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NUMERICAL ANALYSIS OF HOT DEEP DRAWING OF DIN 27MNCRB5 STEEL SHEETS UNDER CONTROLLED STRETCHING

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Abstract. Hot stamping has been widely studied and increasingly applied in the automotive industry. This process is characterized by its ability to stamp high strength steels, yielding products with high mechanical strength, thus reducing the weight of stamped components and therefore the vehicles weight. It also demands less energy because steel sheets are heated by induction, more efficient than electric furnaces. With controlled stretching it is possible to manufacture thinner stamped parts with high mechanical strength, therefore it is necessary to know the formability limits to prevent failure and achieve the largest possible thickness reduction. In this work the hot formability of DIN 27MnCrB5 steel sheets under stretching conditions was evaluated by numerical simulation with the finite element software Forge2008. The numerical results were compared to experimental results. Initially hot tensile tests were simulated to define the strain rate in different regions of the sample and to evaluate the deformation at fracture. For tests at 700, 800 and 900ºC it was found that the strain rates vary from 0.01 to 0.5 s-1. Experimental tensile tests were also carried out with the same conditions as simulated. Both simulation and experiments presented very similar results for the ultimate tensile strength, and therefore it was possible to assume the experimental fracture strain as a consistent input for the numerical models. With the results of the tensile tests, hot Nakazima tests were simulated to evaluate the highest dome which could be formed without failure risks caused by sheet thickness thinning. The simulation results were validated by experimental tests, and as a result, a new numerical strategy was elaborated to define the hot formability based on the plastic instability and necking localization as a function of the stamping temperature and blank dimensions.

1 INTRODUCTION

Hot stamping presents a wide application in the automotive industry from external components that define the body of the vehicle to internal structural components which require durability, rigidity and impact resistance that conventional cold stamping cannot match without subsequent heat treatment. With controlled stretching it is possible to manufacture thinner stamped parts with high mechanical strength, therefore it is necessary to know the formability limits to prevent failure and achieve the largest possible thickness reduction.

Many recent researches have been published analyzing important aspects of hot formability, focusing on materials and products quality.

Turetta et al. [1] state that the restricted application of hot stamping in the industry is due to the lack of basic knowledge on mechanical and microstructural characteristics of sheets at elevated temperature, boundary conditions, sensitivity of the formed component geometrical and mechanical characteristics to all the process parameters. To overcome part of those restrictions, they present a novel test based on the Nakazima´s which allows the determination of sheet formability, reproducing the hot stamping process conditions in terms of cooling rates and phase distributions during and after deformation.

Bariani et al. [2] present an innovative experimental procedure, based on Nakazima test, for evaluating the formability limits in the hot stamping of high strength steel (22MnB5) which is capable of generating formability data suitable for an fe modeling of the process. They concluded that the thermal, mechanical and micro-structural parameters determining the onset of localized necking and fracture can be individually controlled during the tests which results can provide the formability data in the form of combinations of strains that cause the onset of necking and fracture for given temperatures and average strain rates in the metastable austenitic phase.

Naderi et al. [3] characterized the behavior of the steel grade msw1200 blanks under semi and fully hot stamping processes. They concluded that the highest ductility and consequently, the best formability were achieved for the blank which had been semi-hot stamped. They also stated that semi-hot stamping process could be considered as an improved thermo-mechanical process which not only guaranteed a high formability, but also led to ultra-high strength values.

Mohamed et al. [4] show a a set of coupled viscoplastic constitutive equations for deformation and damage in hot stamping and cold die quenching of AA6082 panel parts. The equations can be used to predict viscoplastic flow and plasticity-induced damage of aa6082 under hot forming conditions. They found a good agreement between the process simulation and the experimental results has been achieved, confirming that the physical dependencies in the constitutive equations are correctly formed, and that the equations and finite element model can be calibrated and used for hot stamping of AA6082 panel parts.

Li et al. [5] described the material yield and flow behavior of 22MnB5 steel during hot stamping by an advanced anisotropic yield criterion combined with two different hardening laws. They also constructed an elevated temperature forming limit based on the Marciniak-Kuczynski model.

