Upset bulging as a preforming operation for hot metal gas forming of 22MnB5 tubes

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Abstract. Hot Metal Gas Forming (HMGF) is a coupled process of gas forming and quenching of tubes. This process allows to obtain complex and accurate geometry due to the elimination of springback and high mechanical properties due to the formation of martensite, as a result, the weight of the parts can be reduced. HMGF is widely used in the aerospace and automotive industries to make critical parts from high hardenability steels such as 22MnB5. A typical hot stamped component has 1000 MPa yield stress and 1500 MPa ultimate tensile strength. The main challenge of HMGF process is a significant material thinning and cracking due to the biaxial tension stress state. The paper proposes a preforming method for increasing the forming limits of HMGF by the cold upset bulging of tubes by means of the additional volume of material in the deformation zone. This method allows to obtain one or several waves in the cross section of the tube, which helps to increase the minimum workpiece wall thickness after the forming process by more than 40% and to reduce a probability of the crack formation.

1. Introduction

One of the most important challenges in the modern automotive industry is an improvement of a vehicle efficiency, which is generally defined by the distance traveled per use of a quantified energy [1]. It can be improved by enhancing of the engine efficiency and its hybridization, improving the fuel energy efficiency, decreasing the air resistance due to a more aerodynamic bodywork and a vehicle weight reduction. Reduction of the vehicle weight is one of the important avenue to improve vehicle efficiency and could be achieved both with engineering solutions, such as an architecture and design optimization of a vehicle, and with technological improvements, such as using lightweight materials and innovative manufacturing processes [2]. Substitution of a mild steel or a cast iron with lightweight materials, such as magnesium or aluminum alloys can lead to a vehicle weight loss up to 75%. Using of an advanced high strength steel in critical applications can help to reduce a vehicle weight up to 25%, while increasing the stiffness and safety of the vehicle [3].

Further reduction of a vehicle weight can be reached using the hollow parts and tubes instead of sheet metal welded structures. For example, hydroforming is used today for many structural applications, including frame rails, engine cradles, radiator supports and cross-car beams [4]. The process is well established [5] and usually carried out by the room temperature and widely used for ductile alloys, such as carbon steel and aluminum alloys [6], as well as stainless steel [7]. Hydroforming by the elevated
temperature is also possible [8], but the temperature for fluids is still limited to the range below 350 °C [9] and using hot gas or an alternate media is required [10].

High strength steels and other alloys with low cold formability could be hot deformed by a gas forming [11]. This process can be coupled with a simultaneous heat treatment, how it is done in a press hardening (or hot stamping) [12]. The process of tube gas forming coupled with a quenching of a hardenable steel or alloy is known as hot metal gas forming (HMGF) [13]. A tube or a hollow profile made of high hardenability steel, such as 22MnB5 [14], deforms in a fully austenitized state by means of internal gas pressure in order to fill the die cavity [15]. When the workpiece touches the surface of the cooled dies, it is cooled with a cooling rate above the critical one and martensite is formed. Since the phase transformation of a workpiece takes place in a constricted state, there is almost no springback [12], meanwhile the mechanical properties are very high, typically yield stress is up to 1000 MPa and ultimate tensile strength is up to 1500 MPa (even 2000 MPa).

The stress state of a tube during HMGF is a biaxial tension, which significantly limits the potential of the process. The formability could be predicted by flow limit diagrams, which for 22MnB5 were investigated extensively by Li et. al. [16], Rubešová et. al. [17] and Venturato et. al. [18]. However, only relatively small lateral expansion without additional measures is possible. The formability could be enhanced in the following ways:

- an increase of the material formability by providing a favorable microstructure or using rational process parameters;
- an addition of extra amount of metal to the deformation zone;
- a change of a stress state in a workpiece.

