INFLUENCE OF ROUGHNESS PARAMETERS ON THE HARDENING OF CAST STEEL PLATES

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Abstract. This paper presents the experimental and numerical analysis of the effect of roughness parameters on the hardening of a 148 mm x 148 mm cast steel plate. The temperature distribution on the plate surface was measured at various points, and the infrared camera was used to capture infrared images during the cooling process. In this study, the temperature distribution on the plate surface was evaluated at each pixel image, and the data was collected and recorded using the Therma CAM researcher 2001 software. The results show that the cooling rates on the smooth and rough sides were significantly high at 500°C. Also, it has been found that the total amount of energy is constant over the entire thickness of the sample.

Keywords: Quenching, Metal Properties, Thermal stress, Jet & Nozzle, Leiden frost temperature, boiling curve

1. Introduction

Metal hardening is an important process in various technical applications. In many heat treatment processes, metal work pieces must be hardened in a certain way. The hardening process aims to control the properties of the metal, such as strength, hardness, flexibility. The main advantage of using this process is that it not only achieves the necessary qualities but also reduces the deformation of the work piece.

This study aimed to conduct an experimental investigation of the hardening of smooth and micro-structured surfaces obtained by applying micro-dispersed roughness using a spray nozzle installed...
in a vertical position, observing the heat transfer process and further analyzing the parameters that affect the temperature change [1].

When quenching products from steel alloys, it is very important to ensure the specified cooling rate of a part is maintained; otherwise, the already rebuilt atomic structure of the metal can go into an intermediate state. Meanwhile, cooling that is too rapid is also undesirable, as it can lead to the appearance of cracks on the part or its deformation or other defects such as described in the following:

1. The insufficient hardness of the hardened part is a consequence of low heating temperature, low shutter speed at operating temperature, or insufficient cooling rate. Such defects can be corrected by normalization, annealing with subsequent hardening, or the use of a more energetic quenching medium.

2. Overheating is associated with heating the product to a temperature significantly higher than the required heating temperature for quenching. Overheating leads to the formation of a coarse-grained structure, resulting in increased brittleness of steel. Such defects can be corrected by annealing (normalization) and subsequent quenching at the required temperature.

3. Burning occurs when steel is heated to very high temperatures, close to the melting temperature (1200–1300 °C) in an oxidizing atmosphere. Oxygen penetrates the steel, and oxides are formed along the grain boundaries. Such steel is fragile and impossible to fix.

4. The oxidation and decarburization of steel are characterized by the formation of scale (oxides) on the surface of parts and carbon burnout in the surface layers. Such defects are incorrigible. If the machining allowance allows, the oxidized and decarburized layer must be removed by grinding. To prevent such defects, heating the parts in ovens with a protective atmosphere is recommended.

5. Warping and the occurrence of cracks are consequences of internal stresses. During the heating and cooling of steel, volume changes are observed, depending on temperature and structural transformations (the transition of austenite to martensite is accompanied by an increase in volume up to 3%). The simultaneous change in the volume of the hardened part due to its various sizes and cooling rates over the cross-section leads to the development of strong internal stresses, which cause cracks and warping of the parts during hardening [3,4].

Cooling steel plates with a spray nozzle plays a key role in metal processing. In this study, the experiments used a spray nozzle 460.404 with a jet angle $\theta = 60^\circ$, installed in a vertical position (Fig. 1)

![Figure 1: Front view illustrating spray cooling](image)
In particular, in steel production, spray cooling is widely used in foundry and is also used to improve the final microstructure immediately after heat treatment. The scientific phenomenon is presented in Fig. 2. The heat transfer coefficient $\alpha$ is defined as $\alpha = q / (T_{\text{surf}} - T_{\text{water}})$, and the specific heat flux $q$ passes through four boiling modes.

![Figure 2: Spray cooling mechanism and boiling curve](image2)

![Figure 3: Heat transfer mechanism during spray nozzle quenching](image3)
At the very low-temperature gradient \( \Delta T = T_{\text{surf}} - T_{\text{water}} \), the heat flux in the convective mode is released due to natural convection. With bubble boiling, vapor bubbles form jets until critical heat flux CHF is reached. In the film boiling mode, a stable vapor film is formed between the liquid film and the surface. The Leiden frost point characterizes the minimum heat flux density \( q \) at high temperatures. Below the Leiden frost point, the vapor film becomes unstable until the CHF has been reached again [2, 5].

