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Numerical Simulation to Improve Robustness in Sheet Metal Forming Process Chains

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Abstract. The paper will present developments towards the improvement of the robustness of sheet metal forming process chains. The possibilities and challenges will be demonstrated using two examples. Firstly, the effect of heat treatment to precipitation hardened aluminum sheet metals in order to enlarge the process window for deep drawing operations will be discussed. Numerical simulation can be used to predict the effects of the heat treatment. Using more sophisticated approaches the heat treatment layout and its effects on the forming process can be computed and predicted. Thus the process window can be enlarged and in consequence the process chain will receive an increased robustness. Secondly the integrated tube and sheet hydroforming process that also includes joining operation will be used as an example of the positive impact numerical simulation can have on complex process chains. This highly integrated process chains needs carefully designed tools that ensure robust production. Furthermore, several effects occurring during the forming operations are difficult to understand since the process cannot be stopped at arbitrary moments or easily investigated in situ. The needed understanding and therefor the mandatory input for successful and robust process design has to be derived from advanced numerical models and the according simulation runs.

Keywords: Robust process chains, sheet hydroforming, tailored heat treatment

INTRODUCTION

Global warming is a substantial problem of our society that causes tremendous efforts to reduce fuel consumption of vehicles. These have been identified as one of the main sources of CO₂. The emission of CO₂ by automobiles has thus been subject to increasingly strict regulations [1, 2]. At the same time safety and comfort have to be increased due to customer demands. In consequence, the forming processes and the applied materials have to be adjusted to the requirements.

Innovative forming technologies are one possible approach to pursue these goals. One of these forming technologies is sheet metal hydroforming. The great advantages and potential accompanying this technique lead to a quick further development, especially for the forming of highly complex part geometries [3]. The challenge in applying this technology is found in reducing the number of process steps and finding a suitable process design and recognizing the limits of the sequence.

The application of lightweight materials that also possess high strength is another alternative [4]. Hardenable aluminum alloys and especially the precipitation hardened 6xxx-series have been found most promising [5]. Since the formability of these alloys is fairly limited, different approaches have been taken to overcome them. While the use of patchwork blanks and process combinations is a suitable approach for steel [6, 7], this is not feasible for the aforementioned aluminum alloys. These can be heat treated though. By dissolving the precipitations that are mainly responsible for the strength of the material the formability can be greatly improved in the heat treated areas while the non-heated parts remain at high strength. Though the concept of tailored heat treated blanks (THTB) sounds fairly simple the challenge is to be found in the layout of the heat treated area.

Both approaches need the assistance of numerical simulation in order to limit the experimental effort and the used equipment, time and material.

PROCESSES

This section shall describe the introduced processes in some more detail to provide a general understanding of the possible gains and the included challenges.

Tailored Heat Treated Blanks

The basic principle of THTB is to soften the sheet that is to be deep drawn by means of a short time, local heat treatment in the forming zone. This shall produce material properties that are optimized for the forming process, not the application of the finished product, in the forming zone. The main alloys of the 6000 series' aluminum are silicon (Si) and magnesium (Mg). Usually the sheets are delivered in a natural aged condition (T4). By natural aging coherent MgSi clusters are created leading to distortions of the crystal lattice. These will interfere with the dislocation movements which finally results in the desired material hardening. If these materials are heated above a material-specific temperature level even a short-term heating leads to the dissolving of the MgSi clusters. In consequence the material is softened [8]. Studies on short-term heated AA6016 and AA6181 specimen show that the softened condition remains for approximately 60 minutes after the heat treatment [9]. Then the back-formation of the MgSi clusters as result of natural aging effects slowly restarts and the material is hardened again. For a time-frame of approximately six hours, however, the material softening is preserved sufficiently to be used as THTB in forming processes. After approximately 90 to 100 days the original strength levels that were given before the sheet was heat treated will be completely restored.

The interrelation of mechanical properties of AlMgSi alloys and the maximum temperature $T_{\max}$ of the local heat treatment can be examined by tensile tests conducted according to DIN 10002 for short-term heated samples. Details on the effects on both R_m and $R_{p0.2}$ of the regarded material AA6016 can be found in [10].

