Numerical Investigation on 22MnB5 Thinning Features in Hot Forming

Dong-cheng Li*, Guo-hui WANG, Hua-min LIU and Na-na HAN
Roll Forging Institute, Jilin University, Changchun, People's Republic of China

*Corresponding author

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Abstract. Thinning features of 22MnB5 in hot forming process were investigated by simulation of AUTO-FORM on the base of verification of the results in a published paper. The thinning of 22MnB5 in the isothermal forming process was calculated and the effect of temperature on cracking was evaluated. A mathematics model of forming limit, which is called FLE (Forming Limit Equation), is recommended to predict the cracking of the sheet in the hot forming process in stead of FLD (Forming Limit Diagram). And effect of other parameters, i.e. blank holding force, friction coefficient, thickness of sheet and strain rate, was also investigated.

Introduction

In general, the steel used in cold stamping is the low carbon steels with the carbon content usually 0.08%, 0.15% and 0.2%. This type of steel, characterized by good cold ductility, cold-work hardening, low strength and etc., is used in the automobile industry on a large scale. In order to reduce the vehicle weight and improve safety and crashworthiness qualities, the components made by the ultra high strength steel were developed [1-4].

22MnB5 is the most common ultra high strength steel used for sheet metal forming in the automobile. Components of the material, with martensitic microstructure, are usually produced by the hot stamping process, which includes direct and indirect hot stamping method [4-6]. In addition to parameters of conventional sheet forming, thermal, microstructure parameters should be controlled for good mechanical properties of components during hot stamping process. Hot forming is a complicated process. There are some parameters to affect the forming process. If some parameters are not selected properly, some defects, such as crack, spring-back etc., will be inevitable; and the desired mechanical properties of the forming components will not be achieved. The starting and finishing temperatures of the forming process are the important parameters in the hot stamping process. If the forming temperature is too high, the thickness of the sheet will be so thin that it cracks; if too low, the amount of spring-back will be so big that the dimension of the formed part will deviates from the die largely [7-10].

In recent years, software packages were used to predict results about physics, chemistry, mechanics, engineering etc. in microscopic and macroscopic views and help to get deep information. Usually, they are based on the differential equations or famous laws, and can present satisfactory results. There are some software packages of FEM (Finite Element Method), which are successfully used to analyze processes of materials processing. For sheet metal forming, the FEM software packages, such as PAM-STAMP, DYNA-FORM, AUTO-FORM, have been used to help forecast the defects in products.

This paper will present some calculation results with AUTO-FORM to find a proper forming temperature of 22MnB5 sheet, at which the sheet will not crack in the forming process. On the base of verification by the results that were in a published paper, the investigation was done. The thinning ratio was selected to judge if the sheet cracks. And, a mathematics model of forming limit, which is called FLE (forming limit equation), is recommended to predict the cracking of the sheet in the hot forming process in stead of FLC (Forming Limit Curve) or FLD (Forming Limit Diagram). And the effects of other parameters on the thinning were investigated.
Numerical Method

Software, Investigation Parameters Definitions and Validation

In this paper, FEM software of sheet metal forming, called AUTO-FORM, was used to get data for analysis. In the simulation process, the following equation would be solved.

\[ M \dot{U} + C U = P - F \]

Where, \( U \) is accelerated velocity vector of nodes, \( U \) is velocity vector of nodes, \( M \) is mass matrix of nodes, \( C \) is damp matrix of nodes, \( P \) is external force vector and \( F \) is internal force vector.

Thinning, resulting in sheet cracking, is an important feature in sheet metal forming. The thinning ratio is a selected parameter identifying the level of thinning of sheet. The thinning ratio is defined as \( \eta = (h_0 - h_1)/h_0 \), where \( h_0 \) is the initial thickness of the sheet and \( h_1 \) is the thickness of the sheet after deformation. For validation, a simple example of thinning with experimental results was adopted [11]. The calculation precision of the software for the thinning was evaluated by the example shown in Fig.1 [11]. The initial size of the blank is 360mm×40mm×1.4mm. The properties of the materials are shown in Table 1[12]. The gap between the punch and die is 1.75mm; the friction coefficient is 0.11; the thickness of the sheet is 1.6mm. The simulation results of the sheet thickness after deformation are shown in Fig. 1. The results of simulation and experimental measurement are listed in Table 2. The validated results of Table 2 show that the simulation results are agreeable to experiment results. In stead of experiment, simulation results are acceptable to predict the real conditions for the sheet metal forming in this case.

