

Estimation of Thermal Contact Conductance between Blank and Tool Surface in Hot Stamping Process

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Abstract. In hot stamping, the determination of the thermal contact conductance values between the blank and tool surface during the process is crucial for the purpose of simulating the blank rapid cooling inside the tool using finite element analysis (FEA). The thermal contact conductance value represents the coefficient of the heat transfer at the surface of two solid bodies in contact and is known to be influenced greatly by the applied pressure. In order to estimate the value and its dependency on applied pressure, the process of hot stamping was replicated and simplified into a process of compression of heated flat blank in between the tool at different applied pressure. The temperature of the blank and tool surface were measured by means of thermocouples installed inside the tool. Based on the measured temperature, the thermal contact conductance between the surfaces was calculated using Newton's cooling law equation. The calculated value was then used to simulate the blank cooling inside the tool using FEA commercial software. This paper describes an experimental approach to estimate the thermal contact conductance between a blank made of Boron Steel (USIBOR 1500) and tool made of Tool Steel (STAVAX). Its dependency on applied pressure is also studied and the experimental results were then compared with FEA simulations.

1. Introduction

In hot stamping process, pre-cut boron steel sheet is heated to austenization temperature of approximately 900 to 950°C for 5 to 10 minutes in a furnace to induce the microstructure phase of the blank changing to Austenite microstructure. As the temperature is reached, the blank is transferred as quickly as possible to a hot stamping tool to avoid temperature drop. As the tool is closed, the forming operation takes place where the blank is formed into a shape according to the contour surface of the tool (figure 1). This forming operation must take place before the start of the martensitic transformation. As the tool reach the bottom end stroke, it will dwell for a certain time (depending on the blank size) to allow quenching or rapid cooling to take place. At this stage the blank needs to be cooled down at a minimum cooling rate of 30°C per second to force the microstructure phase transformation of the boron steel blank from austenitic phase to fully martensitic phase thus giving final part strength of 1500MPa (Altan, 2006). Soon after that, the tool is opened to remove the formed blank and this formed blank is ready for the next operation.



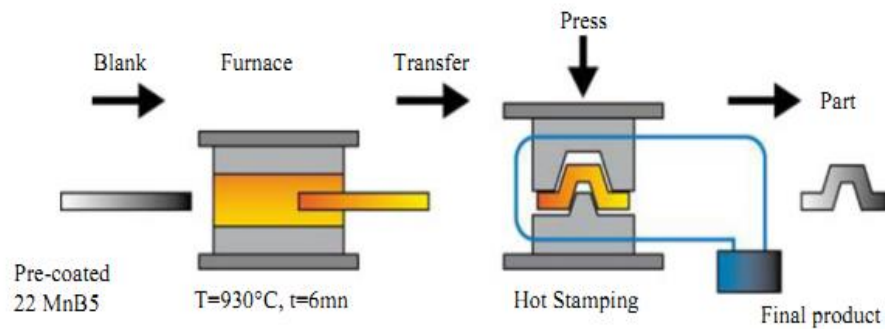


Figure 1. Typical process flow of Hot Stamping process (Abdul Hay et al., 2010).

1.1. Heat transfer in Hot Stamping Process

During forming of the blank, the heated blank always assumed to have perfect contact but in actual some of the surfaces are not in contact due to the surface roughness and waviness of both surfaces. This imperfect contact offers some resistance to heat flow since air has poor thermal conductivity (figure 2). As a result, the heat transfer efficiency or to be specific the thermal contact conductance is greatly reduced (Cengel, 2006). Ideally the blank and die insert interface should have a perfect contact, the presence of air gap in between the blank and die insert surface will reduce the heat transfer efficiency tremendously while the pressure applied to press the two surface against each other is known to be directly proportional to heat transfer efficiency (Merklein and Lechler, 2009).

