INFLUENCE OF THE SURFACE ROUGHNESS ON THE COOLING INTENSITY DURING SPRAY COOLING

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Abstract

The surface roughness plays an important role during spray cooling of hot surfaces in a presence of the boiling. Bubbles are formed in small cavities on the surface during nucleate pool boiling. Enhanced surface roughness causes that more bubbles are formed and it causes increased cooling intensity. The surface with increased roughness has also bigger surface area, which allows higher heat flow between surface and surrounding water. The influence of the surface roughness during pool boiling was investigated by many authors. The increased surface roughness causes shift of the Leidenfrost temperature to higher temperatures and increases critical heat flux during pool boiling. The influence of the surface roughness during spray cooling of hot surfaces was not still sufficiently investigated and it is not known if the effect of the surface roughness is similar like in a case of the pool boiling. Experiments for describing the effect of the surface roughness on the cooling intensity were conducted with water nozzle with flat jet. Test samples were heated in a protective atmosphere at a temperature 730 ºC and then cooled to the room temperature. Test samples were made of the austenitic stainless steel to minimize the forming of the scales on the surface. Results showing influence of the surface roughness on the critical heat flux and on the Leidenfrost temperature are presented.

Keywords: Surface roughness, spray cooling, Leidenfrost temperature, critical heat flux, heat transfer coefficient

1. INTRODUCTION

The water spray cooling is a common cooling method used in many high-temperature industrial applications, such as metal processing or electronics cooling. The spray cooling of hot surfaces is influenced by many parameters [1 and 2] and surface roughness is one of these parameters. Surface roughness plays an important role during cooling of hot surfaces in a presence of the boiling. Bubbles are formed in small cavities on the surface during boiling. Enhanced surface roughness causes that more bubbles are formed and it causes increased cooling intensity [3]. The surface with increased roughness has also bigger surface area which allows higher heat flow between surface and surrounding water.

Scales, which covers the metal surface during hot rolling, influences surface roughness which differs from original scales-free rolled surface [4]. This can influence the cooling during hot rolling [5]. The change of the cooling intensity caused by the change of the surface roughness can also influence the flatness of the product [6] and the cooling of rolls [7].

As described by many heat transfer text books [3 and 8], if a liquid is in near contact with a surface significantly hotter than the liquid's boiling point, the heat transfer boiling phenomena based on the heat flux data or a boiling curve (heat flux versus excess temperature) can be characterized by four different regimes: a) free convection (single-phase), b) nucleate boiling, c) transition boiling and d) film boiling. Based on the boiling curve, at the onset of the film boiling (between the transition boiling and film boiling regimes), the heat flux is minimal and the corresponding temperature is known as the Leidenfrost temperature (T_L) or point. The critical heat flux (CHF) occurs when the heat flux reach the maximum on the boiling curve. The CHF point is the transition point between transition boiling regime and nucleate boiling regime.

Although definitions of the Leidenfrost point and the CHF point were originally based on the heat flux data measured from pool boiling experiments, the minimum heat flux is commonly used for the determination of the Leidenfrost point and the maximum heat flux is used for the determination of the CHF point for spray cooling [9 and 10]. Accordingly, the minimum heat flux criterion is adopted for the present spray cooling study in determining the Leidenfrost temperature and the maximum heat flux criterion is used for determining the CHF point.

The surface roughness influences each boiling regime and its significance can be different in each boiling regime. The influence of the surface roughness will be low during film boiling regime, where the cooled surface is covered by the vapor layer. The cooled surface does not come into direct contact with water and increased surface roughness causes only increase of heat flow transferred by radiation due to enhanced surface area. The decrease of the surface temperature during film boiling causes decrease of the vapor layer thickness. This decrease continues until first peaks of surface roughness come into direct contact with water. This leads to rapid cooling of peaks and it causes increase of the heat flux transferred from the cooled surface. At this time the heat flux reach its minimum (Leidenfrost point) and starts to increase. The temperature at which occurs Leidenfrost point is significantly influenced by the surface roughness. This was observed during immersion cooling experiments [11]. Additional decrease of the surface temperature leads to breaking up of the vapor layer and its destruction (CHF point). It can be expected that surface with higher roughness will have higher critical heat flux due to increased formation of bubbles in surface cavities. The higher CHF for rougher surfaces was observed for immersion cooling [11] and for spray cooling [12].