<table>
<thead>
<tr>
<th>Materials</th>
<th>E(GPa)</th>
<th>( \nu )</th>
<th>( \sigma_s ) (MPa)</th>
<th>( \sigma_b ) (MPa)</th>
<th>( n )</th>
<th>( R_0 )</th>
<th>( R_{45} )</th>
<th>( R_{90} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>22MnB5</td>
<td>210</td>
<td>0.30</td>
<td>341</td>
<td>505</td>
<td>0.222</td>
<td>0.90</td>
<td>0.96</td>
<td>1.05</td>
</tr>
</tbody>
</table>

E-modulus of elasticity; \( \nu \)-Poisson ratio; \( \sigma_s \)-yield strength; \( \sigma_b \)-tensile strength; \( n \)-strain hardening index; \( R_0 \); \( R_{45}, R_{90} \)-anisotropic index

Simulation Preparation

Mesh and Element Type. A U-shaped component was used to investigate the features of 22MnB5 for sheet metal forming, as shown in Fig. 2. Simulation results are influenced by the type and number of element. In this investigation, the shell element is selected, the initial number of element is 49926 and the number of layer is 11. The more the number of element is, the higher the calculation precision is; but the more the time of calculation is. In this investigation, the calculation precision is not different as the number of element is more.

The Material Model and the Simulation Parameters. In this investigation, the material is 22MnB5, whose chemical composition is 0.22%C, 1.25%Mn, 0.25%Si, 0.035%Ti, 0.03%Al, 0.2%Cr, 0.03%B, 0.1%Mn, 0.008%S, 0.0025% P. At different temperatures, the elastic moduli and the Poisson ratios are shown in Fig. 3[12]. The flow stresses at different temperatures are shown in Fig. 4 [13]. The yield stresses at different temperatures are: 338MPa at 300℃, 254MPa at 500℃,

<table>
<thead>
<tr>
<th>Locations</th>
<th>bottom</th>
<th>Corner of the bottom</th>
<th>Vertical side</th>
<th>Corner of the die</th>
<th>Horizontal flange</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental(mm)</td>
<td>1.6</td>
<td>1.4</td>
<td>1.5</td>
<td>1.7</td>
<td>1.9</td>
</tr>
<tr>
<td>Simulation(mm)</td>
<td>1.51</td>
<td>1.38</td>
<td>1.39</td>
<td>1.62</td>
<td>1.88</td>
</tr>
</tbody>
</table>

Table 2. The comparison of cylindrical part’s thickness.
167 MPa at 650°C, 95 MPa at 700°C and 72MPa at 800°C [13]. The parameters of the tools in the forming process were set as: initial thickness of blank is 1.4mm, the gap between the die and the punch is 1.8mm, initial holding force of blank holder is 50kN, the depth of forming is 70mm, the radius of the die is 5mm, the radius of the punch is 5mm, the friction coefficient is 0.15; and the temperatures are separately set to 300°C, 500°C, 650°C, 700°C. The flow stresses for different strain rate at different temperatures are shown in Fig. 5 [13].

**Results and Discussion**

**The Effect of Forming Temperature on Thinning Ratio**

When the thickness of the sheet reduces (thinning) to a certain extent, the sheet will crack. Crack is one of the defects in the sheet metal forming process. When thinning is over 30%, the sheet always starts to crack. The sheet of the high strength steel always forms in high temperature—hot forming, due to restraining the big spring-back in cold forming. The thinning ratio distributions for thickness of 1.8mm on the holding force of 50kN at different temperatures are shown in Fig. 6. The negative is assigned to thinning and the positive is assigned to thickening. With temperature rising, the maximum of the thinning ratio increases. The higher the temperature is, the easier the cracking is. The maximum of the values of the thinning ratio changing with thickness at different temperatures are shown in Fig. 7. The higher the forming temperature is, the higher the maximum of the value of the thinning ratio is. For thickness of 1.8mm, the thinning ratio is 21.2% at 700°C, and is 7.7% at 300°C. The thinning ratio is sensitive to temperature.
The maximum major strains of the neutral layer changing with thickness at different temperatures are shown in Fig. 8. The higher the temperature is, the bigger the maximum major strain is. The higher the thickness is, the higher the maximum major strain is.

In general, the flow stress equation of the materials could be written as

$$\sigma = K \varepsilon^n \dot{\varepsilon}^m$$  \hspace{1cm} (1)

where $n$ is the strain hardenability value, $m$ is the strain rate sensitivity exponent, $n$ is one of the important parameters in sheet metal forming. If $n$ is bigger for a material, the material is easy to be hardened and the same deformation of strain will result in higher degree of material hardening to make the material difficult to deform. For different regions in the deformed sheet, the region that is
easy to deform will result in high strain. The flow stress will increase and make the material in that region difficult to deform. The material in that region will stop deformation. The region that is less easy to deform will start deforming because of no hardening. The reason is that the flow stress will be bigger in the region of the easy deformation than that in the region of less easy deformation. Thus, the different regions will deform uniformly and the difference of the thicknesses at different regions will be little. The whole plastic deformation will be distributed at different regions, the degree of localized deformation will decrease, and the sheet will not be easy to crack in the sheet metal forming process.