The most common methods of the formability enhancement are a heating of a workpiece and an axial feeding of the tube by application of the inner pressure. The success of a tube hydroforming process is highly dependent on the loading paths (axial feed versus pressure) used, which was investigated by Aue-Lan et. al. [19] and Jansson et. al. [20]. The combination of these parameters with considering of a material formability and friction condition helps to avoid a crack formation, as well as a buckling or a wrinkling. Yuan et. al. [21] proposed to utilize useful wrinkles and developed an extended process window of tube hydroforming. Lang et. al. [22] expanded this method and proposed a multi-stage tube hydroforming. Nevertheless, axial feeding during a media-based forming has certain restrictions:

- the inner pressure by the axial feeding should be relatively small due to a seal design;
- applicable only for relatively slow processes;
- used only for cold processes (or a limited range of alloys), when the tube stability is high enough and it wrinkles predictably;
- only for a relatively small friction coefficient.

During HMGF complex friction conditions take place and a friction coefficient can rise up to 0.6 combined with a relative low flow stress of a tube material [23], which makes a tube very unstable and makes eventually an axial feeding challenging. In this case it is possible to preform a workpiece in a cold state. The upset bulging process shows a high potential and can be used for this purpose [24]. The figure 1 shows the possible strategies for increasing the volume of metal in the deformation zone during upset bulging.

![Figure 1](image1.png)

Figure 1. Strategies of the wave formation by the upset bulging.

The aim of the study is to develop and analyze a preforming process by the upset bulging to prevent a tube failure, as well as to increase a tube wall thickness and its uniformity after HMGF.
2. Materials and methods

2.1. Materials
The samples used in the study were made Al-Si coated 22MnB5 welded tubes from ArcelorMittal with 6 m length, outer diameter 40 mm and wall thickness 2 mm. The samples were cut-off with a band-saw and then the ends were turned in order to achieve the desired tube length and perpendicularity of the tube end faces to the tube axis. The chemical composition of as-received tubes is given in table 1.

Table 1. Nominal chemical composition of the 22MnB5 steel (wt.%).

|      | C  | Si | Mn  | P  | S  | Al | N  | Cr  | Ti | B   |
|------|----|----|-----|----|----|----|----|-----|----|-----|
| min  | 0.21| 0.15| 1.10| -  | -  | -  | 0.10| 0.015| 0.0015|
| max  | 0.25| 0.40| 1.35| 0.023| 0.010| 0.080| 0.010| 0.25| 0.045| 0.0040|

2.2. Experimental procedure
The investigated process chain consists of two steps: preforming of the tube by the upset bulging and subsequent hot metal gas forming. Upset bulging and HMGF experimental setup as well as process parameters are described below. After each step the samples were cut along the axis and the wall thickness distribution was examined.

2.2.1. Measurement of a tube thickness distribution
The samples were cut along the tube axis with a Presi Mecatom T330 cutting machine. A diamond cutting disc with a rotation speed of 3500 RPM and feeding rate of 0.5 mm/sec was used to achieve a flat cut surface. Following the cutting a grinding and polishing operations with a Presi Mecatech 300 SPC were performed. The tube flat cut-sections were scanned with a scanner Canon CanoScan LiDe 1100 with a resolution of 2400 dpi. Then the images were digitized as a .dxf file and a tube thickness distribution was measured by means of Autodesk Inventor. The region with a length of 56 mm along the tube axis was measured (cylindrical part with Ø56 mm, transition zone and short part of cylindrical element with Ø44 mm), which corresponds to the measured profile length of 60 mm. The outer surface of a tube was approximated by a polyline with a segment length of 0.5 mm. The normal distance from this points to inner surface of the deformed tube was measured and taken as a tube thickness.

2.2.2. Upset bulging experimental setup
Upset bulging was perform by the hydraulic press SMG HZPU 100 with a nominal force of 1000 kN and a nominal ram speed of 120 mm/s. The experimental die set is shown in figure 2 and consists of two changeable inserts a, mandrel b and holders c, which are installed on the press ram d and the press bed e. The tube e inserts in the gap between a mandrel b and inserts a and deforms with a press ram movement. The length of the deforming part of a tube l_k was controlled by a length of a tube and inserts, the final position h was set by stopping blocks (are not shown).

