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Numerical Model of Heat Transfer Coefficient in Hot Stamping Process

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Abstract: Due to the demands to reducing the gas emissions, energy saving and producing safer vehicles have driven the development of ultra high strength steel. Since the mechanical properties of ultra high strength steel are remarkably high, it has become a major setback for forming process and this has led lead to the development of special forming technique for ultra high strength steel called Hot Stamping. In hot stamping, the ultra high strength steel blank is heated to its austenization temperature of about 900 - 950 °C inside the furnace. Then, the heated blank is transferred to the tool where forming takes place and simultaneously quench the blank inside the tool. As the tool dwells, the microstructure of the blank becomes fully martensite thus giving the final part strength of up to 1500 MPa. In order to have a better understanding of the Hot Stamping Process, a numerical model of heat transfer need to be developed to simulate the temperature changes of the blank as well as validate the heat transfer coefficient (HTC) of the blank and tool contact surface as a function of distance and time. The numerical model is based on the heat transfer at the contact surface between the ultra high strength steel blank (Boron Manganese Steel) and the tool made of Tool Steel (SKD11).

Keywords: Numerical Model of Heat Transfer, Hot Stamping Process, Ultra High Strength Steel

1 Introduction

Metallic materials are the common materials used in automotive industries since the automotive industries starting to produce a car in mass production. Although the development and invention of new plastics material in last thirty years drastically increased, but hasn't changed so much. Among the metallic materials, steel sheet contributing almost half of the materials utilization compared to others metallic materials [1].

In the last few years, more and more automotive component has been produced by ultra high strength steel sheet especially for part which is related vehicle safety and also due to the weight reduction purposes. It is due to the high mechanical properties of the ultra high strength steel gain from heat treatment process during the forming process [2]. Although the ultra high strength steel gain its strength through the heat treatment process, an annealed ultra high strength steel (as per deliver) two times stronger than mild steel which impracticable to be form by cold forming process (normal stamping process) [3] (Figure 1). This led the development of specific technique so called 'Hot Stamping' to form ultra high strength steel.

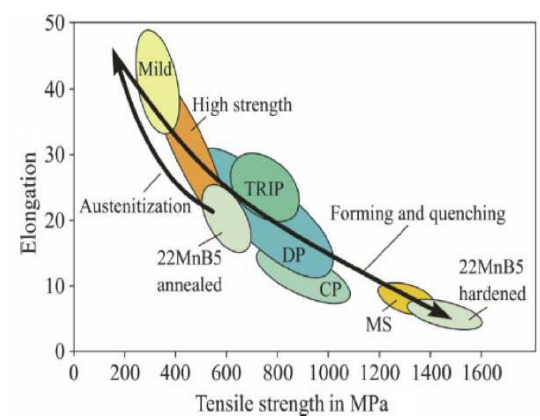

Fig. 1: Graph shows the strength comparison between ultra high strength steel and typical steel for automotive.

1.1 Hot Stamping Process

In hot stamping process, the ultra high strength steel blank is heated to the temperature approximately 1,700

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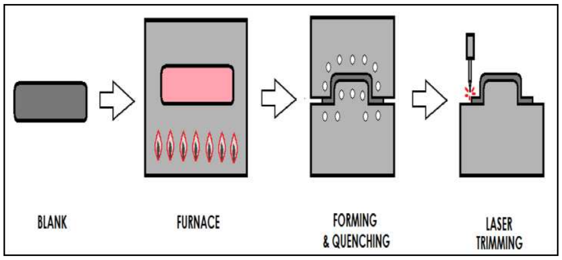

Fig. 2: Direct Hot Stamping Process flow.

degrees F (900 - 950 degrees C) for 5 to 10 minutes in the inside the furnace to change the microstructure of the blank to Austenite structure as shown in Figure 2. To avoid cooling of the part before forming, the blank must be transferred as quickly as possible from the furnace to the press. Then, forming must take place before the beginning of the martensite transformation. Therefore, a fast tool closing and forming process are the precondition for a successful process control. After forming, the part is quenched as the tool dwell at bottom death (closed position), which is cooled by water ducts to transfer the heat out of the tool system.This technique is proven to be effective to reducing the spring-back effect and improved the formability of material thus indirectly reducing the forming force and allowing smaller machine tonnage [4].