Despite the many researches recently published on hot stamping, few results were shown in respect to forming limits. In this work the hot formability of DIN 27MnCrB5 steel sheets under stretching conditions was evaluated by numerical simulation with the finite element software Forge2008. The numerical results were compared to experimental results obtained in tensile and Nakazima tests, both at temperatures and strain rates similar to those found in the actual hot stamping process.

2 MATERIALS AND METHODS

2.1 Simulation of hot tensile tests

The simulation of hot tensile tests with the software Forge 2008 was applied to evaluate the strain rates would more accurate to represent the experimental tests.

Three temperatures were adopted in the finite element models: 700°C, 800°C e 900°C, the friction was assumed high, and the heat transfer very small because the furnace is kept on all the test, with small variations of the test temperature.

The workpiece tested in the simulations had the same dimensions of that tested experimentally. The temperature in the region near to the fixtures was assumed to be 20°C (blue region in Figure 1), while the region under deformation was kept at the furnace temperature (red region). Figure 1 shows the workpiece before (right) and after the tensile test.

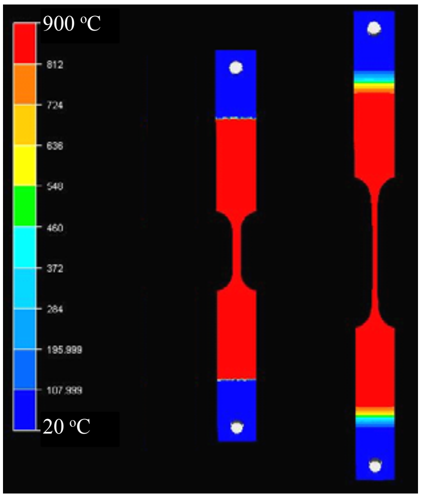

Figure 9: Temperature distribution in the workpiece before (left) and after (right) the hot tensile tes.

From the results obtained in the simulations it was observed that the strain rate along the workpiece presented a range from 0.01 to 0.5 s^{-1} which were defined to the experimental hot tensile tests.

2.2 Hot tensile tests

Hot tensile tests were carried out to evaluate the mechanical behavior of the steel DIN 27MnBCr5 and obtain the data necessary to simulate the hot Nakazima tests.

Workpieces 4mm thick were designed according to standards ASTM E8 M-03 (tensile tests) and ASTM E 21-05 (complementary hot tensile tests). The workpiece dimensions (Figure 2) were adopted in order to avoid the heating of regions near the fixtures reducing the occurrence of flow localization and plastic instability in these regions.

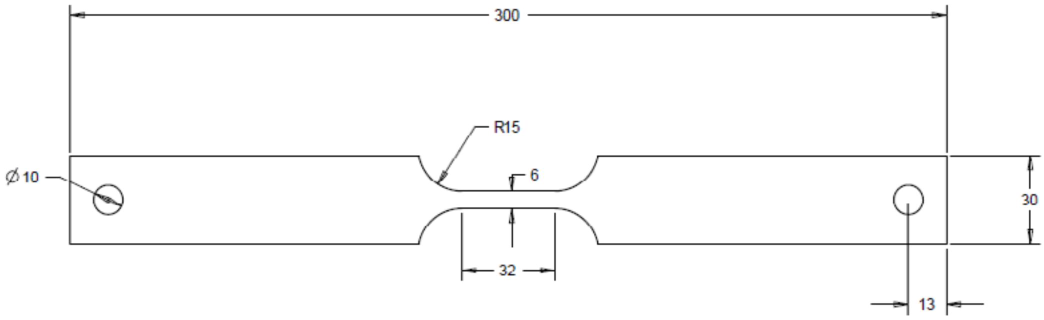

Figure 21: Tensile test workpiece dimension (in mm).

