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Cooling Ability of Smooth and Dimpled Surfaces Determined by Experiment and Numerical Simulation

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The study of the cooling process of a gun barrel is of great importance in the field of ballistics and weaponry. This is because the cooling process directly impacts the gun's accuracy, precision, and longevity. To minimize these effects, the geometry of the barrel is optimized, among other things. The article examines the cooling process of the copper plate and barrel with a structured surface. The study aims to determine the structured surface's effects on heat transfer through radiation and convective components. The work focuses on conducting experiments and numerical simulations to observe and evaluate the cooling process of the studied objects in the environment. The results of experiments and numerical simulations were compared to find out the possibility of substitution of experimental measurement by numerical simulation even in so difficult flow conditions.

Keywords: Structured surface, Barrel, Heat Transfer, Dimple, Numerical simulation

1 Introduction

In firearms manufacturing, the cooling process is essential to gun performance. The maximum number of shots fired from firearms is determined by the cooling capacity of its components. If the number of shots is exceeded, there is an increased probability of damaging the barrel or causing an accident due to overheating of the propellant. For large firearms, studies are being made on cooling with the main medium [1], which increases the technical complexity and weight of the weapon. Next, the idea of dipping the barrel in cooling water arose, which brought many complications due to thermal shock when inserting a very hot weapon into a cold medium [2]. This article describes an attempt to accelerate cooling mainly with the help of natural physical phenomena, for which no additional technology is needed. Therefore, optimizing the barrel's geometry, specifically the barrel's surface, is one of the ways to increase the gun's performance. This article aims to determine how the textured surface affects the heat transfer rate of the cooling process on studied objects and compares the influence of two principles of heat transfer - convective and radiate. The magnitude of the convective heat transfer component could be influenced by TLJ phenomena [3] not solved in this article.

To achieve the mentioned goal, the article presents two approaches: experiment measurement by using a thermal imaging camera and numerical simulation by Ansys Fluent using to solve the finite volume method. The results of those two processes will be compared. So, besides the new possibilities of the barrel cooling process speeding; the new approach of heat transfer measurement was tested to determine cooling ability. Instead of measuring by thermocouples, in the case of the measurement by the thermal imager, the radiation heat transfer is determined too, and the full temperature field of the solved part can be seen. This approach allows to find and solve problematic places of heated bodies.

Experimental measurements and numerical simulations were carried out for theoretical cases of heating the entire volume of the measured bodies to determine the influence of the structured surface. In actual application, uneven heating of the barrel [4] occurs, which is not considered in this article.

2 Measured objects and their preparation

There are four studied samples. The first two samples are square-shaped copper plates with a side 150 mm long. One sample is with a smooth surface; the second is with a dimpled surface with 182 dimples (see Figure 1) [5]. The second two samples are barrels of the CZ BREN 805 gun. Similarly, one sample has a smooth surface, and one with a dimpled surface with 120 dimples (see Figure 2).

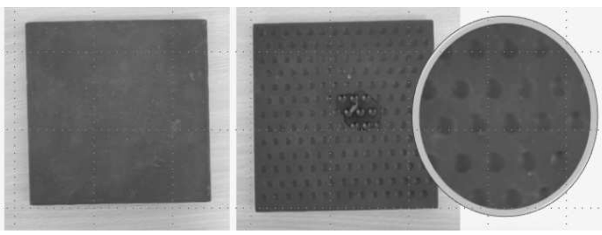

Fig. 1 *Measured square-shaped copper plates*

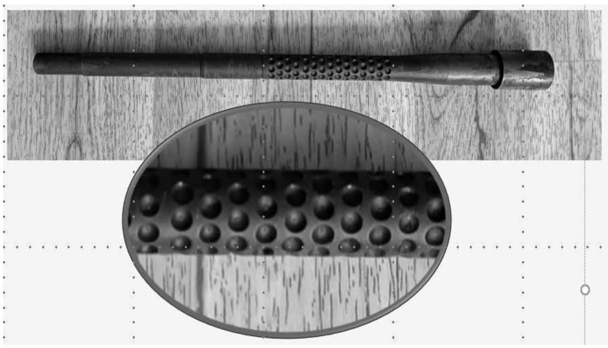

Fig. 2 *Barrel of the BREN 805 gun with dimples*

In order to be able to compare both pairs of samples (with a smooth and dimpled surface), they had to have the same basic parameters and had to be subjected to the same preparations before the measurement:

- the materials of both plates and the materials of both barrels were identical,
- the surface of all samples was provided with a special varnish for non-contact temperature measurement ThermaSpray with a precisely defined emissivity of $\varepsilon = 0.9$,
- structured surfaces were measured using a Surface profilometer TALYSURF CLI 1000 due to the need to accurately determine the size of the heat exchange surface [7],
- all measured objects were heated in a furnace to a specific temperature and were properly placed to measure natural heat transfer.