Figure 2. Upset bulging experimental setup: in the press (a), the view on the bottom tool (b) and the scheme of the upset bulging process (c).
Special die inserts were used for the upset bulging with a wave support (figure 3). The construction of the inserts is able to prevent a folding of a bulge and to obtain a desired multiwave geometry of the preform.

![Die inserts](image)

**Figure 3.** 3D-model (a) and the drawing (b) of the die inserts for the upset bulging with a wave support.

2.2.3. **Hot metal gas forming experimental setup**

Hot metal gas forming was performed by a 3-column hydraulic press hardening machine Dunkes/AP&T HS3-1500 with a 15 MN nominal force and a maximal gas pressure of 700 bar. The geometry of the final part and a bottom tool of a modular tool set for hot metal gas forming are shown in figure 4.

![Experimental setup](image)

**Figure 4.** The geometry of the final part (a) and bottom tool for HMGF (b).

Hot metal gas forming experimental setup is shown in figure 5a. A workpiece $a$ is heated in a furnace up to 980 °C within 5 minutes. After that the heated tube $a$ is placed manually on a bottom die $b$ and closed with a top die (not shown). Leak tightness of the workpiece is ensured by closing of side punches $c$ with a sealing cone. The handling time before the start of a deformation is about 5 seconds. The gas pressure of 700 bar is supplied through the holes in the side punches in 0.5 seconds with a hold of 3 seconds followed by a release in 2 seconds. It was found that it is not possible to obtain the final part without preforming because of the significant thinning resulting in tearing (figure 5b).

![Experimental setup](image)

**Figure 5.** HMGF experimental setup (a) and a teared tube after HMGF without preforming (b).
2.3. **FEM Simulation**

Simulations have been performed by the commercial FEM software QForm (www.qform3d.com) in general forming module.

2.3.1. **Process model**

The workpiece was set as an elastic-plastic body, the tools were set as rigid bodies. The workpiece mesh was created by the QForm mesh generator for parametric geometry. A remeshing was not used. The hexahedral 8-noded volumetric mesh with a mesh density of 4 elements along the radial direction, 75 elements along the tangential direction and 200 elements along the tube axis, totally are approximately 120,000 elements. Thermal processes were taken into account both in cold and hot processes. The initial temperature of the workpiece in HMGF was set as a 980 °C with a subsequent air cooling in 4 s and cooling in dies in 1 s. According to the FEM-simulation the temperature of the tube just before deformation is approximately 850 °C and the cooling rate during the HMGF is approximately 150 °C/s, which is significantly higher that critical cooling rate of 30 °C and leads to the formation of fully martensitic structure [25]. Friction was set by a Coulomb law with a $\mu = 0.12$ in the upset bulging and by a Levanov model with $m = 0.8; \beta = 1.25$ in the hot metal gas forming. The pressure during HMGF was applied to the inner tube surface of the tube as a time-dependent boundary condition according to the experimental parameters described in 2.2.3.

2.3.2. **Material model**

Flow curves at 20 °C were obtained by the uniaxial tension tests by the authors and approximated as a following function:

$$\sigma = 453.393 \cdot \varepsilon^{0.454} + 613.651 \text{ MPa}$$ (1)

Thermophysical parameters of the workpiece and the dies were set according the 21Mn4 and 1.2343 (H11) steels from QForm standard database respectively. The environment was set as an “Air” from QForm standard database. Flow curves of 22MnB5 by the hot metal gas forming were set in a tabular form according to Naderi et. al. [26].