Twelve workpieces were cut-off by water jet and tested in a serve-hydraulic equipment model MTS 810-Flextest 40 (Figure 3) at the same conditions used in the simulations: three temperatures (700°C, 800°C e 900°C) and two strain rates (0.01 s^{-1} and 0.5 s^{-1}), with two workpieces for each combination temperature-strain rate. Since the testing equipment does not allow to set a constant strain rate, and therefore it was necessary to converted the strain rates to deformation speed approximately 30 and 1200 mm/min.

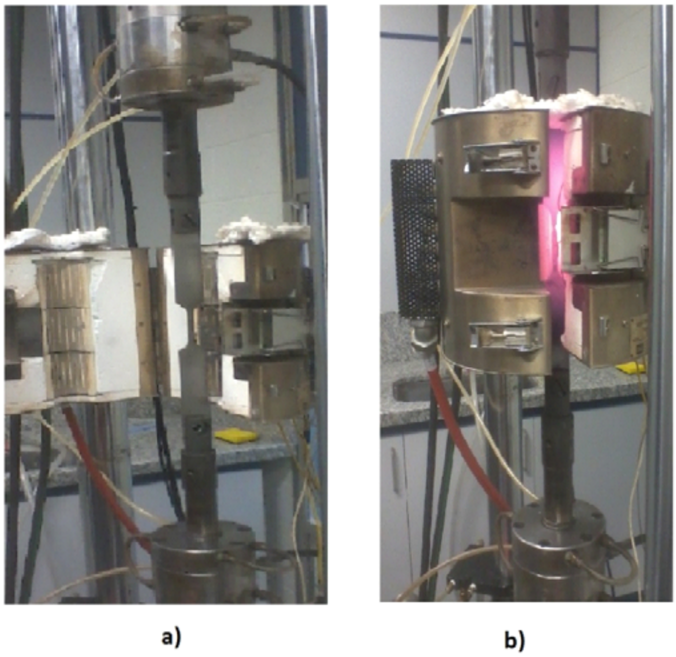

Figure 3: a) the workpiece is positioned in the testing equipment, b) the furnace is open after the hot tensile test.

2.3 Numerical simulation of hot Nakazima tests

The workpieces, the punch, the die and the drawbead were modeled and dimensioned as shown in Figure 4 and Table 1.

The workpieces were modeled with a constant length (200 mm), a constant thickness (4mm) and six different widths (100, 110, 125, 150, 175 e 200 mm), which were chosen to represent the conditions were stretching is expected.

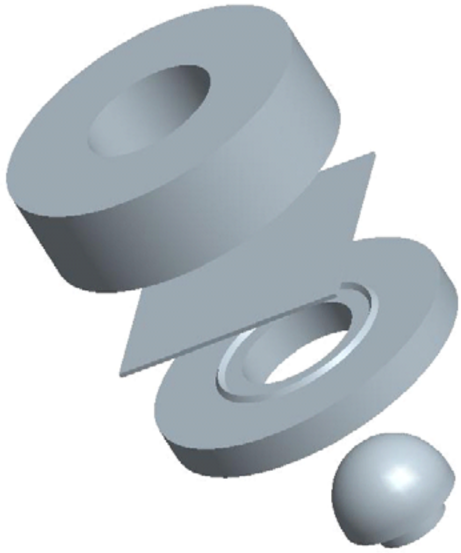

Figura 4: Nakazima test setup - from to top to bottom: die, workpiece, drawbead and punch.

Table 1: Dimensions of the components used in the hot Nakazima tests

<table>
<tr><th>Die</th><th>Drawbead</th><th>Punch</th></tr>
<tr><td>Inner diameter 112 mm</td><td rowspan="2">Inner diameter 102 mm</td><td rowspan="3">Diameter 100 mm</td></tr>
<tr><td rowspan="2">Outer diameter 260 mm</td></tr>
<tr><td rowspan="2">Outer diameter 260 mm</td></tr>
<tr><td>Height 80 mm</td><td rowspan="2">Height of the cylindrical region 20 mm</td></tr>
<tr><td>Fillet radius 10 mm</td><td>Height 30 mm</td></tr>
</table>

The workpiece material was modeled as the steel 22MnB5 since no data are available for the steel 27MnCrB5 studied in this work.

