REWETTING OF HOT SURFACES: EXPLOSIVE BOILING AS CONTACT MECHANISM BETWEEN LIQUID WATER AND SURFACES AT ELEVATED TEMPERATURE

CF Gomez[1], CWM van der Geld[1], JGM Kuerten[1], M Bsibsi[2], and BPM van Esch[1]

[1] Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands.
[2] Tata Steel Nederland Technology B.V., Postbus 10.000, 1970 CA IJmuiden, The Netherlands.

Can liquid water touch a surface at, for example, 600 °C? If yes, how is this possible? And why is this relevant for the industry?

Quench cooling by water jet impingement is applied in a wide range of industrial fields where ultrafast cooling is necessary. Upon impingement onto a sufficiently hot surface, the water undergoes a phase transition from liquid to gas state (boiling). The combination of high convective forces generated by the water jet and the high heat of vaporization leads to high cooling potential. In the steel industry, this technique is applied in the Run Out Table (ROT, figure 1) to reach the desired microstructure and mechanical properties.

The ROT is located between the Hot Rolling and Coiling sections. During Hot Rolling, hot steel slabs are rolled to reach the desired thickness and width. Due to mass conservation, the steel slab increases its length from 20 meters to hundreds of meters long. Simultaneously, the steel slab is accelerated to speeds up to 80 km/h. Before coiling, the steel slabs must be cooled in the ROT from approximately 1200 °C to the desired final temperature, which can vary between 700 and 180 °C depending on the steel grade. In the ROT, hundreds of circular water jets impinge on the moving steel slabs, which are cooled in a matter of seconds. The high surface speeds, the large amount of water jets, and the violence of the boiling activity make this a very complex and chaotic process. Still, a high level of control is required.

Figure 1: Run Out Table: Multiple water jets impinging on the moving, red hot, steel slab.

The cooling speed and temperature distribution of the steel determine its microstructure and mechanical properties, making the ROT a crucial step in the steel making process. Failure to succeed on this step leads to rejection of the steel slab and its reprocessing as scrap, resulting in major economic losses.

Given the high surface temperature of the steel, the main boiling regime present in the ROT is film boiling. The high surface temperature leads to a high vaporization rate and the formation of a vapor layer, isolating the water from the hot surface. During stable film boiling, the surface heat flux is nearly constant and slightly decreasing with decreasing surface temperature. As a result, small surface temperature variations along the steel slab are homogenized by internal conduction, resulting in a self-regulating process. However, steel grades requiring low coiling temperatures might reach the rewetting temperature in the ROT: the surface temperature decreases to a point where the vapor film is broken. Rewetting (i.e. water-surface contact) then occurs and the heat flux increases drastically. Rewetting leads to a sharp increase in heat flux resulting in a fast decrease of the surface temperature, meaning that small temperature variations along the steel slab are exacerbated [1]. Uneven surface rewetting leads to uneven cooling and therefore poor product quality, non-reproducible processing, and deformation of the steel slabs. This makes rewetting one of the most relevant phenomena occurring during quenching in the ROT.

Experimental studies in literature have reported contact between liquid water and surface (rewetting) to occur at surface temperatures up to 900 °C [2]–[4]. Theoretically, at temperatures above the Thermodynamic Limit of Superheat (TLS, equal to 302 °C in the case of water [5]), liquid water cannot maintain a superheated state anymore. As a consequence, a sudden phase transition is bound to occur to the energetically favored vapor state, also denominated explosive boiling. The possibility of rewetting to occur at temperatures exceeding the TLS of water has been an open discussion in the field for years. If the reported rewetting temperatures are accurate, it is still unclear what mechanism allows water to maintain contact with a surface at such elevated temperatures. Some have hypothesized rewetting mechanisms involving intermittent dry and wet periods and explosive boiling [6], [7]. However, there is a lack of experimental data to prove these hypotheses due to the short duration and small scale of the rewetting phenomenon. During this project, detailed visualization of the rewetting phenomenon was made possible by using a borescope.

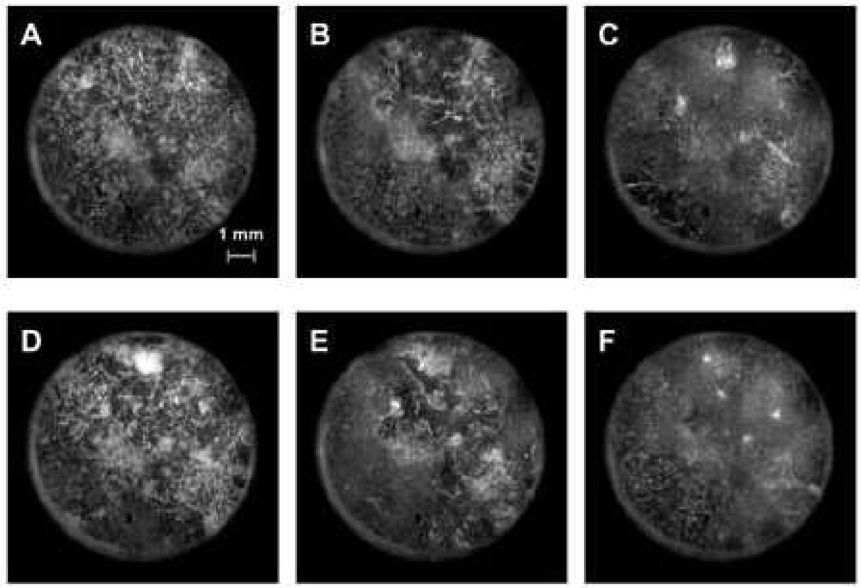

Figure 2. Intermittent boiling during sandblasted plate quenching; initial plate temperature of 650 °C and water jet at 25 °C. The circle corresponds to the 9 mm diameter stagnation zone. Time after jet impingement: A: 9.931 ms; B: 10.111 ms; C: 10.214 ms; D: 10.308 ms; E: 10.456 ms; F: 10.493 ms.