In the Table 1 are presented properities of all measured objects.

Tab. 1 *Parameters of copper plates and BREN barrels*

Measured sample		m [kg]	c_p [J·kg^{-1}·K^{-1}]	A [m^2]
Copper plate	smooth	2.037	384.6	0.0225
	dimpled	1.828	384.6	0.0232
BREN barrel	smooth	0.586	470	0.0191
	dimpled	0.571	470	0.0196

Where:
m…sample's mass [kg],
c_p…specific heat coefficient [J·K^{-1}·kg^{-1}],
A…heat transfer surface [m^2].

3 Measurement and its evaluation

3.1 Measurement of the samples

To proper heat transfer measurement, flat plates were put into a heat-isolating material bed so the heat was transferred to the surrounding environment only through one measured surface. The barrels were placed into a room space so heat was transferred in all directions without the effects of unwanted heat transfer by contact conduction. The entire cooling process was recorded by the FLIR thermal imaging camera, which provides an automatic time record of the temperature measurements. The experimental setup for measuring heat transfer of the barrel is illustrated in Figure 3.

Fig. 3 *Heat transfer experiment setup of barrel*

3.2 Evaluation method

The method developed to measure the cooling rate of heat transfer using the gradient of the cooling curve and identify the convective and radiative components of heat transfer from the surface of the body under investigation uses general laws of thermal convection (Newton's law of cooling) and thermal radiation (Stefan-Boltzmann's law) [6].

Data measured from the thermal imaging camera were used to determine the radiation component of heat flux:

$$Q_r = A \cdot \varepsilon_1 \cdot C_0 \cdot \left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right] \quad (1)$$

Where:
ε_1…emissivity of an object [-],
C_0…blackbody radiant coefficient [$W \cdot m^{-2} \cdot K^{-4}$],
T_1…object's surface temperature [K],
T_2…surrounding environment temperature [K].
The total heat flux was determined from samples material properties and time of cooling:

$$\dot{Q} = \frac{dQ}{d\tau} = m \cdot c_p \cdot \frac{dt}{d\tau} \quad (2)$$

Where
Q…total heat
t… current object's temperature [°C],
τ…time [s].
The heat is transferred to the surrounding environment simultaneously by convection and radiation, so the convective component of heat flux was determined from their sum:

$$\dot{Q}_c = \dot{Q} - \dot{Q}_r \quad (3)$$

For objective evaluation of samples with different properties, the convective heat transfer coefficient was calculated:

$$\alpha = \frac{\dot{Q}_c}{A \cdot (t_1 - t_2)} \quad (4)$$

Where:
t_1…object's surface temperature [°C],
t_2…surrounding environment temperature [°C].

3.3 Results of the measurement

A detailed description of the copper plates measurements and evaluation was published and discussed in the article "Cooling ability of smooth and dimpled surfaces" [5]; only a brief conclusion of the buoyancy-driven flow case will be given in this article.

Figure 4 shows the cooling curves of smooth and dimpled plates. The smooth plate was cooled from temperature 130°C to 41°C during 4035 seconds, and the dimpled plate during 3795 seconds. The dimpled plate was cooled faster by 240 seconds, even if the total heat transfer and its convective component were higher for the smooth plate. So, the cooling course can affect the speed of the cooling process. The time change gradient of total and convection heat transfer is steeper from the beginning - with the highest temperature and highest heat transfer. (The reason for this phenomenon will be studied in the following work.)