The initial temperature was assumed to be 900°C, the tools temperature 17°C the room temperature 20°C, and the punch speed 12mm/s, equal to the speed of the hydraulic press used in the experimental hot Nakazima tests.

Table 2 shows the values of some parameters assumed in the simulations for the quadratic finite element, friction and heat transfer.

Table 2: Parameters used in the simulation of hot Nakazima tests

Parameter/Component	Die	Workpiece	Drawbead	Punch
Finite elemento edge size (mm)	9.209	1.5874	7.120	4.311
Friction condition	High	High	High	High
Heat transfer condition	Medium	Medium	Medium	Medium

3. RESULTS AND DISCUSSION

3.1 Simulation of hot tensile tests

Figure 5 shows the results obtained in the simulation for the ultimate tensile strength distribution in the workpieces as a function of the test temperature. These results are obtained when the workpiece length in simulation is the equal to the length observed in the experimental test at the ultimate strength. The simulation results will be compared in this work to the experimental results to validate the simulation models.

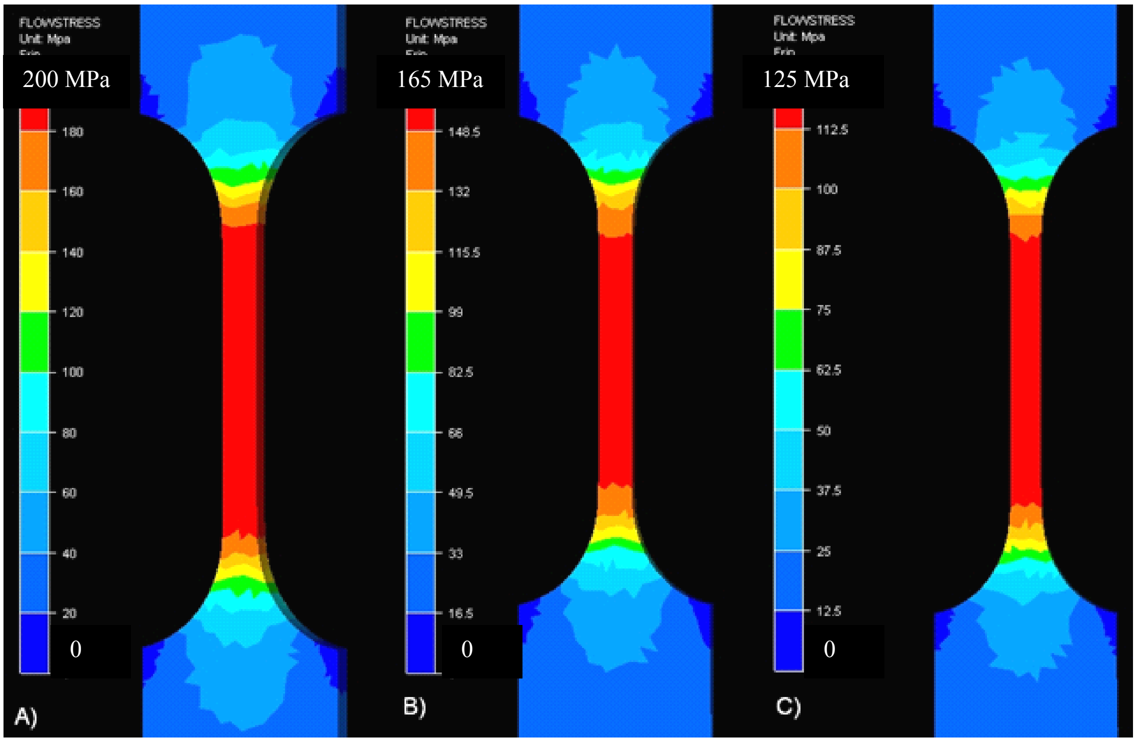

Figure 5: Ultimate tensile strength distribution during the hot tensile test
a) 700°C, b) 800°C, and c) 900°C.