1.2 Ultra High Strength Steel

Ultra high strength steel also known as Boron Steel classified as Low Alloyed Steel. This material contains Carbon (C), Manganese (Mn), Silicon (SI) and Boron (B) as an alloying element. The presence of the Boron has greatly improved the hardenability of the steel [6]. The pre-processing Boron Steel has a Ferritic-Pearlitic microstructure has with a tensile strength of about 600 MPa while hardened Boron Steel exhibits a Martensitic microstructure with strength of about 1500 MPa.

Generally Boron Steel will be coated with aluminum-silicon to avoid any oxidation occurs during heating process since it has a direct contact with atmospheric oxygen. During heating, this protective coating is transformed into an alloyed layer of Fe-Al-Si that is highly adherent to the substrate and providing excellent corrosion resistance [7].

2 Methodology

In order to have a better understanding of the heat transfer in hot stamping process, this study will use three different approaches:

1. Numerical model of heat transfer – to simulate the temperature changes of the blank as well as calculating the heat transfer coefficient (HTC) of the blank and tool contact surface.
2. Software analysis – to validate the result from the numerical model
3. Experimental – to record the actual temperature change over time of the blank and tool as well as to study the heat transfer dependency.

In this paper will focus on the first approach using numerical model. The numerical model is based on the heat transfer at the contact surface between the Ultra High Strength Steel blank which is the Boron Manganese Steel and the tool made of Tool Steel (SKD11). Since the main objective of this study is to study the heat transfer so the blank and tool is keep flat to eliminate the heat generated during forming take place as shown in Figure 3.

In order to model the heat transfer process, the partial differential equation (PDE) that governs the heat transfer process needs to be solved. In this case, the partial differential equation is “non-steady one dimension heat transfer” with derivative boundary condition will be solved using Finite Different Method (Crank Nicolson Method) [6] to calculate the temperature for every time step for each nodal point.

2.1 Assumption

In this numerical model, it is assumed that:

1. Heat is transferred in unidirectional and normal to the tool surface.
2. The blank and tool is in perfect contact and heat flux is constant at all point on the blank and the tool interface.
3. The heat flux generated due to heat convection is negligible since the area relatively small.

2.2 One Dimension Heat Diffusion Equation

Consider a 2.0 mm ultra high strength steel blank heated inside the furnace to the temperature 1223 K and brought into contact with the tool surface (assuming that no heat loss during transferring the blank into the tool) with the initial temperature 303 K and the tool is closing instantaneously. As the tool closed, the cooling process take place and the blank will cooled down at rate 30 K/s in average (rate of heat loss = 70.01 J/s) while the tool cooling at a rate 50 K/s. Ideally the heats transfer in unidirectional from the core of the blank (at distance x = thickness/2) toward the tool surface.

From 1st law Statement for closed, nonworking system and heat conduction out of the element during unsteady flow (12):

$$Q_{\text{net}} = Q_{\text{in}} - Q_{\text{out}} \tag{1}$$

So one dimension heat diffusion equation at blank can be written as (13):

$$c\,\rho\,A\,dx\,\Delta T = q(x)\cdot A - q(x+dx)\cdot A \tag{2}$$

Steel grade	C (%) min - max	Si (%) max	Mn (%) min - max	P (%) max	S (%) max	Cr (%) min - max	B (%) min - max
Docol 20MnB5	0.17 - 0.23	0.40	1.10 - 1.40	0.030	0.015	0.10 - 0.30	0.0008 - 0.0050
Docol 30MnB5	0.27 - 0.33	0.40	1.15 - 1.45	0.030	0.015	0.10 - 0.30	0.0008 - 0.0050
Docol 38MnB5	0.36 - 0.42	0.40	1.15 - 1.45	0.030	0.015	0.10 - 0.30	0.0008 - 0.0050
Docol 27MnCrB5	0.24 - 0.30	0.40	1.10 - 1.40	0.030	0.015	0.30 - 0.60	0.0008 - 0.0050
Docol 33MnCrB5	0.30 - 0.36	0.40	1.20 - 1.50	0.030	0.015	0.30 - 0.60	0.0008 - 0.0050
Docol 39MnCrB6	0.36 - 0.42	0.40	1.40 - 1.70	0.030	0.015	0.30 - 0.60	0.0008 - 0.0050

Fig. 3: Chemical composition of the Boron Steel by ASSB [6].