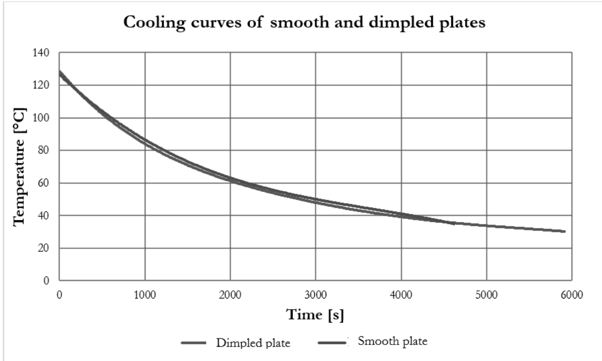

Fig. 4 *Cooling curves of smooth and dimpled plates*

Figures 5 and 6 show graphs of the heat transfer rate and its components of smooth and dimpled plates during buoyancy-driven flow, which means no forced air flow rate.

The radiative component is in the case of the natural heat transfer very important. On average the proportion is 46.1 % from total heat transfer for smooth plate and 48.6 % for the dimpled plate. The radiative component is not negligible in the calculations of heat transfer into the surrounding environment during buoyancy-driven flow.

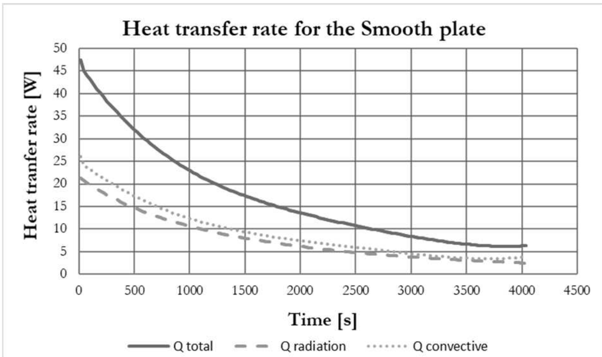

Fig. 5 *Heat transfer rate for smooth plate in case of buoyancy-driven flow*

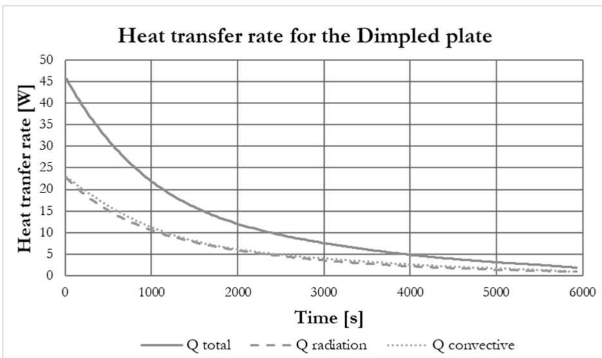

Fig. 6 *Heat transfer rate for dimpled plate in case of buoyancy-driven flow*

Figure 7 shows the cooling curve of smooth and dimpled barrels in the case of buoyancy-driven flow without a forced flow rate. The difference between both curves is bigger than in the case of plates to the benefit of the dimpled variant. The smooth barrel was cooled from temperature 200°C to 35°C during 2970 seconds (49.5 minutes), and the dimpled plate during 2070 seconds (34.5 minutes), so the dimpled plate was cooled faster by 900 seconds (15 min).

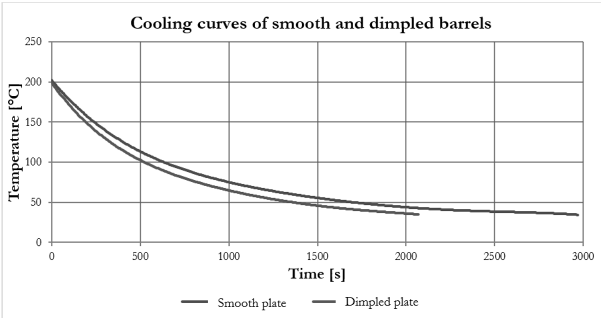

Fig. 7 Cooling curves of smooth and dimpled barrel

Figures 8 and 9 show graphs of heat transfer and its components for the case of BREN barrels. In high temperature is the radiation component of heat transfer much more bigger than the convective component. At a temperature of 200°C, the heat transfer is from 68 % of the radiation component. The radiation component on average is 52.4 %.

Figure 10 draws total and convective heat transfer coefficients, that show the increased influence of dimpled surface on the speed of barrel cooling.