When raising the temperature, the material hardenability value $n$ will be reduced. At the higher temperature, the recovery and the recrystallization will occur easily. The material will be difficult to harden and necking. The higher the temperature is, the smaller the value $n$ is and the easier necking is. The temperature must be low enough to avoid cracking. From Fig. 7, the thinning ratio is about 10% at 500°C, which is an acceptable temperature for forming. The thinning ratio is about 15% at the temperature of 650°C, at which the sheet is easy to crack. At a temperature, the thinning ratio and the maximum major strain increase slightly for different thicknesses. The higher the temperature is, the bigger the maximum major strain is. For thickness of 1.2mm, the maximum major strain is 0.045 at 300°C; and 0.118 at 500°C; and 0.167 at 700°C. The higher the temperature is, the smaller the material hardenability value $n$ is and the easier necking is. Thus, the thinning is heavier, the major strain is bigger, and more likely the cracking of the sheet is.

Figure 7. The maximum absolute value of thinning ratio changes with thickness at different temperatures.

Figure 8. The maximum major strain of neutral layer changes with thickness at different temperatures.

Figure 9. The forming limit diagram from simulation at different temperatures, (a) 300°C (b)500°C (c)650°C (c) 700°C.
A Forming Limit Equation for Hot Forming

The forming limit diagrams (FLD) of 22MnB5 from the simulation, where the defect is cracking, no wrinkling, are shown in Fig. 9. The area of green points is safe; the yellow is dangerous; and the area above the red line is the cracking region. The slope of the border line of the green area is almost 1 for every temperature.

In the forming process, the total strain can be expressed as:

\[
\varepsilon = \varepsilon_1 + \varepsilon_2 + \varepsilon_t = \varepsilon_i + \varepsilon_p + \varepsilon_e + \varepsilon_t
\]  
(2)

where, \(\varepsilon_e = (\varepsilon_1 + \varepsilon_2 + \varepsilon_t)/3\), \(\varepsilon_i = \varepsilon_1 + \varepsilon_2 + \varepsilon_t\), \(\varepsilon_c\) the elastic component of the strain \(\varepsilon\), \(\varepsilon_p\) the plastic component of the strain \(\varepsilon\), \(\varepsilon_t\) the strain of thickness, \(\varepsilon_1\) major strain, \(\varepsilon_2\) minor strain, and \(\varepsilon_t \geq \varepsilon_1\).

So,

\[
\varepsilon_1 + \varepsilon_2 = \varepsilon_3 + \varepsilon_t
\]

(3)

After unloading, the elastic part of the deformation will recover, i.e. \(\varepsilon_3 = 0\). And the equation (2) will be:

\[
\varepsilon_1 + \varepsilon_2 = \varepsilon_0 - \varepsilon_t
\]

(4)

We assume the material is not compressibility. So, \(\varepsilon_p = 0\). And the equation will be:

\[
\varepsilon_1 + \varepsilon_2 = -\varepsilon_t = C
\]

(5)

When the strain reaches a certain value, we usually think that the sheet of the material is extremely likely to crack. Because the thickness is reductive in the sheet metal forming process, the plastic deformation will occur in the forming process to restrain the formation and propagation of the micro crack. The stress condition relates to the formation of micro crack. The hydrostatic stress can be expressed as: \(\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3\), where \(\sigma_1, \sigma_2, \sigma_3\) are the principal stress in the three principal directions.

