Spray cooling for quenching is widely used in the USSR and abroad. It is used both after surface heating and through heating of machine parts. Spray cooling is characterized by a high liquid input, since heating per unit volume of liquid amounts to 1-2°C. The smaller the part and the more intensive the spray, the larger the input of cooling liquid and the higher the cost of the quenching operation.

One of the important characteristics of spray cooling is the possibility of controlling the rate. The rate can be controlled by changing various parameters of the spray itself and the sprayer, while the intensity is generally controlled in different stages of cooling by changing the input of liquid and the rate of discharge from the sprayer. Controlling the input, one can change the total quantity of liquid required for complete cooling of the part. Thus, a study of the possibility of using controlled spray cooling for quenching parts is not only of theoretical but also of practical interest.

The intensity of the spray can be controlled to reduce or accelerate heat removal in various stages of cooling [1, 2] and also to reduce the cost of the quenching liquid with retention of the maximum rate of heat removal in the center of the part throughout the range of cooling temperatures [3]. Our work also concerns this problem.

The experiments were made with plates of steel 45 of thickness \( h = 1-20 \text{ mm} \). One side of the plates was cooled by means of a water spray with output \( M = 0.7-0.1 \text{ m}^3/\text{sec} \cdot \text{m}^2 \). Nichrome - Constantan thermocouples were spot welded to the side opposite the spray by means of the KPT-4 apparatus (All-Union Scientific-Research Institute of High-Frequency Current). Cooling curves were recorded with the N-105 loop oscillograph. The beginning of cooling coincided with the beginning of temperature recording. Cooling was controlled by means of a timing device (VZU).

The mechanical properties were determined after heat treatment of plates with \( h = 10 \text{ mm} \) of steels 45, 45G, 36G2S, and 38KhNMA.

Cooling can be judged overall from the change in the temperature of inner layers (inner surface or center). So long as the front of heat removal from the surface cooled directly by the spray does not move into the inner layers (center) of the part, the temperature drops very little. The time for propagation of the heat wave from the cooled surface to the center of the part is called the time lag of the beginning of cooling in the center and designated as \( \tau_0 \). The experiments showed that the variation of \( \tau_0 \) with the thickness of the part (for plates with \( h = 1-20 \text{ mm} \)) can be expressed fairly accurately by the equation

\[ \tau_0 = 0.01h^2. \]

The center begins to cool when the heat removal front reaches it. As for any layer through the section of the part, the cooling rate begins to rise in the center, reaches a maximum value at some temperature, and then declines. The thicker the part and the higher the temperature to which it was heated, the higher the temperature at which the maximum cooling rate is reached; the cooling rate was higher at 700-600°C.

The purpose of this work was to determine the cooling time for a part of any thickness at which the water input can be substantially reduced with retention of maximum cooling rates in the section of the part most distant from the cooled surface.

It is known that to obtain the maximum cooling rate in the center of a part of any size it is theoretically sufficient to cool the surface to ambient temperature and then maintain this temperature on the surface (to

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Fig. 1. Cooling rates on the inner surface of plates (h = 10 mm) with controlled cooling by a water spray of various intensities (M). 1) Weak spray (M \approx 0.1 \text{ m}^3/\text{sec} \cdot \text{m}^2); 2) 0.5 sec of strong spray (M = 0.7) then weak spray; 3) 1 sec of strong spray, then weak spray; 4) 4 sec of strong spray, then weak spray; 5) strong spray (M = 0.7).

Fig. 2. Effect of plate thickness (steel 45) on total (τ_{\text{tot}}) and critical (τ_{\text{cr}}) cooling time with a strong water spray (M = 0.7 \text{ m}^3/\text{sec} \cdot \text{m}^2) in the range of 900-1000°.

avoid its being heated by the hotter inner layers of the piece) until the part is completely cooled.

In practice, cooling of the surface is achieved with a fairly strong water spray (M \approx 0.7-1.0 \text{ m}^3/\text{sec} \cdot \text{m}^2). However, sharp reduction of the intensity after some time (0.5-0.6 sec from the beginning of cooling in this work) did not ensure the highest cooling rates in the inner layers of the plate, which were achieved by using a spray of maximum intensity until the entire plate was completely cooled (Fig. 1, curves 5 and 2).

Evidently, the temperature changes in different layers through the section of the plate when cooling of the surface begins are accompanied by phase transformations in these layers, leading to a change in their thermophysical characteristics.

For this reason, the value and rate of heat flow from the center of the plate to the cooled surface change.

At the same time, the cooling rate in the center of a plate 10 mm thick reached during controlled spray cooling proved to be higher than the rate obtained by cooling the plate with a weaker spray (Fig. 1, curves 1 and 2). Evidently, the intensive cooling at the beginning of the process ensures retention of higher cooling rates in the inner layers of the plate during subsequent cooling with a much weaker spray. It was necessary to find the optimal duration of intensive cooling at which reduction of the intensity of the spray does not cause a reduction of the cooling rate in the inner layers.

Reduction of the intensity of the spray when the heat removal front reaches the center of the plate (in time τ_0) did not ensure retention of the highest possible cooling rate attainable in the inner layers (Fig. 1, curve 3).

Reducing the water input at the time the maximum cooling rate was reached in the center of the plate had almost no effect on the character or rate of subsequent cooling, although cooling in the center occurred somewhat more slowly in the range of 400-300° (Fig. 1, curve 4).

Special experiments showed that the water input can be reduced by a factor of 6-8 at this stage as compared with the initial input. Greater reduction of the water input is undesirable, since cooling of the entire plate fluctuates (it is even possible for the surface layers to be heated by the inner layers).

The process of controlled spray cooling occurs in the following manner.