The present paper deals with the change of the Leidenfrost point and the CHF point due to different surface roughness during spray cooling. The influence of the surface roughness was experimentally investigated. Austenitic stainless steel samples with different surfaces (polished, rolled and milled) were prepared. The surface profile was measured for each sample and then each sample was heated and cooled by a spray with identical cooling conditions.

2. EXPERIMENTAL MEASUREMENT

Five samples with dimensions 150×60 mm and thickness 25 mm were made of the austenitic stainless steel (EN 1.4828) to minimize the forming of scales on the surface. Each sample had different surface profile. Three samples had milled surface (A, B and C), one had original rolled surface (D) and the last one was grinded (E) (**Figure 1**). Each sample was equipped by two thermocouples which were symmetrically positioned 20 mm far from the center of the sample. The thermocouple junction was 2 mm under the tested (cooled) surface.

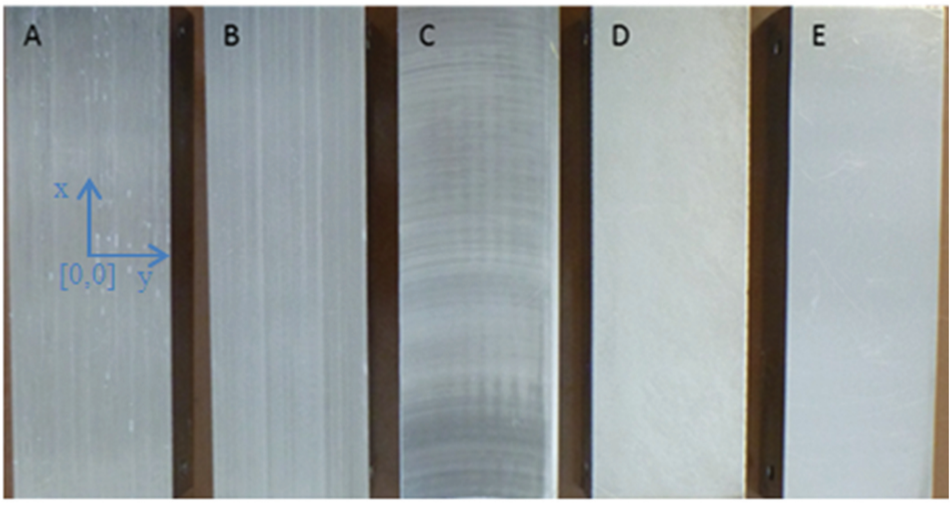

Figure 1 Photo of samples (A, B and C - milled, D - original rolled and E - grinded)

2.1. Roughness measurement

The surface profile was measured by optical profilometer with resolution 1 µm. The profile height (z axis) was measured for each sample in two lines (x axis and y axis) with the length 10 mm, where thermocouples were located in the centers of lines (the point [0, 0]). Examples of measured surface profiles are shown in **Figure 2** for milled surfaces and in **Figure 3** for rolled and grinded surfaces. The comparison of computed average statistical roughness parameters (Ra and Rz) is in **Table 1**. The average value is obtained as an average between the value for x axis and y axis.