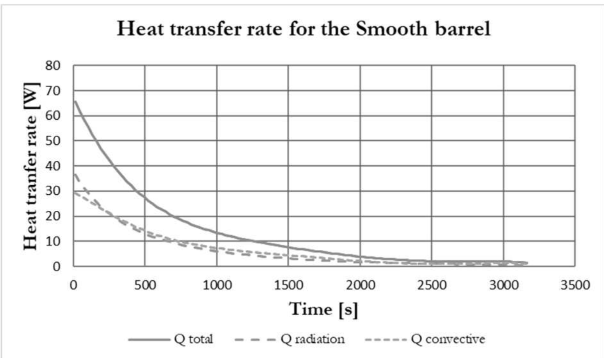

Fig. 8 Heat transfer rate for smooth BREN barrel in case of buoyancy-driven flow

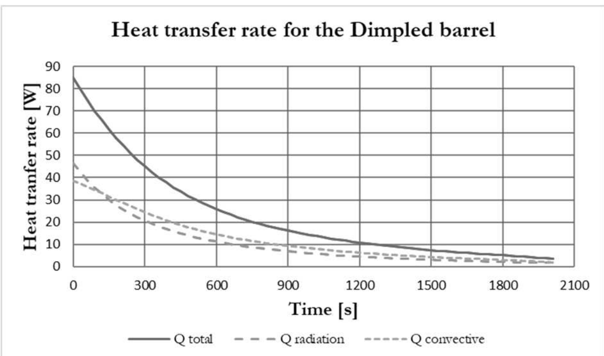

Fig. 9 Heat transfer rate for dimpled BREN barrel in case of buoyancy-driven flow

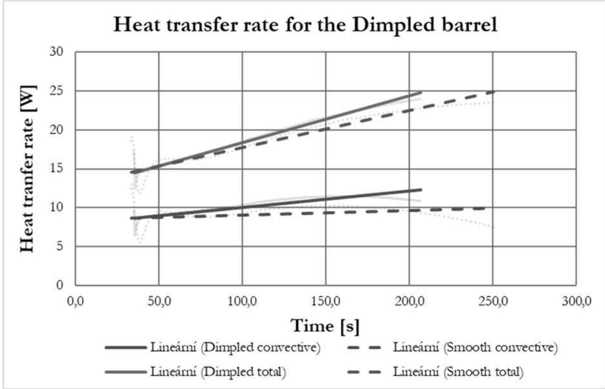

Fig. 10 Heat transfer coefficients of smooth and dimpled barrels

4 Numerical simulation

This part aims to find a suitable method to calculate the solved problem to achieve the results of numerical simulation as much as similar to experimental findings and measurements.

Because the barrel has a more complex structure and requires more effort during simulation execution. Simulation was performed first with the flat copper plate to test the method's reliability before it was applied to the barrel.

The simulation phase is carried out in 3 main steps: 3D modeling, meshing in ICEM, and simulation in Ansys Fluent.

4.1 The numerical simulation setting

The heat transfer of measured plates and barrels occurs between the sample solid surface and the surrounding environment, so the method of finite volumes was used to solve this. Figure 11 shows the boundary condition setting for the copper plate numerical simulation – a big cube presents the surrounding environment, the green area is the heated copper plate, the gray area is the heat-insulating material, the red area represents the pressure outlet and the all 4 blue areas from the rest of faces are the pressure inlets. The setting of barrels simulations was similar – the barrels were put into a cube without the insulating material.

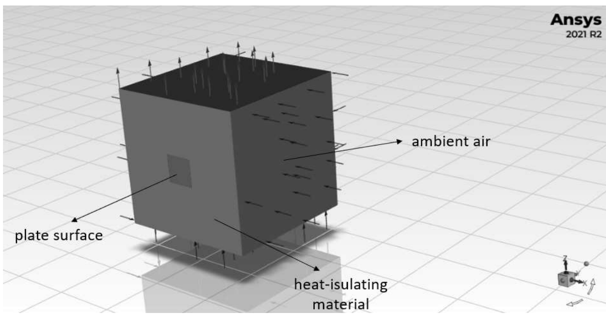

Fig. 11 The boundary condition setting in Ansys Fluent for copper plate case

Because of the computational demand of the used finite volumes method, only the stationary solver was performed. The temperature of the heat transfer surface was set as the constant and thermodynamic quantities were monitored - besides others total and radiation heat flux on the boundary conditions surfaces, total and radiation specific enthalpy, and surface heat transfer coefficient of the heated surface.