Integrated Manufacturing

Double Sheet Hydroforming

In double sheet hydroforming two metal sheets are formed in a tool cavity using a high pressure fluid injected between the sheets. Although the used appliances (hydraulic press, laser cutting machines), many of the process parameters (blank geometry, lubricants) and the semi-finished material (steel and aluminum sheets) are very similar to those employed in conventional deep drawing, still many differences persist between the two technologies. In particular the blank holder forces and consequently the contact pressures needed to provide tightness between the blanks are much higher (5 to 30 N/mm² instead of 1 to 10 N/mm² recommended for deep drawing [11]). Also the material flow in hydroforming is different. In deep drawing the blank draw-in is controlled by the punch stroke and by an appropriate distribution of drawbeads in the flange, while the blankholder is primarily needed to avoid wrinkling. In hydroforming draw-in occurs when the tensile load in the sheet generated by the inner pressure is higher than the retaining action of the blankholder in the sheet flange. Therefore draw-in is influenced by many concurrent factors like the blankholder force, the contact pressure distribution, the blank geometry and the tribological conditions. Because of these differences many of the design rules and process laws developed for deep drawing are not directly applicable to double sheet hydroforming.

Integrated Process Chain

Load optimized parts are often characterized by very complex shapes and by an efficient use of different materials. These essential properties can be achieved with the hydroforming technology. Combining the described double sheet hydroforming with the well-established tube hydroforming and introducing the joining and cutting steps into that process sequence would be of great benefit.

The desired sequence has 4 steps. In the first step the lower sheet and the tube are placed into the tool. The upper sheet is then positioned onto the tube (Figure 1a) and onto special guiding elements, who secure a horizontal position of the sheet during the following tool closing operation (Figure 1b). During the tool closing operation the sheets are pre-formed by the tube into the die cavity in the junction area between tube and double sheet. Then the tube is upset with an axial force by the docking cylinder (Figure 1b). The hydroforming fluid flows through a channel in the docking cylinder and forms the two blanks and the tube against the die cavity. At the end of the forming process the clinching punches, which were retracted in apposite holes in the blank holder, are actively moved and join the two sheets in six points in the flange (Figure 1c). Due to the hydroforming operation a joining by hydroforming between tube and double sheet is also realized. Finally the component can be taken out of the press and finished by additional welding and cutting operations in the adjacent laser station (Figure 1d).

FIGURE 1. Integrated process chain [12]

The advantage of combining tube and double sheet hydroforming is the possibility of manufacturing a complex shaped part with three different materials in just one process. The material strength and the wall thickness of the two sheets and tube can be optimized for any specific application. In addition, the component presents three characteristic areas. The tube area has no flange and thus reveals a high stiffness, due to the closed cross section profile. The sheet area has larger cross sections and presents a flange, which is required for the assembly and joining with the adjacent components. The junction area is essential for the connection between the tube and the two sheets and is also the most critical area during the forming process.

The challenges for the application of this process sequence are the blank and tool design especially in complex areas as well as the adaptation of the blankholder force to the process progress in order to avoid process failure by tearing or wrinkling as well as leakage. Usually numerical simulation is applied to do the process design.

NUMERICAL SIMULATION

The advantage of the FE simulation in sheet metal forming consists of the fact that manufacturing processes of complex parts can be calculated and thus process limits for a set of parameters can be defined [13].

