The cooling rates thereby derived from the above analysis are also listed in Table II.

5. Discussion

The method of defining the mean cooling rate from the experimental curves, i.e. by a single linear value, is somewhat arbitrary, because the instantaneous cooling rate falls continuously with decreasing temperature. Thus, as an example, the maximum cooling rate in Fig. 5, based on the slope of the initial part of the curve, is estimated to be 510 K s^{-1}, which compares with the quoted mean value of 116 K s^{-1}.

With this limitation in mind, the mean quench rates determined for air (47 K s^{-1}) and oil (116 K s^{-1}) are in reasonable agreement with the theoretical estimates of 22.6 and 51.3 K s^{-1}, respectively. However, for the case of water quenching, there is a significant difference between the measured mean cooling rate (347.5 K s^{-1}) and the calculated value (1356.8 K s^{-1}), based on the assumption of laminar fluid flow. The discrepancy is somewhat less if turbulent flow conditions are assumed to prevail.

The observed perturbations in the water quenching curve, however, suggest that experimental inaccuracies are a more likely explanation for the lack of agreement in this case. In particular, measurement errors can become more significant at high quench rates as a consequence of poor heat transfer to the thermocouple; this introduces thermal lag and leads to underestimation of the true cooling rate.

6. Conclusion

Measurements have been made of quench rates for standard steel tensile specimens of a martensitic stainless steel, following elevated-temperature heat treatment. Cooling rates of 47, 116 and 347.5 K s^{-1} have been determined for quenching into air, oil and water, respectively.

A theoretical procedure has been outlined for estimating the cooling rates which gives reasonable agreement for air and oil quenches. Differences between experiment and theory for the water-quench conditions are attributed to practical limitations which lead to underestimates of the true cooling rate.

The simplified calculations proposed can readily be extended to other quenching media, specimen materials and test piece geometries.

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