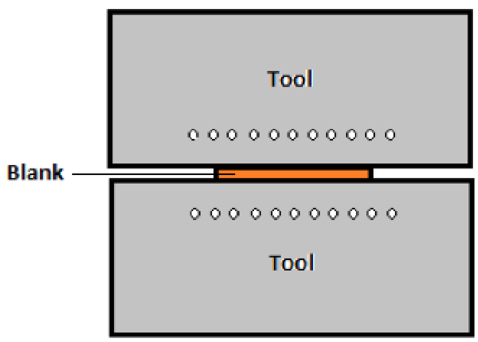

Fig. 4: Illustration of the tool and the blank for the numerical model.

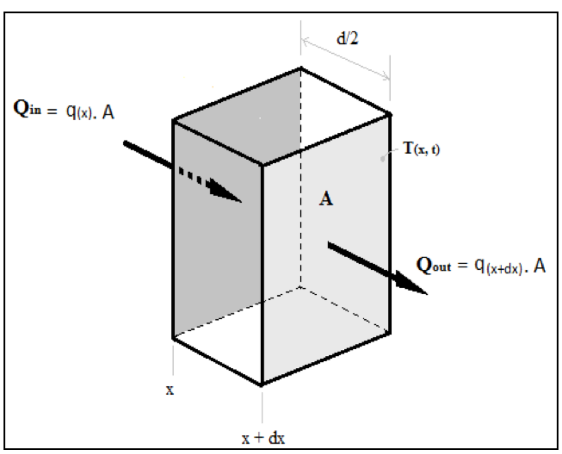

Fig. 5: Heat flow through half thickness of the blank.

Where c is the specific heat (J/kgK), ρ is the density (kg/m^3), A area in (m^2), q the heat flux (w/m^2) and T is the temperature (K). By dividing the equation (3) with the volume of the element, the equation becomes:

$$c\rho\,\Delta t = \frac{q(x) - q(x+dx)}{dx} \tag{3}$$

By applying Fourier Law the equation (4) becomes:

$$\rho c \frac{dT(x,t)}{dt} = -kA\frac{d^2T(x,t)}{dt^2} \tag{4}$$

when $T > Ms$.

Where k is the thermal conductivity (J/m.s.K), $T(x,t)$ temperature at distance x and time t and Ms is the martensite formation temperature. Since there is heat generated due to metallurgical phase transformation from austenite to martensite at the blank, so the equation (4) becomes:

$$\rho c \frac{dT(x,t)}{dt} + Qm = -kA\frac{d^2T(x,t)}{dt^2} \tag{5}$$

when $T < Ms$.

Where Qm is the heat generated due to phase transformation from austenite to martensite. The same method could be applied to the tool and one dimension heat diffusion equation become:

$$\rho c \frac{dT(x,t)}{dt} = -kA\frac{d^2T(x,t)}{dt^2} \tag{6}$$

2.3 Finite Difference Element (Crank Nicolson Method)

In the last section, the derived heat transfer equation for the blank and the tool (equation 5, 6 and 7) classified as partial differential equation. To solve the partial

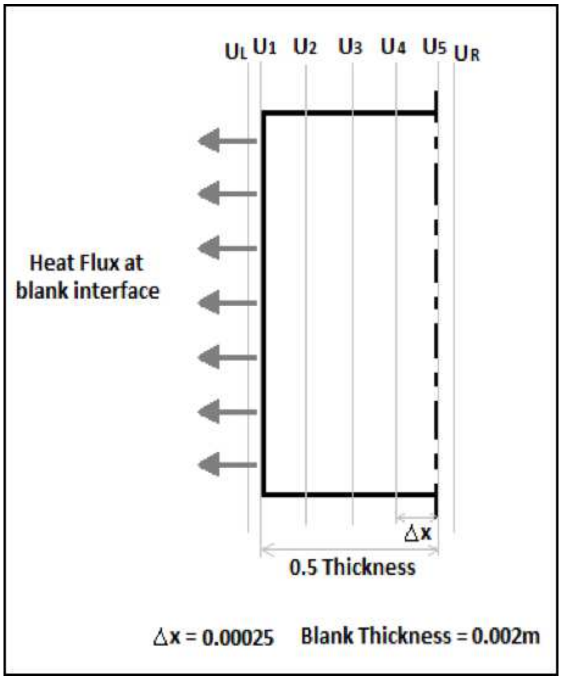

Fig. 6: The element divided into a numbers of grids.

differential equation that governs the heat transfer process, the finite difference element method based on Crank Nicolson approach is used [5].