3.2 Hot tensile tests

Table 3 presents the mean value of the results from two tests carried out in each combination temperature-strain rate.

Table 2: Results of the hot tensile tests

Temperature and strain rate	Ultimate tensile strength [MPa]	Elongation [%]
700°C and 0,01s^{-1}	111.74	51
700°C and 0,5s^{-1}	171.32	53
800°C and 0,01s^{-1}	105.14	55
800°C and 0,5s^{-1}	153.60	50
900°C and 0,01s^{-1}	71.50	60
900°C and 0,5s^{-1}	108.72	64

Table 4 shows the results obtained for the ultimate tensile strength in simulations and experimental tests, which present good agreement with differences between experimental and average simulation results less than 10%, and therefore simulation can be used to predict the ultimate tensile strength as a function of temperature and strain rate.

Table 3: Results of simulations and hot tensile tests

Ultimate tensile strength [MPa]	700°C	800°C	900°C
Experimental	171.32	153.6	108.72
Simulation	180-200	148.5-165	112.5-125

3.3 Numerical simulation of hot Nakazima tests

Figure 6 shows the evolution of the dome during the test. The last picture shows the stamped part and the respective element finite mesh.

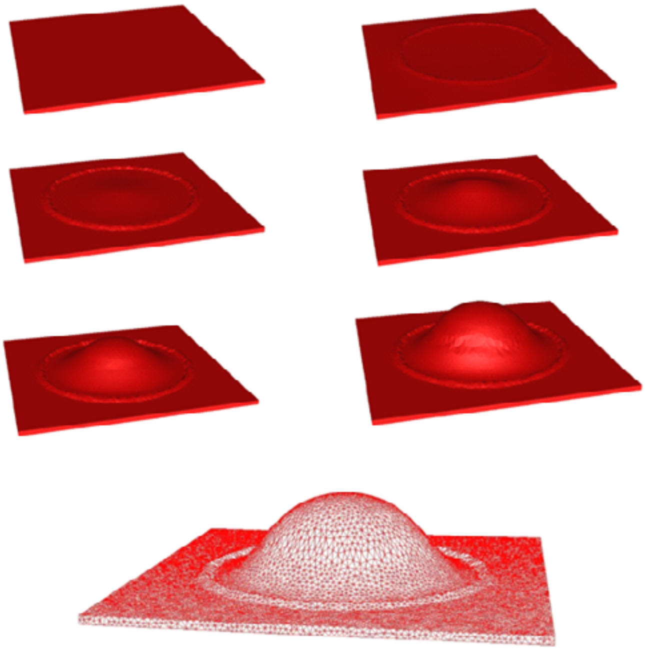

Figure 6: Evolution of the dome formed during the hot Nakazima test.

Figures 7 and 8 present respectively the distribution of equivalent plastic strain and the vertical displacement of the workpiece at the moment the surface flow stress reached the ultimate tensile strength obtained in the experimental hot tensile tests (Table 2) in a specific location which presents the same temperature used in the experimental tests.