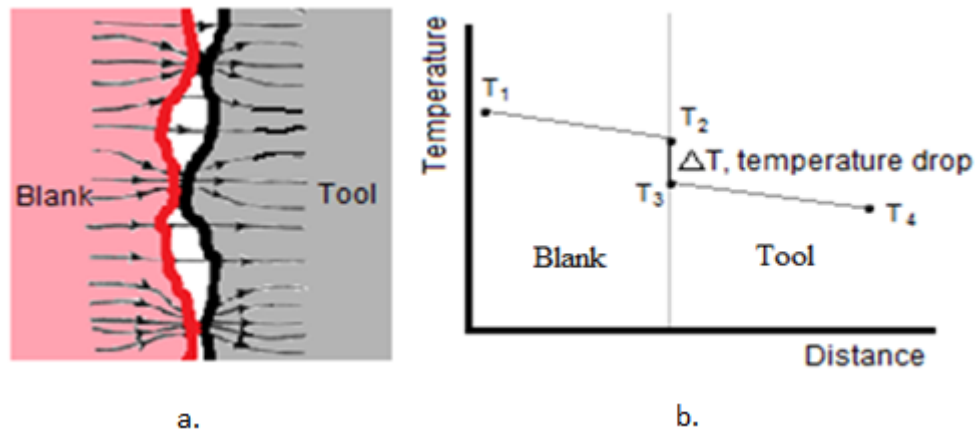


Figure 2a. Illustration of imperfect contact between heated blank and tool
b. the temperature different between two surfaces (Zahari Taha, 2012)

Based on Newton cooling law and an assuming that the of total heat transfer to the tool is equal to the rate of heat changes in the blank, so the heat transfer coefficient or the thermal contact conductance, h_c is given by (Merklein et al., 2009):

$$h_c = \frac{C_p \cdot \rho v}{A \cdot t} \ln \frac{T(t) - T_\infty}{T_0 - T_\infty} \quad 1$$

Where h_c is the thermal contact conductance, A is contact area, C_p is the specific heat of boron steel and ρ is the density of boron steel, v volume of boron steel, T_t blank surface temperature at time t , T_0 initial blank temperature and T_∞ infinite blank temperature

2. Methodology

In order to estimates the thermal contact conductance, h_c as well as studies its dependency on applied pressure, the actual process of hot stamping process is simplified into a simple compression of heated flat blank in between the tool as shown in figure 3. To maintain the consistency and repeatability, the

simplified process is designed to press the flat blank in between the experimental tool without any permanent deformation of the blank specimen.

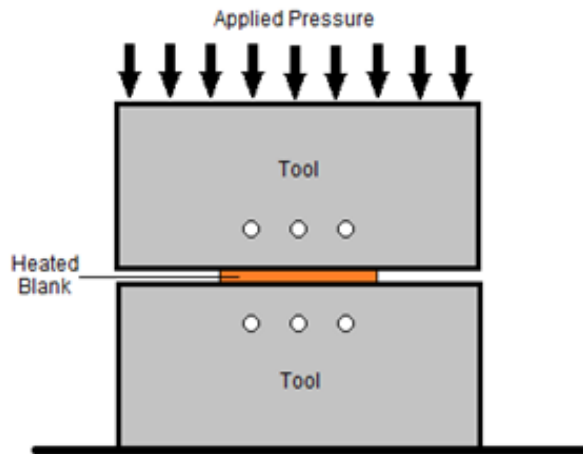


Figure 3. A simple compression of the heated blank/specimen between a set of experiment tool replicate the actual hot stamping process.

2.1. Finite Element Analysis

The finite element analysis is carried out using COSMOS Works finite element analysis software. The main purpose of this analysis is to simulate the blank temperature change based on thermal contact conductance value from the previous research work (Merklein et al., 2009). Assuming the heat transfer to the tool with the same magnitude but different direction (symmetrical), the FEA simulation is simplified by modelling the half thickness blank and lower tool only as shown in figure 4.