3. **Results and discussion**

3.1. **Analysis of the free upset bulging**

For the investigation of the tube bulging and folding behavior during the free upset bulging a simulative study was performed. Length of the deforming part of a tube, which consists of an initial distance between dies and two radii of a matrix, as well as an initial tube thickness, were used as variable parameters and varied in a range of 20 mm to 60 mm with a step of 5 mm and 2 to 4 mm with a step of 1 mm respectively. Design of experiment of the free upset bulging analysis is presented in the table 3. The final distance between dies was set so that no obvious wrinkles were left with a high probability after the hot metal gas forming.

| Variable                          | Levels |
|-----------------------------------|--------|
| Length of the deforming part of a tube, mm | 20, 25, 30, 35, 40, 45, 50, 55, 60 |
| Tube wall thickness, mm           | 2, 3, 4 |

The results of the simulation study are summarized in figure 6. As it can be seen, starting with a certain length of the deforming part of the tube, stability of the tube during the deformation is not enough to form an open wave, and it becomes a closed fold, that cannot be successfully deformed during the hot metal gas forming. For the 2 mm thick tube critical length of the deforming part of the tube is approximately 35-40 mm, for the 3 mm tube – 45-50 mm, and for the 4 mm tube – 50-55 mm.
Figure 6. Effect of the process parameters on the wave formation in the free upset bulging.

Folding started with a formation of a second wave, which closes further without significant deformation of the first wave. This mechanism of the tube folding during a free upset bulging is shown in figure 7a. It is possible to avoid a formation of a closed folds by means of a ring-shaped supporting die (figure 7b).

Figure 7. Folding of a tube during the free upset bulging (a) and a principle of the upset bulging with a supporting die (b).

3.2. Upset bulging with a supporting die
A supporting die constrains the metal flow outwards and stops a formation of an unstable wave, which helps to deform another wave. A principle of the upset bulging with a supporting die is shown in figure 7b.

A behavior of a tube during an upset bulging with a supporting die was investigated depending on the length of the deforming part of a tube and the diameter of the supporting die in the ranges of 20-80 mm and 42-50 mm respectively. Design of experiment of the upset bulging study with a supporting die is given in table 3.

When the gap between a mandrel and a supporting ring is only 2 mm, by all lengths of the deforming part of the tube in the studied range thickening occurs. Increasing the gap to the length of the deforming part of the tube up to 40 mm also causes thickening, and for larger length of the deforming part of the tube, first two and then three waves are formed. In the range of supporting die diameter of 46-50 mm and length of the deformed part of the tube of 30-40 mm, formation of a formed bulge with an explicit cylindrical area is possible. With an increasing of the diameter of the supporting die a formed bulge is no longer possible because the gap is too large. With a supporting die diameter of 52 mm the formation of three waves is no longer possible due to the loss of tube stability and the formation of a closed fold.
The results of a simulative study of the upset bulging with a supporting die are summarized in figure 8. When the gap between a workpiece and a supporting die is only 2 mm, by all lengths of the deforming part of the tube in the studied range a thickening occurs. Increasing the gap in case of the length of the deforming part of the tube up to 40 mm also causes thickening, and for larger length of the deforming part of the tube, at first two and then three waves are formed. In the range of supporting die diameter of 46-50 mm and length of the deformed part of the tube of 30-40 mm, formation of a formed bulge with an explicit cylindrical area is possible. With an increasing of the diameter of the supporting die a formed bulging is no longer possible because the gap is too large. With a supporting die diameter of 52 mm the formation of three waves is no longer possible due to the loss of tube stability and the formation of a closed fold.

### Table 3. Design of experiment of the upset bulging study with a supporting die.

| Variable                                      | Levels |
|-----------------------------------------------|--------|
| Length of the deforming part of a tube, mm    | 20 30 40 50 60 70 80 |
| Diameter of the supporting die, mm            | 42 44 46 48 50 52 - |

| Length of the deforming part of a tube, mm    |
|-----------------------------------------------|
| 20                                           |
| 30                                           |
| 40                                           |
| 50                                           |
| 60                                           |
| 70                                           |
| 80                                           |
| 90                                           |

| Diameter of the supporting die, mm            |
|-----------------------------------------------|
| 42                                           |
| 44                                           |
| 46                                           |
| 48                                           |
| 50                                           |
| 52                                           |

Blue – thickening, yellow – free bulging, purple – formed bulging, orange – two waves, green – tree waves

**Figure 8.** Effect of the process parameters on the wave formation in the upset bulging with a supporting die.

The formation of one, two or three waves is accompanied by the addition of extra metal volume in increasing order. Thus, for parts with a short-expanded element along the tube axis, one wave can be recommended, and for long parts, preforming with the formation of 3 waves is preferable, as this provides the maximum accumulation of metal in the deformation zone.