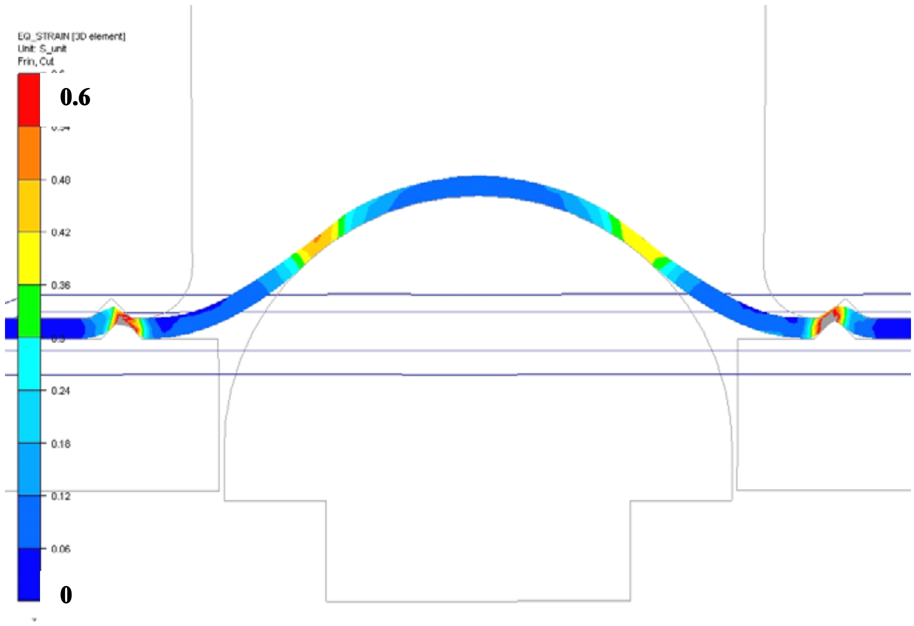

Figure 7: Nakazima test – distribution of equivalent plastic strains when necking initiates - workpiece 200mm wide.

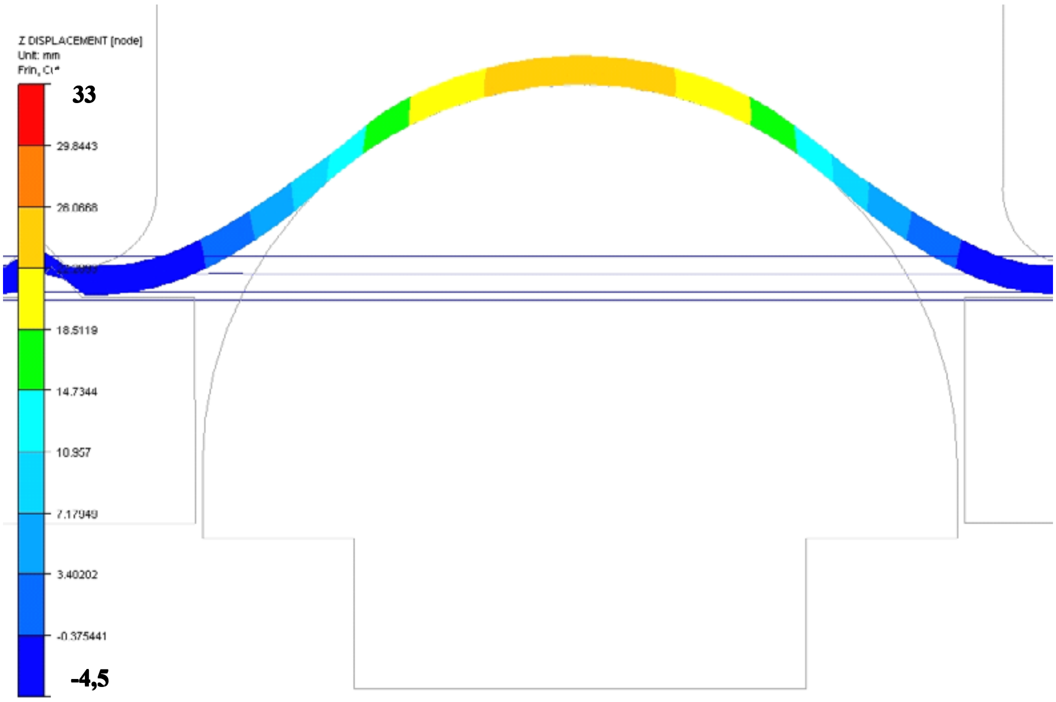

Figure 8: Nakazima test – distribution of vertical displacements (mm) when necking initiates - workpiece 200mm wide.

Table 4 presents the simulation results for the ultimate equivalent plastic strain (obtained in figures like Figure 7) at the location where the surface flow stress reaches the same value of the ultimate strength obtained in the experimental hot tensile test, and at the same temperature of the tensile test. These results are in good agreement with major and minor strains obtained experimentally by Dahan et al. [8] in similar hot Nakazima tests with the 22MnB5 steel.