In the analysis, the flat rectangular blank assigned as Boron Steel material is pressed inside the tool assigned as Tool Steel material. The finite element analysis is consisted of two analysis which is; first analysis on blank cooling during transferring from furnace to the tool to estimate the final temperature of the blank after transferring to the tool. While second analysis is analysis of blank cooling inside the tool to simulate the temperature change of the blank as it is in contact with the tool.

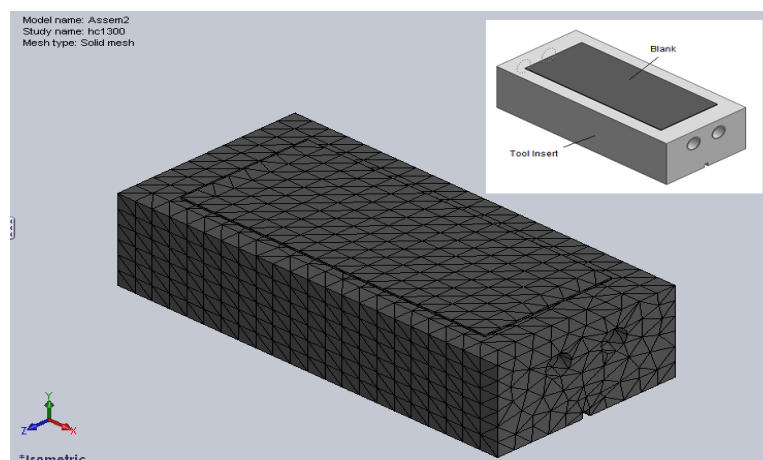


Figure 4. 3D model of experimental tool insert and the half thickness blank used in thermal analysis.

Table 1: Summary of thermal load and boundary condition in FEA simulation for each element

No	Element	Thermal load and boundary condition
1.	Blank	<ul style="list-style-type: none"> - Initial blank temperature based on analysis of heat loss during transferring.
2.	Tool Insert	<ul style="list-style-type: none"> - Initial tool temperature of 25°C. - Heat convection to cooling fluid: 4877.4 W/m²K (based on calculation). - Heat convection to air: effective value based on and air temperature at 30°C - Thermal contact conductance based on the calculated values.
3	Cooling Fluid	<ul style="list-style-type: none"> - Fluid temperature of 25°C

2.2. Experimental setup

The experiment is conducted by compressing the blank specimen heated to austenization temperature (950°C) in the experimental tool for a predetermined duration. The test specimen is made off coated boron steel (code name USIBOR 1500P) with dimensions of 120.0mm (length) X 50.0mm (width) X 1.7mm (thickness) and the tool insert with an initial temperature of 25°C is made of STAVAX Tool Steel material chill water circulated in the cooling channel. The experiments are repeated at different value of applied pressure from 0, 5, 10, 20, 30 and 35MPa. Pressure is applied to the specimen by means of hydraulic cylinder pressing the upper tool as shown in figure 5. At the same time thermocouples measure the blank and tool temperature. Based on the measured temperature values, the thermal contact conductance between the blank and tool calculated using equation 1.

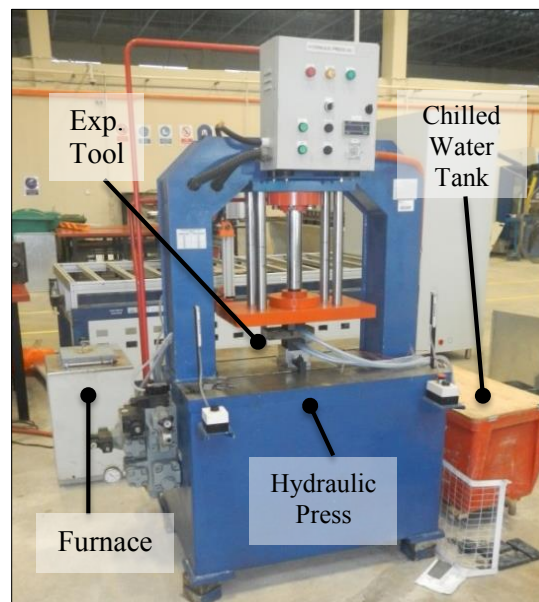


Figure 5. The actual setup for the experiment to estimate the thermal contact conductance between blank and tool surface.

