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Title: A Study of the Implications of Air Cooling of Hot-Rolled Asymmetrical Sections

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The air cooling pattern across hot-rolled structural steel sections was investigated, and a regression equation for the heat-transfer coefficient for a typical section was developed. The nonuniform cooling of stock leads to camber, which necessitates straightening and thereby influences the residual stress pattern across the section. Some microstructural variations were also found to have resulted from the nonuniformity in cooling rates.

Keywords asymmetric sections, distortion, heat transfer, rolling, steel

1. Introduction

Structural steel sections produced by the hot rolling process often suffer from nonuniform cooling because of the irregularity in mass distribution across their sections. This leads to camber of the rolled stock, thereby necessitating straightening. Because it is a cold working process, straightening results in increased levels of residual stresses. Often the phenomenon of camber becomes so acute as to make impossible the feeding of stock into the straightening machine. Recourse is then taken to expedients such as cutting of the warped ends, a process that leads to delays and further aggravation of camber of the succeeding bars.

An attempt has been made in this paper to investigate air cooling of hot-rolled structural steel sections with a view to getting a better insight into the process and its impact on material properties.

2. Cooling Experiments

Samples of structural steel sections (90 × 90 mm angle and 125 × 65 mm channel), each of 200 mm length, were instrumented with thermocouples (chromel-alumel) of 3 mm diameter at different locations across the sections. The holes into which the thermocouples were inserted were typically 4 to 5 mm deep. The samples were then heated in an electric furnace to a temperature of 1000 °C, with a soaking period of half an hour. The cold junctions of the thermocouples were connected to a digital (Wahl) temperature recorder to measure the temperature profile. The interval of recording was set at either 30 or 90 s. Subsequent to cooling, test specimens were taken from the pieces from different locations for investigation of microstructure and residual stresses.

3. Heat-Transfer Coefficients in Air Cooling

Figure 1 shows a typical cooling curve for air cooling of an angle section (90 × 90 × 6 mm). The difference in temperature between the mass-intensive portion (apex) and the thinner portion (flange) observed in the laboratory experiments is less pronounced than that in the production line. This is so because the stock during actual rolling develops a temperature difference of about 50 to 70 °C by the time it emerges from the finishing stand, which was not the case in the laboratory samples. However, a difference of about 45 °C was observed between the temperatures of the flange location (10 mm from the edge) and the apex location (10 mm from the apex tip) by the first 90 s of cooling. A difference of about 0.5 °C/s between the cooling rates of the corresponding portions was observable during this period.

The temperature-time data obtained experimentally were used for estimation of the heat-transfer coefficients during air cooling. A lumped system analysis (which is valid for $Bi < 0.1$) was used, and the heat-transfer coefficients for successive temperature intervals were evaluated using the following:

$$h = \frac{mC_p}{A\Delta t} \ln\left(\frac{T_1 - T_\alpha}{T_2 - T_\alpha}\right) \qquad \text{(Eq 1)}$$

where Δt is the time taken for the temperature to drop from T_1 to T_2, A is the area exposed to cooling, and $T_\propto$ is the ambient temperature. The values of C_p, which is a temperature-dependent property, were taken from the following equation:

$$C_p = 493.71 + 2.3T \text{ for } 1075\text{K} \leq T \leq 1350\text{K}^{[1]} \qquad \text{(Eq 2)}$$

The values of h, computed using Eq 1, from successive pairs of temperature-time data, were plotted against the mean temperature of the respective intervals (Fig. 2); the temperature variation within the intervals was assumed to be uniform. The correlation between h and T for the case of air cooling of an angle section (90 × 90 × 6 mm) was found to be

$$h = 0.008T^2 - 0.9372T + 328.13 \qquad \text{(Eq 3)}$$

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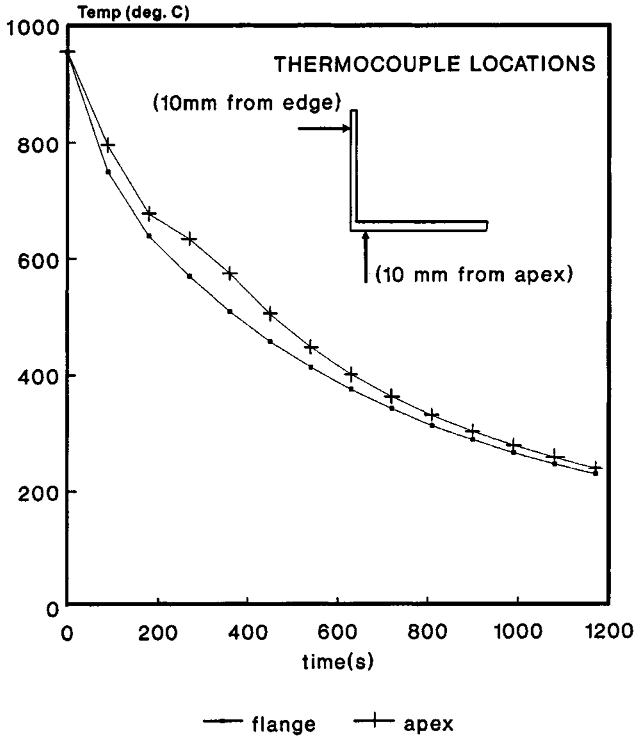


Fig. 1 Cooling curve (air cooling)