The experimental setup used during this project consists of a water tank connected to a circular jet nozzle. The water jet impinges into a sandblasted, preheated test plate, at initial temperatures up to 650 °C. A borescope is installed inside the water tank, aligned with the jet nozzle, and connected to a high-speed camera. As a result, the boiling activity in the jet stagnation zone can be recorded at 81 kfps and the nature of boiling during rewetting can be investigated in detail.

The high-speed recordings showed that when a water jet at 25 °C impinges onto plates at initial temperatures below 300 °C stable nucleate boiling activity occurs. At initial temperatures above 300 °C, the high-speed recordings showed vigorous and seemingly chaotic boiling activity. At this point, the great detail provided by the high-speed recordings became crucial. When observing this chaotic boiling activity at 2 fps playback speed (40000 times slower than reality), a pattern was perceived: bubbles nucleate simultaneously over the complete jet stagnation zone (figures 2A and 2B) and grow for a period of time before collapsing simultaneously, leaving the jet stagnation zone free of bubbles (figure 2C). After some time, bubbles nucleate in the complete stagnation zone again, repeating the process (figures 2D, 2E, and 2F). This is the first direct observation of intermittent boiling activity during quenching by water jet impingement.

The frequency of this intermittent boiling activity was estimated based on the high-speed recordings. The estimations resulted in frequencies between 2 and 40 kHz, depending on plate temperature, length scale, and surface finish. The analysis showed that the intermittent boiling activity occurs both in smooth and rough surfaces and only at initial plate temperatures above the Thermodynamic Limit of Superheat of water. The frequency at which the intermittency occurs decreases for decreasing surface temperature and follows correlations regarding single bubble growth theory when occurring in areas below 0.4 mm2. These results were carefully analyzed and correlated with theory and literature. The following hypothesis was presented (see figure 3) to explain the mechanism by which rewetting can occur at surface temperatures above the TLS.

Upon rewetting, the water temperature in the vicinity of the hot surface rises above the saturation temperature, leading to superheating (figure 3, step 1). If the surface temperature is higher than 300 °C, the water temperature reaches the TLS and the water suffers explosive boiling to the more favored vapor state: sudden bubble nucleation occurs in the complete jet stagnation zone (figure 3, step 2). The bubbles grow rapidly, leading to a bubble-rich state. At some point, the growth of the bubbles leads to contact with the subcooled, bulk water coming from the jet stream. Upon contact with the cold water, the bubbles implode (figure 3, step 3) and the cold water occupies the space previously filled by the bubbles, leading to a bubble-less state (figure 3, step 4). If the surface temperature is still sufficiently high, the water temperature rises and the sequence is repeated. This leads to a new boiling regime, denominated cyclic explosive boiling. For the first time, a rewetting mechanism hypothesis is presented and backed up with direct, detailed visualization of the boiling activity.

In the following stages of the project, the experimental setup was modified to allow quenching of moving, hot steel

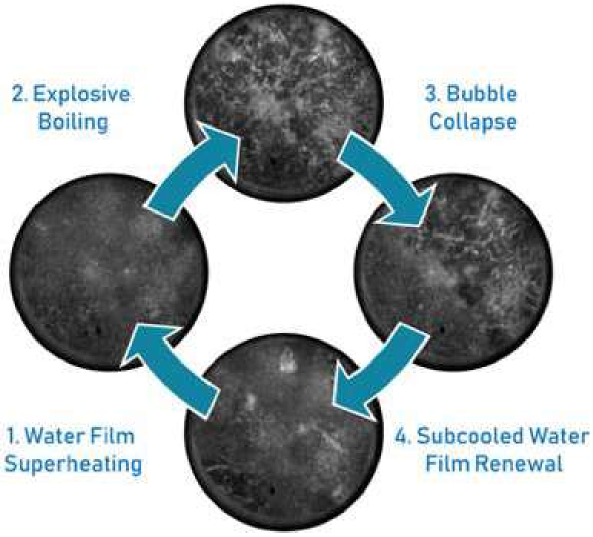

Figure 3. Rewetting mechanism hypothesis: cyclic explosive boiling.

plates. The use of a linear unit enabled the study of quenching of surfaces moving at speeds up to 8 m/s, higher than ever before and for the first time in a speed range comparable to the real application. The new setup combines the high speeds recordings here presented with heat flux estimations, resulting in a complete set of data with great potential to reveal the detailed physics of quenching in the Run Out Table.

For more information, feel free to consult our complete publication: https://doi.org/10.1017/jfm.2020.232

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