3. Results

As been discussed previously, the studies done to estimate the thermal contact conductance between the blank and tool surface as well as to analyze the influence of applied pressure on the thermal contact conductance based on FEA Analysis and validate by experimental approach.

In general, the result of both approach (FEA and experiment) shows almost a similar pattern. Based on the result graphs both approach shows the blank temperature dropped suddenly as soon as the analysis start (in case of FEA) or the blank in contact with the tool (in case of experiment). At the end of analysis/experiment, the blank temperature cools down to a temperature of below 100 °C within 12 second. Based on the graph of temperature change over time, the blank shows a similar pattern for all value of thermal contact conductance but with different cooling path as well as maximum temperature as shown in figure 5 below.

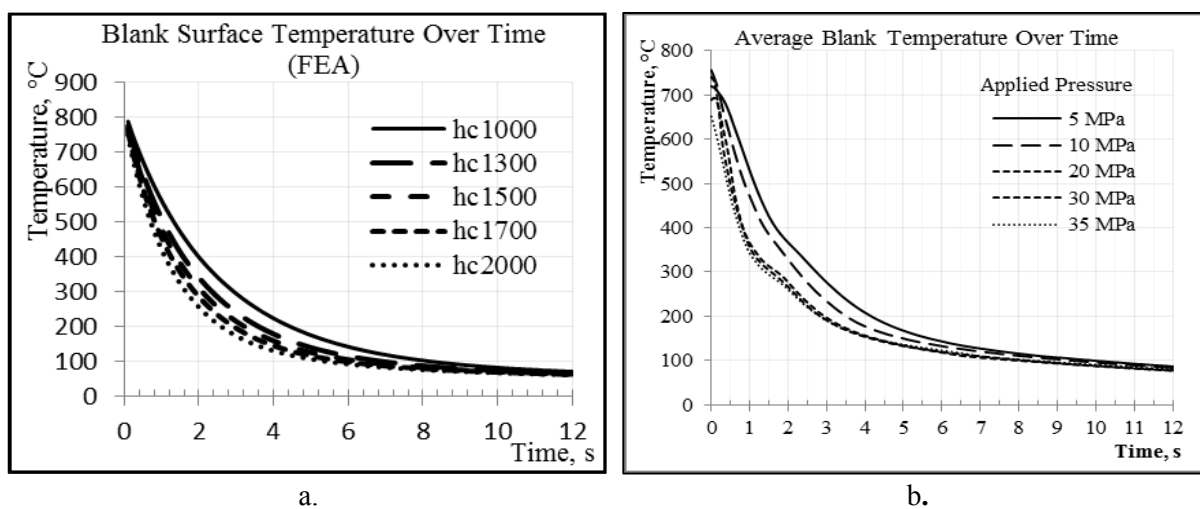


Figure 5 a. Blank temperature changes over time in FEA analysis
b. Blank temperature change over time in experimental work

Based on the results, average thermal contact conductance value is calculated according to equation 1 and plotted against blank temperature as shown in figure 6. It is observed that, the thermal contact conductance between the blank and tool varies with the blank temperature. At any values of applied pressure, the average thermal contact conductance between the blank and tool surface increase from its initial value to a peak value at temperatures between 400 to 500°C. Beyond that the average thermal contact conductance values start to decrease. The average thermal contact conductance value also increases with increasing value of applied pressure from 5 to 30MPa but slightly decreases at applied pressure of 35MPa.