Heat Treatment of THTB

For THTB this aspect is very important, because the additional heat treatment process step increases the number of variables for the forming process. The purpose of the numerical simulation is to identify and quantify the most feasible distribution of the mechanical properties for the forming process of a component and the corresponding lasers parameters. A 3D FE-model created in ABAQUS is being used for this challenge. The essential difference between a conventional blank and a THTB is that the mechanical property distribution is not homogenous. In consequence the local softening of the blank due to the local laser heat treatment is to be modeled and considered during the forming step. The softening results from the heat treatment. In consequence the total modeling consists of 3 steps. In the first step, the heat treatment by laser irradiation is modeled and the resulting heat distribution in terms of maximum temperature in the specimen is derived. These calculated heat treatment result is interpreted and a THTB is generated as input for the deep drawing simulation. The interpretation based on the material characterization data published in [14]. As a result of the thermal simulation the temperature as a function of time for all nodes is gained. The nodal maximum temperatures $T_{\max, \text{node}}$ are extracted and the mean value $T_{\max, \text{element}}$ for every finite element is calculated. To implement the relation between $T_{\max, \text{element}}$ during the heat treatment and the according mechanical properties, the results of the tensile tests are approximated with the hardening description appropriate for aluminum alloys of Hocket-Sherby, which is characterized by an asymptotic saturation level B for $\varphi \rightarrow \infty$ and by an exponent, which contains the logarithmic plastic strain φ .

$$k_f = B - (B - A)e^{(-m\varphi^n)} \quad (1)$$

The Hocket-Sherby parameters A , B , m and n are interpolated stepwise to generate flow curves corresponding to the specific $T_{\max, \text{element}}$ value. Thus it is possible to assign the adjusting mechanical properties to every single element. The result of this analysis step is the input for the forming process.

In general a homogeneous blank with an optimized geometry for drawing should be irradiated at the border in order to maintain a stable condition T4 in the inner area, where the punch force is applied. In the boundary area the material is softened (condition W). Transient effects at the beginning and at the end of the laser heat treatment are to be avoided as they would lead to uneven draw-in. In Figure 2 the $T_{\max, \text{distribution}}$ resulting from an irradiation with the laserpower $P_L = 600$ W, the laser scan speed $v_L = 33.3$ mm/s and the laser spot diameter $d_L = 20$ mm is illustrated.

FIGURE 2. $T_{\max}$ -distribution for (a) continuous and (b) adjusted laser power [14]

The THTB realized by an irradiation with constant laser power (Figure 2a) shows an inhomogeneous heat treatment result. The initial maximum temperatures are comparatively low, because of the small ratio between heated and cold mass. In contrast, the final temperatures are too high, as this area is preheated due to the thermal flux. The inhomogeneous material properties would lead to problems during the sequential forming process. This property distribution thus ought to be avoided. In Figure 2b the $T_{\max}$ -distribution realized with optimized laser power during the heat treatment process is shown. In this case the initial power of 900 W is linearly decreased during the first 2 s to 600 W and for the last 3 s down to 400 W. The result is an evenly distributed heat treatment and therefore uniform draw-in conditions are given. The influences of different heat treatment parameters and scanning strategies or layouts of the irradiated areas on the forming process can be examined by mechanical simulation.

Deep Drawing of THTB

The FE-simulation of the deep drawing process is not different from the simulation of deep drawing processes for conventional sheet metal blanks. It begins with the step 'blank holder closing' to clamp the blank between die and blank holder followed by the actual drawing due to the punch motion. The calculated stress (Figure 3a,b) gives information about the achieved forming improvement of the THTB when compared to conventional deep drawing of sheets in the T4 status. Furthermore it is possible to evaluate the effect of different heat treatment conditions on the forming behavior. Because of the locally softened flange area plastic deformation starts at a lower stress level than during conventional deep drawing. In addition a significantly higher work hardening distribution of the T4 blank in comparison to the THTB can be observed. A further positive characteristic of THTB is the decreased wrinkling tendency in the flange. Figure 3c,d contrasts the contour results at a drawing depth of 38 mm of the T4 blank and the THTB for a reduced blank holder force $FBH = 2.5$ kN. Thus it is possible to draw THTB applying lower blank holder forces which means less friction forces and therefore an improved draw in without wrinkling.

FIGURE 3. Stress distribution for the use of (a) a conventional blank and (b) a THTB. Appearance of wrinkles for the use of (c) a conventional blank and (d) a THTB [10]

The numerical results were confirmed by experimental investigations. Rectangular cups were deep drawn using process parameters determined in the FE calculations. Some of the results of these experiments are shown in Figure 4. It is not possible to realize a drawing depth of 45 mm using T4 blanks because both wrinkles and fracture (Figure 3a). The potential of the improved strategy using a THTB is demonstrated in Figure 3b. Using the same parameters for the deep drawing process the cup could be formed without errors, which corresponds to the numerical results.