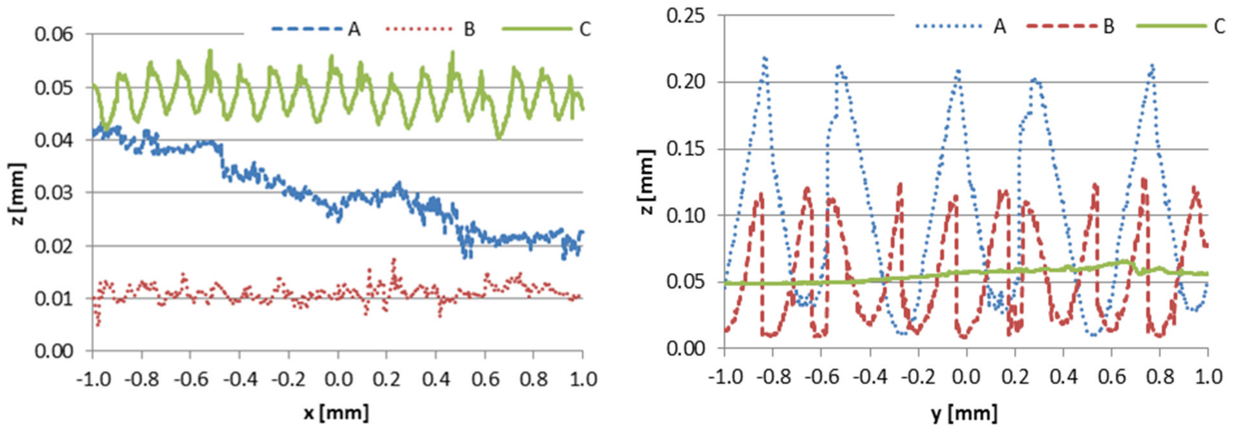

Figure 2 Measured surface height for milled surfaces (A, B, C)

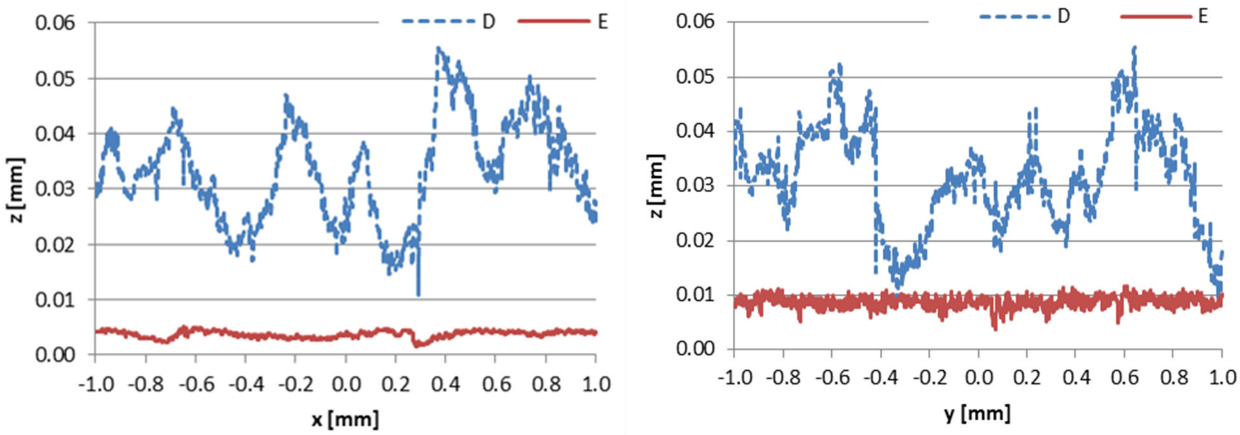

Figure 3 Measured surface height for original rolled (D) and grinded (E) surfaces

Table 1 Surface roughness statistical parameters (Ra and Rz)

	A - milled	B - milled	C - milled	D - rolled	E - grinded
Ra [µm]	24.4	14.5	1.4	7.3	0.4
Rz [µm]	91.2	50.6	9.55	34.4	2.2

2.2. Spray cooling intensity measurement

A laboratory experimental apparatus developed for testing nozzles used for spray cooling during continuous casting of the steel was used to test the cooling intensity of surfaces with different roughness's (**Figure 4**).