4.2 Preprocessing

All computed cases were modeled in SolidWorks and imported to Ansys ICEM for mesh creation. The surfaces of plates and barrels were modeled as inverted imprints. In Figure 12 is the detailed mesh of the dimpled plate.

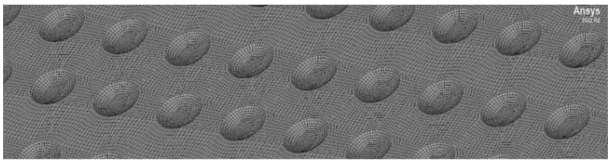

Fig. 12 *Detail of the dimple plate mesh*

In general, the numerical simulation was set as a steady-state flow with the pull of gravity. Because of convection and radiation heat transfer simulation, the energy model was set as On, and the radiation model was chosen as Discrete Ordinaries (DO). The turbulence model was changed during the simulation - the natural convection heat transfer creates the air flow rate itself. When the heated surface has a high temperature, the natural flow is faster than when the heated surface has a low temperature. So the laminar model was set in case of a slow flow rate, and the k-omega model was set in a fast flow rate. The Boussinesq density was chosen in the material setting of air. The Boussinesq density is a widely used approximation for buoyancy-driven flow.

4.3 Results of numerical simulation

The equation of heat transfer calculation mentioned above was used for the evaluation of numerical simulation data.

The cooling curves were determined from the total heat transfer. The duration Δτ corresponding to the temperature change Δt during the cooling process based on equation (2) was determined using numerical mathematics:

$$\Delta\tau = \frac{Q(t_i+1) - Q(t_i)}{\dot{Q}_{aver}} = \frac{m \cdot c_p \cdot \Delta t}{\dot{Q}_{aver}} \quad (5)$$

Where:

$\dot{Q}_{aver}$…average total heat transfer rate [W]:

$$\dot{Q}_{aver} = \frac{Q(t_i+1) + Q(t_i)}{2} \quad (6)$$

An average total heat transfer rate value between two temperatures t_i and t_{i+1} was calculated by using an approximation function for total heat transfer values gained by simulation.

The cooling of the smooth plate determined by numerical simulation is almost perfectly the same as the cooling curve measured by the experiment. The cooling curve of the dimpled plate is in Figure 13, and the difference between measured and numerically determined data is very small.

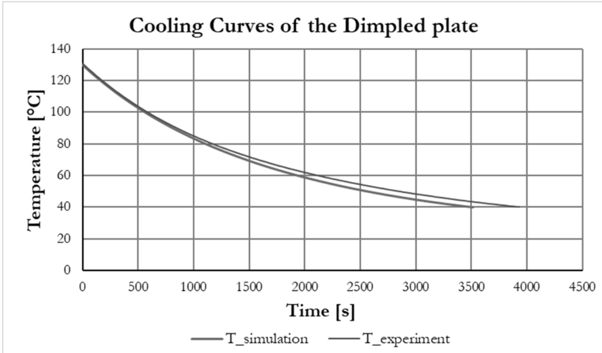

Fig. 13 *Dimpled plate cooling curves from experiment and numerical simulation*

Figures 14 and 15 show comparisons of heat transfer rates between measurement and simulation. The change in the simulation curve trend is caused by the change in the simulation model from laminar to k-omega.

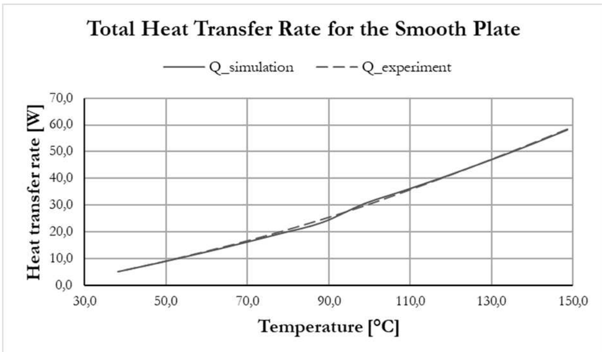

Fig. 14 *Graphs of heat transfer from experiment and numerical simulation for the smooth plate*