The simplified Crank Nicolson Method formula:

$$R=\frac{k\Delta t}{c\rho(\Delta x)^2} \tag{7}$$

$$\begin{aligned} &-RU_{i-1}^{j+1}+(2+2R)U_i^{j+1}-RU_{i+1}^{j+1} \\ &=RU_{i-1}^{j}+(2+2R)U_i^{j}-RU_{i+1}^{j} \end{aligned} \tag{8}$$

where k is the thermal conductivity (W/mK), c is the specific heat (J/kgK), ρ is the density (kg/m^3), Δx is the distances spacing between the grid (m), Δt time spacing (s).

All five grid on the element will be treat with equation (8) generating 5 algebraic equation with 10 unknowns. This algebraic equation will be solve using simultaneous equation by rearrange the equation to form a set of 5×5 matrix equation:

$$\begin{pmatrix} (2+2R) & -R & 0 & 0 & 0 \\ -R & (2+2R) & -R & 0 & 0 \\ 0 & -R & (2+2R) & -R & 0 \\ 0 & 0 & -R & (2+2R) & -R \\ 0 & 0 & 0 & -R & (2+2R) \end{pmatrix}$$

$$=\begin{pmatrix} (2-2R) & R & 0 & 0 & 0 \\ R & (2-2R) & R & 0 & 0 \\ 0 & R & (2-2R) & R & 0 \\ 0 & 0 & R & (2-2R) & R \\ 0 & 0 & 0 & R & (2-2R) \end{pmatrix} \tag{9}$$

2.4 Derivative boundary at blank side

At blank interface, $x=0$

$$-kA\frac{dT}{dx}=\frac{-kA(U_2-U_L)}{2(\Delta x)}=-hcA(T_{\text{blank}}-T_{\text{tool}}) \tag{10}$$

$$\text{rate of heat loss } =-hcA(T_{\text{blank}}-T_{\text{tool}})=-70.01 \tag{11}$$

$$U_L=U_2-0.00135 \tag{12}$$

Where k is the thermal conductivity (W/mK), A is the area (m^2), Δx is the distances spacing between the grid (m), hc is the thermal contact conductance (W/m^{2}K) and A is the area of contact (m^2).

At blank core, $x=1.0$

$$-kA\frac{dT}{dx}=\frac{-kA(U_4-U_R)}{2(\Delta x)}=0 \tag{13}$$

$$U_R=U_4 \tag{14}$$

Compute the R value using equation (8) with $\Delta t=1$ s.Treat U_1 grid on the blank with equation (9) (Crank Nicolson Method) this will lead to a set of algebraic equations:

$$\begin{aligned} &-86.494U_L^{j+1}+174.988U_1^{j+1}-86.494U_2^{j+1} \\ &=86.494U_L^{j}-170.988U_1^{j}+RU_2^{j} \end{aligned} \tag{15}$$

Substitute equation (12) into equation (15):

$$\begin{aligned} &174.988U_1^{j+1}-172.988U_2^{j+1} \\ &=-170.988U_1^{j}+172.988U_2^{j}-0.24 \end{aligned} \tag{16}$$

Treat others grid on the blank with equation (9) (Crank Nicolson Method) this will lead to a set of algebraic equations:

$$-86.494U_1^{j+1} + 174.988U_2^{j+1} - 86.494U_3^{j+1} = 86.494U_1^j - 170.988U_2^j + RU_3^j \quad (17)$$

$$-86.494U_2^{j+1} + 174.988U_3^{j+1} - 86.494U_4^{j+1} = 86.494U_2^j - 170.988U_3^j + RU_4^j \quad (18)$$

$$-86.494U_3^{j+1} + 174.988U_4^{j+1} - 86.494U_5^{j+1} = 86.494U_3^j - 170.988U_4^j + RU_5^j \quad (19)$$

$$-86.494U_4^{j+1} + 174.988U_5^{j+1} - 86.494U_R^{j+1} = 86.494U_4^j - 170.988U_5^j + RU_R^j \quad (20)$$

Substitute equation (14) into equation (20):

$$\begin{aligned} &-172.988U_4^{j+1} + 174.988U_5^{j+1} \\ &= 172.988U_4^j - 170.988U_5^j \end{aligned} \quad (21)$$