As comparison (Merklein et al., 2009) the thermal contact conductance between a blank made of boron steel USIBOR 1500P and metallic tool, the result (figure 8) shows a similar pattern. It's concluded that the thermal contact conductance value increases with increasing value of applied pressure and this value varies with the blank temperature. The results from Merklein (figure 7) shows the thermal conductance values to be slightly lower than the average thermal contact conductance value from the experiment (figure 6). This is due to tool material properties which influence the heat transfer between the contact interfaces. A tool material with high thermal diffusivity property will disperse the heat from the tool surface in contact with the blank to the cooling channel faster causing lower tool surface temperature achieved and lower thermal contact conductance values. In addition, at high pressures (≥ 20 MPa) the thermal contact conductance value will decrease instantaneously as it reached the peak value. In contrast with low thermal diffusivity material, the thermal contact conductance value will remain stagnant value while before it starts to decrease. In addition to that, the

average thermal contact conductance between the blank and tool is then calculated based on the experimental results and this calculated value will be used in finite element analysis.

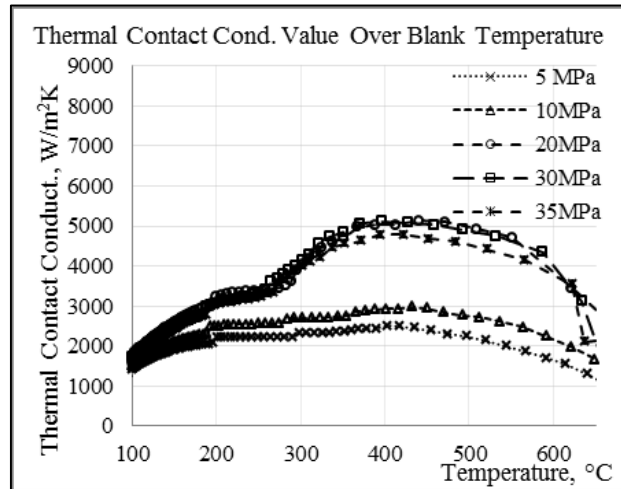


Figure 6. Calculated thermal contact conductance between blank (boron steel) and tool (STAVAX) tool steel) as function of temperature of the blank.

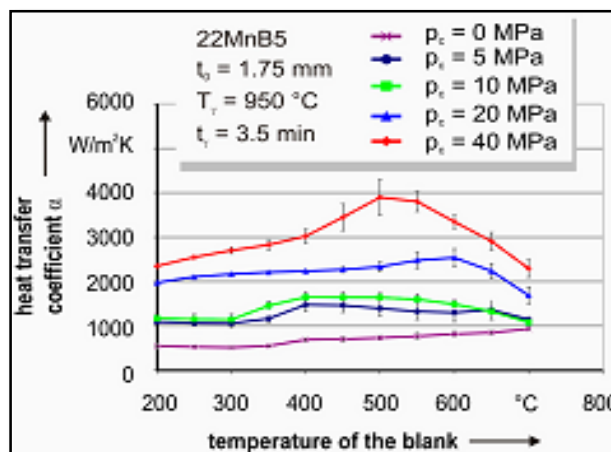


Figure 7. Result of calculated thermal contact conductance at various applied pressure by Merklein (Merklein et al., 2009).

4. Discussion

Although the FEA simulation and experimental results have shown the correlation between both parameters (applied thermal contact conductance and applied pressure) but the FEA simulation result show some deviation compared to actual experimental results. In the FEA result graphs shows that at any value of applied pressure the results correspond to the experimental result for the austenite microstructure phase only (temperature region $\geq 400^\circ\text{C}$). Whereas at temperature region less than 400°C where the phase transformation from austenite to martensite occurs, the FEA simulation result starts to deviate as shown in graph figure 8-12. This is because of the FEA simulation did not account for the internal heat generated due to phase transformation from austenite to martensite. The phase transformation releases about 135KJ/kg heat and this internal heat generates as function of martensite transformation rate (Abdul Hay et al., 2011).