The hydrostatic stress would take effect in the forming process to restrain the formation and propagation of micro crack. The more the hydrostatic pressure component of the stress \(\sigma_m\) is, the more difficult the formation and propagation of the micro crack is. The equation (5) can be called forming limit equation (FLE). It can used to judge if the sheet crack. When the strain of thickness \(\varepsilon_t\) is \(\varepsilon_0\) (safe strain for cracking), the sheet is safe and the equation could be called the safe area equation. When the strain of thickness \(\varepsilon_t\) is \(\varepsilon_c\) (cracking strain), the sheet will crack and the equation could be called the cracking area equation. Usually, \(C\) is not a constant. It is a function of stress, i.e. a function of \(\varepsilon_1\) and \(\varepsilon_2\). Therefore, the equation (5) is not linear. When \(C\) is constant, the function of equation (5) is a line, and can be draw a line in Fig. 10. The line \(\varepsilon_1 + \varepsilon_2 = C\) is divided into two part by the red pint. The magenta part is region for \(\varepsilon_1 \geq \varepsilon_2\) and the black part is for \(\varepsilon_2 \geq \varepsilon_1\). Because \(\varepsilon_1\) is major strain and \(\varepsilon_2\) is minor strain, the magenta part \(\varepsilon_1 \geq \varepsilon_2\) is FLD. The green part, which is below the line of FLF i.e. \(\varepsilon_1 + \varepsilon_2 = \varepsilon_0 \leq C\), is safe area. It is identical with Fig. 9. The equation (5) can easily be used to predict if a point on the deformed sheet is safe. For 22MnB5, the safe strain for cracking \(\varepsilon_c\) is 0.35. The FLE of safe region of cracking is \(\varepsilon_1 + \varepsilon_2 = 0.35\).

The Effect of Parameters on Thinning Ratio

There are other parameters except temperature in the sheet metal forming process, such as blank holder force, blank thickness, friction, and strain rate. Fig. 11 shows the effect of the parameters on thinning at different temperatures. The effect of the blank holder force on the thinning is shown in Fig. 11(a). The higher the temperature is, the faster the change of the thinning ratio is. The effect of the blank holder force is more obvious. With the blank hold force increasing, there is less of the material flowing into deformation area. The material of deformation mainly focuses on the material under the punch. When the temperature is lower, recovery and crystallization is difficult to occur.
Due to higher flow stress, more of the material will flow into the deformation area and the thinning ratio will change slowly. The effect of the thickness on the thinning ratio is shown in Fig. 11(b). The effect of the thickness is not more obvious than the blank holder force. With the thickness increasing, there is more material in the deformation area and the strain will be small. Thus, there will be small strain hardening. So, localization is easy and the thinning ratio will increase. The effect of the friction coefficient on the thinning ratio is shown in Fig. 11(c). There is a little effect of friction on thinning ratio. With temperature increasing, the thinning ratio will increase. When temperature is higher, the recovery and the recrystallization is easy to occur, the material is not easy to harden, the flow stress is not easy to rise, there will be little materials flowing into the deformation area, and the deformation focuses on thinning area. The thinning ratio is not sensitive to the friction coefficient, because there is little change in the material flowing into the deformation area when friction coefficient changes. The effect of the strain rate on thinning is shown in Fig. 11(d). When temperature is low at 300°C, the thinning ratio does not change with the increasing of strain rate because the strain rate sensitivity exponent m in equation (1) is close to zero. When temperature is over 500°C, the thinning ratio decreases with the strain rate rising. When raising temperature, the dislocation is easy to move and pile up resulting in the resistance of deformation. So, the yield strength will rise and the strain rate sensitivity exponent m will not be zero. Thus, the deformation will be uniform, the localization is not easy to occur and thinning ratio will decrease. The high the temperature is, the bigger the strain rate sensitivity exponent m is and the more obvious the effect of the strain rate is.

Conclusions

In hot sheet metal forming of the high strength steel, the temperature is a key parameter to affect the thinning ratio, thus cracking. At an elevated temperature, the recovery and the recrystallization will be easy to occur, the material is not easy to harden and the strain hardening index is small. Thus, the deformation is easy to localize and lead to sheet cracking. When at a low temperature, the material is easy to harden; the flow stress at the location of high thinning ratio will be hardened substantially and will be higher than that of low thinning ratio. The deformation localization is not easy to take place and the sheet deformation will be uniform at different locations.

In the sheet metal forming process, the plastic deformation occurs. After unloading, the plastic strains in the sheet satisfy $\varepsilon_1 + \varepsilon_2 = -\varepsilon_t = C$, which was called FLE in this paper. It could be used to judge if the sheet cracks at a location. The FLE is identical to simulation results with AUTOFORM. The FLE of safe region of 22MnB5 for cracking is $\varepsilon_1 + \varepsilon_2 = 0.35$.

The thinning ratio is sensitive to the blank holder force. At an elevated temperature, the dislocation will be easy to move and pile up to result in the yield strength raising and the flow stress rising.

Figure 10. The diagram for Forming Limit Equation (FLE).

Figure 11. The effect of parameters on the maximum thinning ratio.
is sensitive to strain rate. The thinning ratio decreases with strain rate at an elevated temperature and does not change with strain rate at a low temperature. The thinning ratio increases with the thickness of the sheet at a certain degree. The thinning ratio increases with the friction factor because of the little material flowing into deformation region.

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References