2. Experimental Method

The main components of the experimental setup are presented in Fig. 4.

![Test setup—Oven (1), Steel plate (2), Computer (3), Infrared camera FLIR SC3000 (4), Experimental cabin (5), Nozzle (6), Pump (7), Water tank (8).](image)

The main component of this installation is the guide rail, which allows the insertion of a metal sample into the furnace for heating. As a first step in the process, the steel plate is heated in the furnace to a temperature of 520 °C. After heating, the stove is immediately installed in the cab with the help of a rail for cooling. The distance between the nozzle and the plate can be easily changed. Profiles allow configuring the test bench according to changes. A video camera records the process from the wetting site. The infrared (IR) camera FLIR SC3000 is used to record infrared images for the cooling process, on the other side of the steel plate. This site is covered with black graphite paint with an emissivity of 0.94. An IR camera measures temperature with a frequency of 150 Hz and a window of \( 240 \times 80 \) pixels. The heat transfer mechanism is shown in Fig. 3. In all experiments, a steel plate with the dimensions of 148 mm x 148 mm and thickness \( s = 7 \) mm had an initial temperature \( T_0 = 500 \) °C (± 3 °C). Liquid cooling was performed using tap water having a temperature of 18 °C and a volumetric flow rate of \( V_0 = 1.2 \) l/min.
3. Result and discussions

The temperature distribution of the plate was measured at 40 points to obtain the most accurate results. For the spray nozzle, the first measurement point was taken visually at the center of the spray cone. The next 39 measurement points were spaced at 2-pixel intervals, see Fig. 5. Then using software, the temperature curves were plotted over time at each point.

Curves were plotted until the temperature of the farthest measuring point from the center reached 80 °C. Ratio profile image temperature over time is presented in Fig. 6.

Figure 5: IR image of a steel plate heated to 500 °C

Figure 6: Graph of temperature versus time of the steel plate cooling process
The temperature curves over time for two points of smooth rough sides are presented in Fig 7. It can be seen from the results that the dashed lines represent the temperature curves for the rough side. In the case of a smooth side, the two lines of the mid and far points are close to each other. In other words, the cooling rate of the steel plate is practically independent of the location of the point. In the case of a rough surface, the two lines are more distinct.

Figure 7: Comparison of temperature curves for different radii of smooth and rough surfaces (Steel, $H = 50$ mm, $T_w = 18$ °C, Spray nozzle 460.404, $\beta = 60$°)

Figure 8: Comparison of temperature curves for different radii of smooth and rough surfaces (Steel, $H = 100$ mm, $T_w = 18$ °C, Spray nozzle 460.404, $\beta = 60$°)
Thus, cooling begins earlier on the plate with a smooth side; however, the roughness plate reaches the temperature of 100 °C faster.

Fig. 8 shows the results obtained during the cooling of steel at a distance of 100 mm from the nozzle to the plate. In this experiment, the water travels a distance twice as large as in the previous experiment. It is evident from the results that the cooling rates on the smooth and rough sides vary greatly. Starting at 500 °C, the smooth-side cooling is significantly faster than the rough-side cooling because the water reaching the plate does not have the adequate speed for spreading over a rough surface as fast as over a smooth surface. Water spreads rather slowly on uneven surfaces as well. However, 100 °C is achieved in two experiments at almost the same time.

4. CONCLUSIONS

The effect of surface roughness during cooling was investigated, and a comparison was made between the variable parameters of a 148 mm x 148 mm steel plate. Operational parameters, such as the initial temperature of the sample, the temperature of the refrigerant (tap water), and the volumetric flow rate, remained unchanged during all experiments.

It was concluded that the plate with a smooth side has a higher heat transfer than that with a rough side due to the roughness on the surface of the plate and the difficulties of water spreading over the rough surface in an upright position.

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