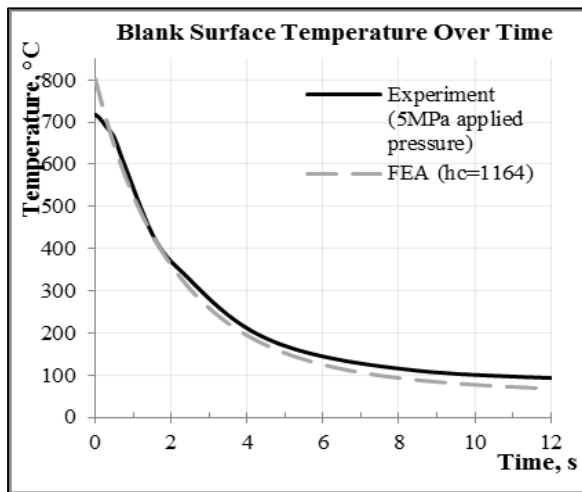


Figure 8. Comparison of blank temperature change over time between the experimental (5MPa applied pressure) and the FEA simulation (calculated $h_c=1164\text{W/m}^2\text{K}$).

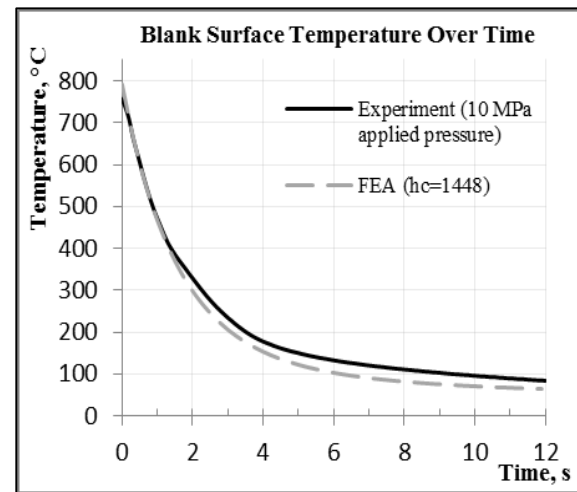


Figure 9. Comparison of blank temperature change over time between the experimental (10MPa applied pressure) and the FEA simulation (calculated $h_c=1448\text{W/m}^2\text{K}$).

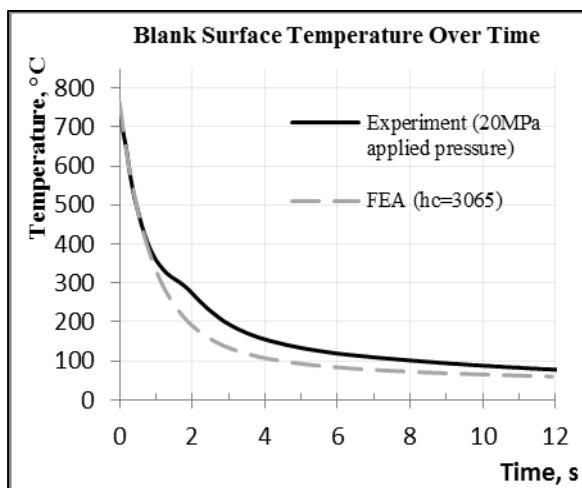


Figure 10. Comparison of blank temperature change over time between the experimental (20MPa applied pressure) and the FEA simulation (Calculated $h_c=3065\text{W/m}^2\text{K}$).