FIGURE 4. Experimental results confirming the numerical investigations [34]

Integrated Manufacturing

The actual geometry of the sample component (Figure 5c) presents some challenging features, which affect the process robustness and require the execution of additional operation in order to achieve a satisfying forming result.

A first problem is related to the geometry of the tool in the joining zone between tubular component and metal sheets. The tool insert in this area presents a bead (Figure 5a) that prevents the tube to penetrate the cavity between the metal sheets during the process when an axial force is applied. The bead fulfills its function, but constraints at the same time the draw-in of the sheets in the tube-sheet joining zone. A second problem concerns the appearance of leakage during the forming process. The problem occurs as well during the preforming as in the final calibrating stage. The presence of a bead in the joining zone results in an irregular geometry which makes the distribution of the clamping force applied by the tool on the overlapping area not homogeneous. As a result leakage occurs already by a low internal pressure. This problem is solved in the existing process with the aid of sealing fibers mixed with the hydroforming medium [15]. Those components gather along the edge of the part during the process, thus helping to close the gaps between the blanks. The actual geometry of the component presents an additional gap between the sheets due to its geometry and therefore unavoidable. The gap, well visible in Figure 5b, forms in the initial holding stage, when the sheets wrap around the tubular component bending in the overlapping area. In the existing process two sealing profiles made of synthetic foam are placed at the outer surface of the tube in order to close the gaps. Without these components the reachable pressure is not even sufficient for the preforming stage of the process.

FIGURE 5. Sample geometry and arising challenges [16]

A solution of the mentioned problems requires the modification of the geometry of the tool in the joining zone and the use of a different tubular component consisting of two overlapping tubes joined by welding. The new geometry enables to abandon the inserts with bead, because the tubular component is now axially fixed by the sheet pair itself, as the tube gets in contact with the face side of the sheets. The new geometry leads to an improved draw-in of the sheets and realizes a smooth overlapping surface of tube and sheet pair, thus improving the sealing effect of the clamping force and allowing a correct forming of the part without sealing fibers.

The process was simulated using the Finite Element software PAM-STAMP 2G of the company ESI-Software. The geometry of the tool was drawn in a CAD-software, imported in PAMSTAMP and meshed. The two concentric tubular inserts were created in the FE-software as independent objects and connected with rigid bar elements in order to avoid any relative movements between them, reproducing in this way the effect of the weld seam. The process was simulated using the Finite Element software PAM-STAMP 2G of the company ESI-Software. The two concentric tubular inserts were created in the FE-software as independent objects and connected with rigid bar elements in order to avoid any relative movements between them.

By means of numerical investigation the inner tubes wall thickness was determined to be 3.0 mm to withstand deformation when the tool is closed and thus guarantee sealing during the hydroforming step. During the stamping stage unexpected wrinkles occurred in the simulation where tube and sheet met. By investigating different wall

thicknesses, blankholder forces and materials, it was found that aluminum AA5754 presents the highest wrinkling tendency while DC04 and TP800 did not show this problem. The reason is the sharpness of the wrinkles introduced in the early stages of the forming process. If the sharpness of the wrinkles is low they can be removed during the process. Regardless of the chosen process parameters wrinkling could not be avoided for the aluminum sheets. The result of the numerical study was a slight modification of the part geometry and the fact that it cannot be produced from AA5754 using the suggested process chain. Production using the two steel grades however is possible and has been conducted as seen in Figure 5.

SUMMARY

The brief survey has shown that by means of numerical simulation the two presented examples of innovative sheet metal processing were greatly improved. The application would not have been possible in the case of the hydroforming process sequence without the insight gained from the simulation. Information on the feasible materials and the needed redesign of the tools could be gathered. For the THTB the improved insight into the process internals is even more evident since the stress distribution could not be measured during a real process but can be visualized using validated numerical models. Understanding the process the heat treatment could be improved. Forming results not possible without THTB were reached in simulation and reality. The ongoing research towards better numerical modeling of forming processes will help to further improve the capabilities of metal forming.

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