Table 4: Simulation results of hot Nakazima tests - ultimate equivalent plastic strain versus workpiece width

Workpiece width (mm)	Ultimate equivalent plastic strain [ ]
100	0.48
110	0.36
125	0.32
150	0,38
175	0.40
200	0.42

For all the tests at 900 °C it was observed that necking initiates after three seconds for most of workpiece widths simulated, corresponding to a dome height near 31 mm.

Figure 9 shows the variation of temperature as a function of the process time for a specific line in the workpiece 200mm wide. The temperature profile is an essential information to achieve the best cooling conditions wich will produce a uniform martensite microstructure after stamping and final cooling within the tools.

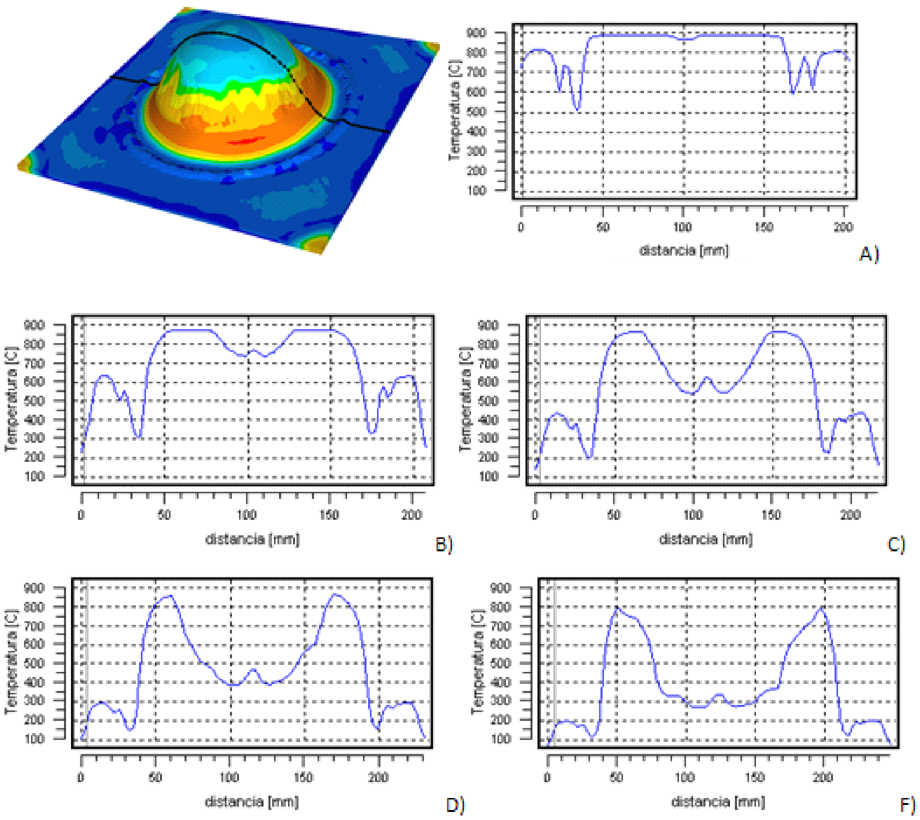

Figure 9: Nakazima test – variation of temperature in the workpiece (along the process, workpiece 200mm wide: A) 1s, B) 2s, C) 3s, D) 4s, and F) 5s.

The most significant reduction of temperature is observed in the regions in contact with the tools. In the region where the necking initiates, punch causes a high cooling rate in the center of the workpiece while the lateral regions are kept heated, and are only significantly cooled when the center of the workpiece reaches 400°C.

The maximum cooling rate observed at the center of the workpiece 200mm wide was 110°C/s, and the minimum 20°C/s. According Naderi et al. [6] 20°C/s is the minimum cooling rate necessary to form a uniform martensite microstructure in the 27MnCrB5 steel. Otherwise MetalRavne [7] presents a Continuous Cooling Transformation Diagram in which the minimum necessary cooling rate is 38°C/s. Therefore, some regions of the workpiece will present martensite after the hot Nakazima test where cooling rates are greater than 40°C/s, assuming they were correctly predicted in the simulations.