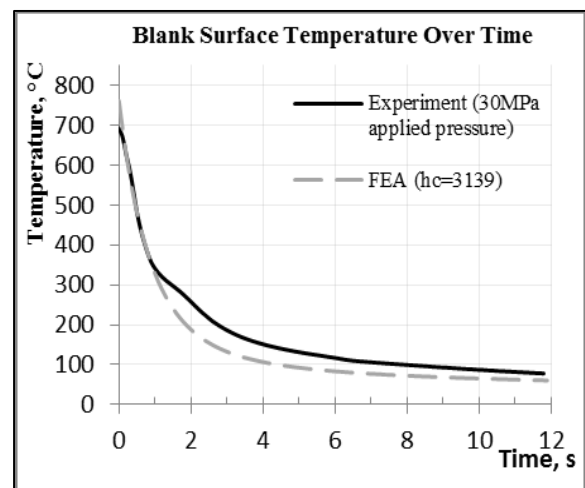


Figure 11. Comparison of blank temperature change over time between the experimental (30MPa applied pressure) and the FEA simulation (Calculated $h_c=3139\text{W/m}^2\text{K}$).

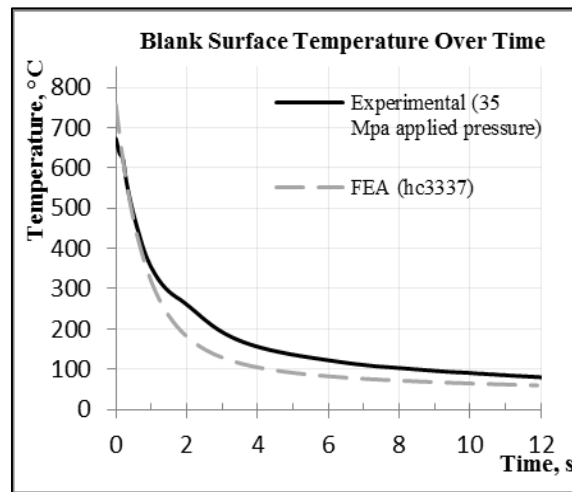


Figure 12. Comparison of blank temperature change over time between the experimental (35MPa applied pressure) and the FEA simulation (Calculated $hc=3337\text{W/m}^2\text{K}$)

The cooling rate of the blank in the actual experiment is calculated by dividing the temperature difference (austenization temperature – exit temperature) with the total time taken (from the moment the blank leaves the furnace until the blank reach the exit temperature). The average cooling rates of the blank is found to be 60.0, 63.6, 66.4, 67.0 and 67.6 °C/s for the applied pressure of 5, 10, 20, 30 and 35 MPa respectively as shown in figure 13.

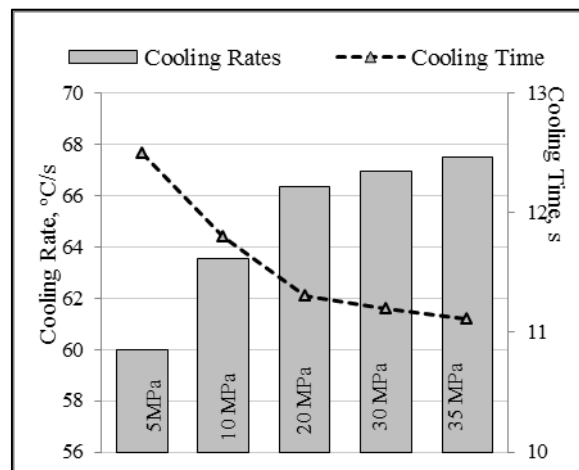


Figure 13. Comparison of average blank cooling rates and blank cooling time achieved in the actual experiment.

5. Conclusion and future work

The main aim of this research is to estimate the thermal contact conductance value between the blank and tool surface in contact during hot stamping and to investigate the influence of applied pressure on the thermal contact conductance value. The FEA simulation was found to be closed to the experiment results during the austenite microstructure phase. While during the phase transformation from austenite to martensite: for example:

- The FEA simulation need consider the internal heat generated due to the microstructure phase transformation.

- In order to have a better understanding in actual hot stamping process, mechanical deformation of the blank as well as the sliding friction between the blank and the tool surface need to be considered.

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