A steel frame held three major parts of the apparatus: the test sample, a moveable mechanism with a nozzle and a heater. The test sample was placed into a lift, which allowed the sample to move up, removing the furnace and positioning the nozzle under the test sample. The flat jet nozzle was positioned on the moveable mechanism under the test sample. The spray angle of the nozzle was 80°. The flow rate at 0.2 MPa was 1.9 $dm^3 min^{-1}$. The spray height was 300 mm. The nozzle moved at a velocity of 4 m min^{-1} under the static test sample in the direction of y axis of the sample and nozzle passes under the center of the test sample.

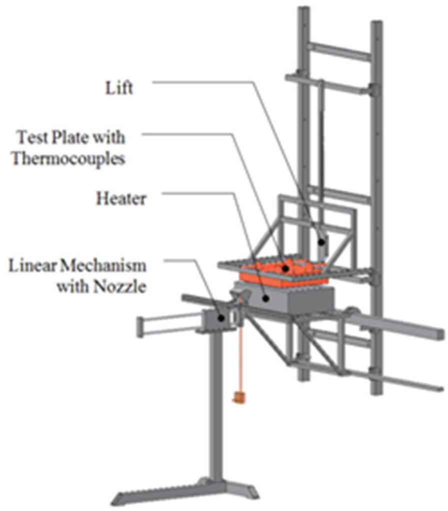

Figure 4 Experimental apparatus

The test sample was placed in an electric furnace and was heated in a protective atmosphere to the initial temperature of 730 °C. Deflector was closed and the pressure of the water was set at 0.2 MPa. Then the furnace on rails was moved out. The moving mechanism with the spraying nozzle with closed deflector moved to a defined position under the hot test sample, and the deflector was opened and spraying nozzle started movement under the hot test sample. The nozzle moved in one direction with opened deflector and returned with closed deflector. This was repeated until the temperature at all measured points was below 50 °C. The data acquisition system recorded temperatures of both thermocouples, the temperature of the coolant and the position of the nozzle with frequency 60 Hz during the entire experiment. The water temperature was around 17 °C for all experiments.

3. RESULTS AND DISCUSSION

After measurement, an inverse heat conduction problem was used to compute the time dependent heat transfer coefficient, the heat flux and the surface temperature. Beck's sequential approach, which uses a sequential estimation of the time varying boundary conditions and future time steps, was employed [13].

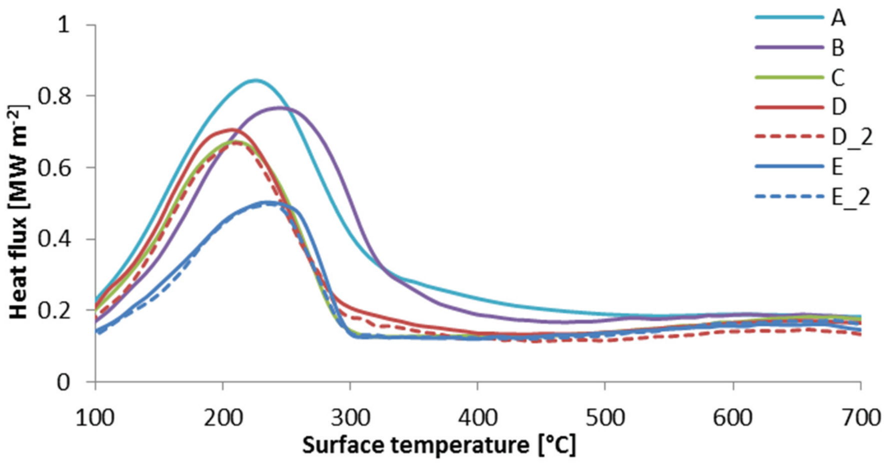

Figure 5 The dependence of the heat flux on the surface temperature for different surfaces (A, B and C - milled, D - rolled and E - grinded)