Rearrange the equation and transform it into a matrix form:

$$\begin{pmatrix} 174.988 & -172.988 & 0 & 0 & 0 \\ -86.494 & 174.988 & -86.494 & 0 & 0 \\ 0 & -86.494 & 174.988 & -86.494 & 0 \\ 0 & 0 & -86.494 & 174.988 & -86.494 \\ 0 & 0 & 0 & -172.988 & 174.988 \end{pmatrix}$$

$$= \begin{pmatrix} 170.988 & 172.988 & -0.24 & 0 & 0 \\ 86.494 & -170.988 & 86.494 & 0 & 0 \\ 0 & 86.494 & -170.988 & 86.494 & 0 \\ 0 & 0 & 86.494 & -170.988 & 86.494 \\ 0 & 0 & 0 & 172.988 & -170.988 \end{pmatrix} \quad (22)$$

Simultaneous equations for temperature distribution at the blank need to be solved using matrix operation:

$$Au^{j+1} = Bu^j \quad (23)$$

$$u^{j+1} = (A - B)u^j \quad (24)$$

3 Results

Figure 7 shows the temperature change over the time by the blank. Based on the numerical model, the blank take about 50 s to reach the Ms temperature (< 400 °C), with temperature (based from numerical model) descending gradually less than 20 K/s for 50 s (Figure 8).

During the actual process, the cooling of the blank represent by the exponential pattern compared to the graph plotted from the numerical model (Figure 8). It is observed that the actual process take less than 10 s to reach the Ms temperature, the temperature where the martensite microstructure starts to build up. At this point, it is critical to have the blank cooled to a temperature of less than < 400 °C in the first 15 s of the quenching process. Otherwise the cooling path of the blank will be dragged into phase mixture between austenite and bainite reducing the strength of the final microstructure as well as the final part.

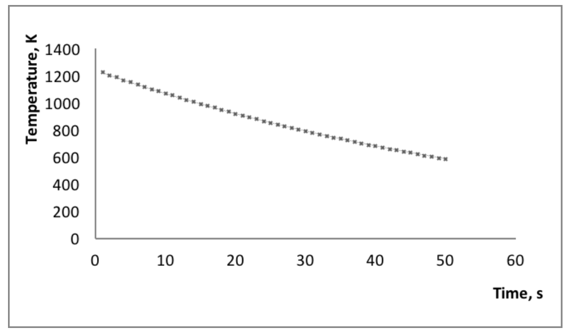

Fig. 7: The temperature change over time based on the numerical model.

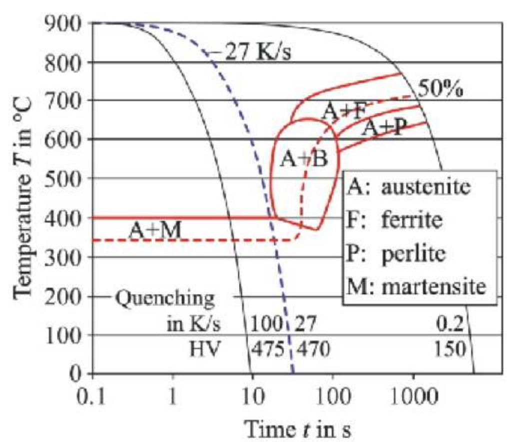

Fig. 8: The critical cooling rate of ultra high strength steel blank during hot stamping process [1].

It is due to the defined rate of heat loss at the blank (cooling rate 30 K/s or 70.01 J/s) is based on the average cooling rate of the blank causing the temperature of the blank (based from numerical model) to decrease gradually. As compared to the actual graph, the cooling rate for the first 10 s reached up to 100 K/s. This numerical model could be improved with the use of actual data taken from a future experiment.

4 Conclusion

The main focus of study presented in this paper is to model the temperature changes at the blank while the tool temperature will be measure in experiment that will be conduct later as well as to model the thermal conductance behaviour in a function of time for the actual cooling rate value.. By knowing both interface temperature (blank and tool), the heat transfer coefficient or thermal contact resistance (Rc) at the interface could be calculate using

$$R_c = \frac{T_{\text{blank}} - T_{\text{tool}}}{\phi} \tag{25}$$

Where R_c is the thermal contact resistance at the blank and tool interface, T_{blank} is temperature of the blank in Kelvin (K) and T_{tool} is tool temperature in Kelvin (K) and ϕ is the heat flux density (w/m^2)

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