### 3.3. Experimental results of upset bulging

According to the numerical study in 3.2., preformed workpieces with one, two and three waves were produced. The workpiece with one wave was obtained by free upset bulging, while workpieces with two and three waves were obtained by upset bulging with a supporting die with a 48 mm diameter (figure 3). The length of the deforming part of a tube was 32 mm for obtaining of one wave and 68 mm for obtaining of two and three waves. The final distance between dies was 10.8 mm, 32.5 mm and 28.3 in the case of one, two and three waves respectively. Appearance and a cross-section of preformed tubes with one, two and three waves are shown in figure 9. The plastic strain is localized in the wave formation zone and the maximum value is 0.84, 0.50 and 0.55 in the case of one, two and three waves respectively.
3.4. **Hot metal gas forming of preformed tubes**

The preformed workpieces shown in figure 9 were deformed by HMGF. Appearance and cross-section after HMGF of preformed tubes with one, two and three waves are shown in figure 10. In the most cases of the hot metal gas forming of workpieces preformed with one wave tearing occurs. Workpieces preformed with two waves in all cases have been cracked. The most stable results with almost no failures were obtained by preforming with 3 waves. In addition, this leads to a maximum accumulation of metal in the deformation zone. It can also be seen that there is a significant thinning of the tube wall in samples preformed with one and two waves after HMGF, while the sample with three waves shows significantly less thinning.

![Figure 9](image)

**Figure 9.** Appearance (a) and a cross-section of preformed tubes with one (b), two (c) and three (d) waves. The plastic strain distribution and a cross-section are shown by the color and in black respectively.

3.5. **Comparison of experimental and simulated tube thickness distribution**

As mentioned in the section 2.2.3. and can be seen in figure 10, the production of the final part using non-preformed tube as well as preformed tube with 2 waves was unsuccessful. Therefore, for these conditions only the FEM-simulated data are presented, while for the preformed samples with one and three waves the experimental distribution of the wall thickness after HMGF is also presented (figure 11).

HMGF of tubes without preforming leads to a significant thinning up to 1.13 mm. Preforming with one wave significantly reduces a thinning in central part of the workpiece, but thinning up to 1.2 mm in the rounding area still remain. Preforming with two waves could lead to a significant reduction in thinning, but this method was not successful in experimental studies.

The best result was obtained with preforming with three waves, which led to a thinning only up to 1.65 mm, which is approximately 45% thicker than minimal wall thickness of a workpiece without preforming.

Analysis of the results shows, that the simulation is able to predict a final form of the workpiece after the upset bulging with a satisfactory accuracy (figure 9) as well as a tube thickness distribution after HMGF (figure 11).
4. Conclusions
The upset bulging process as a preforming operation for hot metal gas forming of 22MnB5 tubes was implemented and investigated.

1. It was shown, that the upset bulging is suitable as a preforming operation for HMGF of 22MnB5 tubes and is an efficient method to prevent a tube failure, as well as to increase a tube wall thickness and its uniformity after HMGF.

2. The best result was obtained with preforming with three waves, which allows to produce a part and led to a thinning only up to 1.65 mm, which is approximately 45% thicker, that minimal wall thickness of a workpiece without preforming, obtained by the simulation.

3. The simulated and experimental geometry of the workpieces after the upset bulging as well as a tube thickness distribution after HMGF are consistent, so the creditability and rationality of simulation are verified.

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Figure 11. Comparison of experimental and simulated tube thickness distribution after HMGF.
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