Further, dependences of the heat flux on the surface temperature and the position in the cooling section were obtained for all thermocouples. Then, dependences of the heat flux on the surface temperature were obtained as an average value of the heat flux along the position on the interval with the length 10 mm with center at the position of the thermocouple. Each sample was equipped with two thermocouples. These thermocouples were symmetrically positioned and so the cooling was similar at these positions. The average value of the heat flux was computed from both thermocouples. The dependence of the average heat flux on the surface temperature for all samples is shown in **Figure 5**. The dependences of the obtained Leidenfrost temperatures, critical heat flux temperatures, minimal heat fluxes and critical heat fluxes on the surface roughness (Ra or Rz) are shown in **Figure 6**. The dependence of the Leidenfrost temperatures on the surface roughness was slightly better for parameter Rz than Ra and so the dependence on the parameter Rz is shown in **Figure 6**.

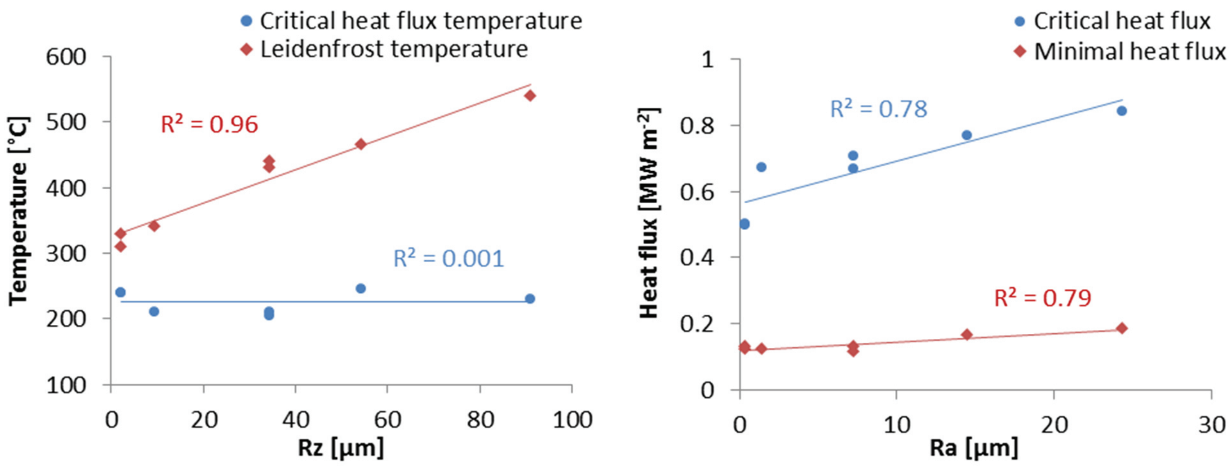

Figure 6 The dependence of the heat flux on the surface temperature for different surfaces (A, B and C - milled, D - rolled and E - grinded)

Experiments showed that the Leidenfrost temperature increases with increased surface roughness (Ra, Rz). This confirms results observed during immersion cooling [11]. It is evident that the Leidenfrost temperature linearly depends on the surface roughness parameter Rz (**Figure 6**). The original rolled surface slightly differs from the linear trend. The minimum heat flux linearly increases with increased surface roughness for milled surfaces (**Figure 6**). The rolled and grinded surface slightly differs from the trend of milled surfaces. There is no visible trend of data for temperature at critical heat flux. This differs from results of immersion cooling, where big differences of temperature at critical heat flux were observed for small changes of surface roughness [11]. The critical heat flux increases with increase of the surface roughness. The rolled and grinded surface slightly differs from the trend of milled surfaces. The differences of critical heat flux are not as big as during immersion cooling [11].

4. CONCLUSION

Experiments showed that the surface roughness significantly influences the Leidenfrost point and critical heat flux point for spray cooling. It was observed that the critical heat flux increases with surface roughness, but the change is not as significant as for immersion cooling. Further, it was observed that the Leidenfrost temperature linearly increases with increasing surface roughness.

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