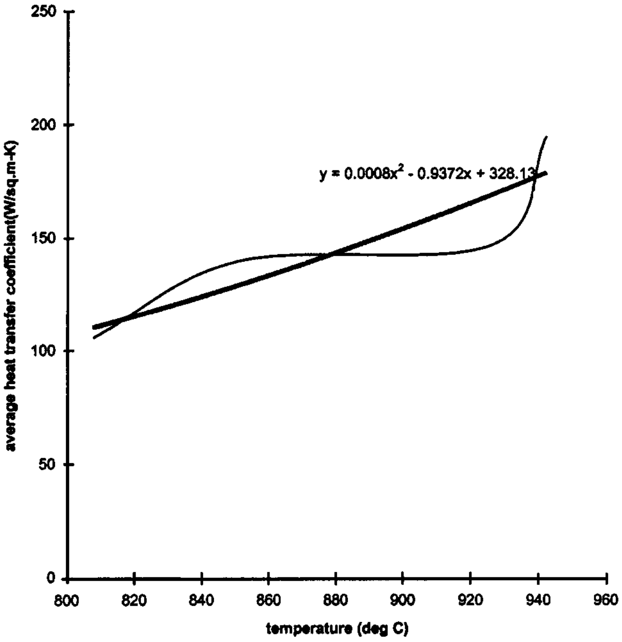


Fig. 2 Heat-transfer coefficients in air cooling

The *h* values given by Eq 3 may actually be underestimates, because, in the considered temperature range, phase transformations in steel result in the release of latent heat.

4. Impact of Nonuniform Cooling

4.1 Camber

Because the thinner portions of an asymmetrical section experience a lower temperature drop, for the same heat loss, than the other parts, they have a tendency to contract, which is opposed by the relatively hot portions. As a result, tensile stresses develop in the thinner portions and concomitant compressive stresses develop in the others.[2,3] Because the yield strength of steel is low in the high-temperature ranges, the thermal stresses cause hot upsetting, or plastic deformation, of the stock. Such deformations are permanent and reflect as camber of the stock. Camber values of 125 to 255 mm have been reported for angles (90 × 90 × 6 mm).

In actual rolling, camber of the stock can lead to considerable delays due to problems in feeding of the stock to the straightening machine. Besides, straightening, which is necessitated by camber, results in increased residual stresses because of the cold working process. The overall impact of camber on production and productivity is therefore extremely deleterious.

5. Microstructure

The cooling curves obtained from the laboratory experiments indicate a difference in the cooling pattern across the section in the temperature range where transformation takes place. Within this range, the minor difference in the cooling rates resulted in some microstructural variations across the section (Fig. 3). Samples taken from the flange location of a channel showed a higher pearlite volume fraction (9.58%) than that taken from the corner location (7.29%). Some difference in the ferrite grain size was also observable.

6. Residual Stresses

The impact of nonuniform cooling on residual stresses is both direct and indirect. Residual stress measurements on specimens of channels subjected to straightening indicated the following pattern of variation across the section: the web and the flange had compressive stresses, while the others had tensile stresses (Fig. 4). This can be explained by the development of an opposite pattern of stresses initially (tensile on the web and flange and compressive elsewhere), which gets reversed on straightening. The initial pattern of stresses is attributable to the higher rate of cooling of the thinner portions, leading to the development of tensile stresses in these parts and compressive stresses in the others. During straightening, the stock is cold worked, which leads to a reversal of the stress pattern.

7. Conclusions

A regression equation for the heat-transfer coefficients likely to be encountered during air cooling of a structural steel section (angle 90 × 90 × 6 mm) has been determined for the temperature range 800 to 950 °C. Calculations of the heat-transfer

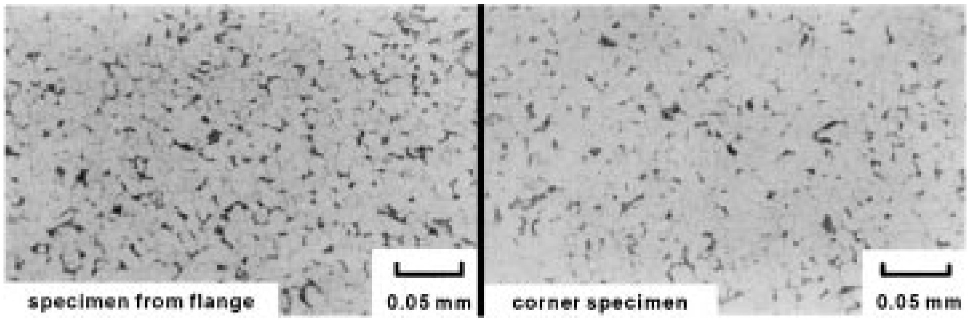
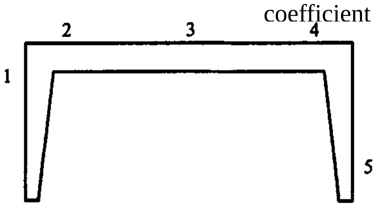


Fig. 3 Optical micrographs



Location	Stress (MPa)
1	67.83
2	35.33
3	-95.89
4	42.19
5	-59.35

Fig. 4 Residual stress distribution

were done over time intervals of 30 or 90 s, ignoring the heat of transformation.

Because the impact of cooling subsequent to hot rolling on the overall productivity of structural mills is of considerable significance,[4] homogenization of the temperature profile across the section until the metal reaches the elastic stage is imperative. In order to achieve this homogenization, strategies for selective cooling of the thicker portions coupled with uniform cooling of the entire section[5] are required. This should help in reducing camber, residual stresses, and microstructural nonuniformity.

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