Workpieces with other widths presented temperature profiles very similar to 200mm wide workpiece, but with lower cooling rates, and consequently, higher final temperatures, as observed in Figure 10 that shows the variation of temperature as a function of the workpiece width, after five seconds stamping.

The region of the workpiece in contact with the punch is reduced with decreasing widths, so less heat is transferred from the workpiece to the punch. Therefore, one solution is reduce the punch temperature to force higher temperature gradients and cooling rates in the workpiece.

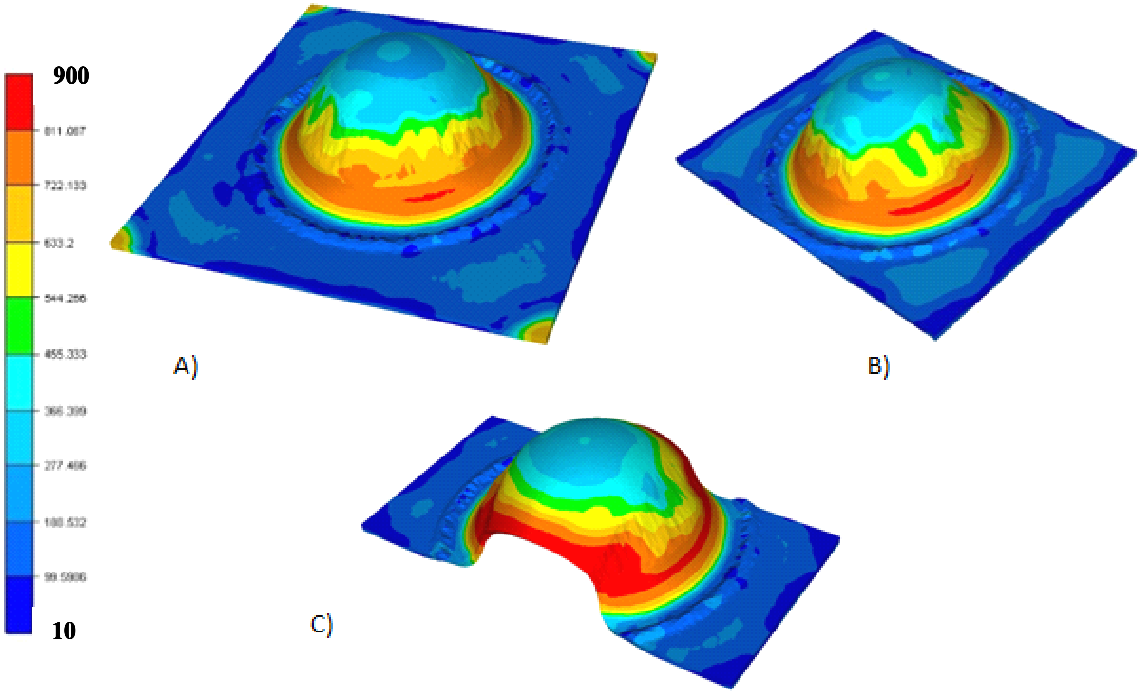

Figure 10: Nakazima test – variation of temperature (ºC) in the workpiece, after stamping for 5 seconds, workpiece width: A) 200mm, B) 150mm C) 100mm.

4 CONCLUSIONS

The main objective of this work was to evaluate the hot formability of DIN 27MnCrB5 steel sheets under stretching conditions, by numerical simulation and experimental tests.

The models used to simulate the hot tensile tests and the hot Nakazima tests presented results with good agreement to the experimental results, so they can be used to predict the forming limits as a function of stamping temperature and workpiece thickness.

The most significant reduction of temperature was observed in the regions in contact with the tools. In the region where the necking initiates, punch causes a high cooling rate in the center of the workpiece while the lateral regions are kept heated, and as consequence, causing inhomogeneities in the final microstructure.

The region of the workpiece in contact with the punch is reduced with decreasing widths, so less heat is transferred from the workpiece to the punch, and consequently, lower cooling rates, and higher final temperatures.

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