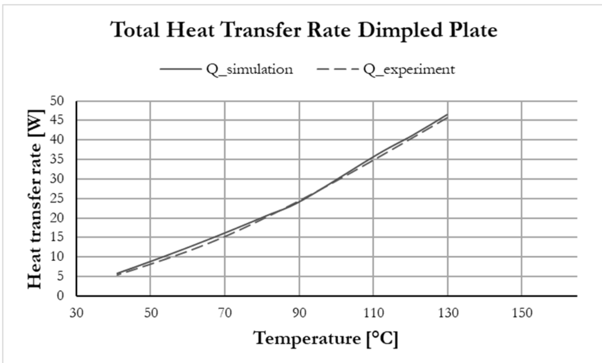

Fig. 15 *Graphs of heat transfer from experiment and numerical simulation for the dimpled plate*

In the case of barrels (see Figure 16), the difference between cooling curves from measurement and numerical simulation is bigger. The reason is probably in the use of a steady-state method of numerical simulation, which doesn't include unsteady flow above the cylindrical barrels. The Kármán vortexes above the barrels (see Figure 17) change the course of flow and the speed of cooling.

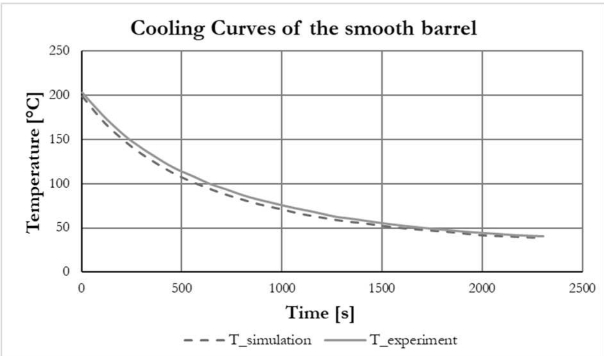

Fig. 16 *Smooth barrel cooling curves from experiment and numerical simulation*

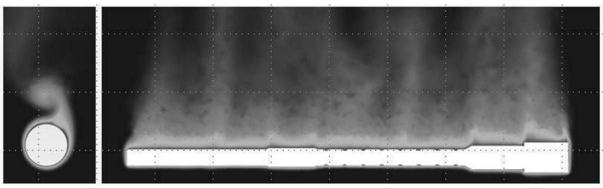

Fig. 17 *The visualization of the temperature field of the dimpled barrel with detail of barrel cross-section on the left*

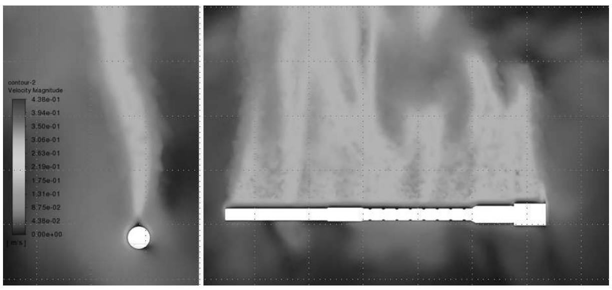

Fig. 18 *The visualization of the velocity magnitude field of the cooled dimpled barrel*

5 Conclusion

The experimental results show that the dimpled surface has a positive effect on increasing the heat transfer rate of the barrel to the environment. The cooling process of the barrel with a dimpled surfaced surface is faster than that of a smooth surface by 15 minutes - instead of the 49.5-minute cooling of the smooth barrel is the 34.5-minute cooling of the barrel with a dimpled surface.

From the comparison of measured data and data gained from numerical simulation, it can be seen that CFD steady-state simulation using ANSYS Fluent software is a reliable method to describe the buoyancy-driven heat transfer process on plane objects, and can be used as a substitution method for determination of radiation and convective heat transfer of various structured surfaces.

For cases of the cylindrical-shaped barrel is necessary to use a transient approach because of the Kármán vortex origins. This study, including the study of Reynolds number influence, will follow this article.

As another possibility of developing the idea of accelerating the cooling of components by modifying the surface structure, it is also possible to think about the material of the cooled component itself. With appropriately chosen casting technology, milling and surface treatment, various surface properties can be achieved, which can contribute to speeding up the cooling process. [8], [9], [10].

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