Improved formability of HMGF components by preforming in an upset bulging process

R Haase¹, M Werner¹, V Kräusel¹, A Alimov², A Sviridov² and S Härtel²

¹ Fraunhofer Institute for Machine Tools and Forming Technology, Chemnitz, Germany
² Brandenburg University of Technology Cottbus-Senftenberg, Cottbus, Germany

E-mail: rico.haase@iwu.fraunhofer.de

Abstract. Hot Metal Gas Forming (HMGF) is a well-established combination of a profile hydroforming operation and an in situ hardening process. Roof rails and camshafts are typical applications. A significant limitation of the component geometry is the strain-related material thinning. In the polar coordinate system of the tube-shaped parts, the strain can be divided into circumferential and longitudinal portions. To achieve higher expansion ratios in circumferential direction, a longitudinal compression is necessary. In a conventional, non-tempered process setup this is achieved by an axial feeding movement during the forming operation. Under tempered conditions, in particular by friction coefficients well above 0.3, this is no longer possible in a controlled process. Anyhow, a beneficial material pre-distribution is required to enlarge the circumferential strain before material failure occurs. In the proposed preforming operation, the longitudinal compression is achieved by offset bulging. Based on aspect ratios between initial diameter, wall thickness, initial length and compression stroke, a specific, controlled wave pattern is achieved on the specimen. Subsequently, the semi-finished parts undergo the HMGF process in an austenitisation, transfer, forming and quenching procedure. By means of continuous, finite element based simulation and related model calibration in experimental trials, a significant increase in geometric complexity is achieved.

1. Hot Metal Gas Forming

The Hot Metal Gas Forming technology does combine the forming operation of predominantly profile- or pipe-typed work pieces with an inline heat treatment by a die quenching process. The process route starts with the initial austenitisation of the material by elevation of its temperature above Ac3 followed by a swift transfer into the forming device, application of the media pressure and rapid cooling due to the pressurized contact of the work piece towards the lower tempered forming die. In a large scale series application, the dies are equipped with an active cooling system to derive the repeated heat input by the processed parts. The forming operation of the tempered specimen followed by the quenching and thus hardening procedure does provide a unique combination of formability and mechanical properties of the finished product.

2. General strain conditions

Due to the pipe-typed characteristic shape of the work pieces, their geometric appearance can be described in a polar coordinate system rather relevant than in the Cartesian tripod. The geometry is then defined by the shape of the cross section along the components characteristic centre line. Starting from a pipe with circular initial section, geometric features can be formed by the application of the media
pressure from the enclosed volume. A minor decrease of the section length is also possible, but heavily restricted by the wrinkling tendency of the sheet metal and therefore is no further regarded in this paper. By the applied media pressure, the metal membrane of the work piece starts to expand freely into the surrounding die cavity. Under those initial conditions, a biaxial stretch strain is observed. Utilizing the aforementioned Cartesian coordinate system, the strain condition can be divided into a longitudinal and circumferential portion. Taking the expansion of a single segment as an elementary forming feature, the strain values can be described as

$$\varepsilon_{\text{circ}} = \ln \left( \frac{dU_1}{dU_0} \right)$$

(1)

For the free, circular expansion with constant radii along the Cartesian angle it can be reduced to

$$\varepsilon_{\text{circ}} = \ln \left( \frac{r_1}{r_0} \frac{d\varphi}{d\varphi} \right) = \ln \left( \frac{r_1}{r_0} \right)$$

(2)

Following the same consideration in the longitudinal direction of the elementary forming feature the strain can be described through the length ratio in undeformed versus bulged state, as illustrated in Figure 1.

$$\varepsilon_{\text{long, bulge}} = \ln \left( \frac{l_1}{l_0} \right) = \left( \frac{2r*\sin\left(\frac{\alpha}{2}\right)}{l_0} \right)$$

(3)

Figure 1. Bulged preform of a hydro formed pipe with dimensions relevant for calculation.

$$\delta = \frac{\alpha}{4} = \arctan \left( 2 * \frac{r_1-r_0}{l_0} \right) ; \quad r = \frac{l_0}{2*\sin\left(\frac{\alpha}{2}\right)}$$

(4)

For industrial relevant parameter combinations, this mean longitudinal strain value during the bulged state $$\varepsilon_{\text{long, bulge}}$$ is several factors smaller than the circumferential strain $$\varepsilon_{\text{circ}}$$. As soon as the work piece gets in contact in the middle area of the form feature, the movement is restrained by the severe friction between the wall of the cavity and the pressurized specimen.
Assuming a cylindrical shape of the form feature with conical transitions towards the surrounding geometry as illustrated in Figure 2, the mean longitudinal elongation of the final shaped component can be estimated as:

$$\varepsilon_{long,cyl} = \ln\left(\frac{l_0 - 2(r_1 - r_0) \tan \phi}{l_0} \right) = \ln\left(\frac{l_0 + 2(r_1 - r_0) \left(\frac{1}{\sin \phi} - \frac{1}{\tan \phi}\right)}{l_0}\right)$$

(5)

![Figure 2. Cylindrical form feature with conical transition area.](image)

As the contact area is growing from the centre towards the conical areas, the width of the formed membrane decreases and therefore longitudinal strain increases progressively. This effect is amplified, the more the pre-shaped bulge and final part geometry diverge. Due to the fact, that the cylindrical areas usually represent functional faces and short transition zones are intended, the localised longitudinal strain plays a crucial role for functional density of hydro formed parts. By this biaxial strain state, the elongations in longitudinal and transversal direction superimpose towards an excessive thickness reduction. Derived from volumetric consistency, thickness strain equals to:

$$\varepsilon_{th} = -(\varepsilon_{circ} + \varepsilon_{long})$$

(6)

For practical applications, not only a compensation of the longitudinal strain during bulging, but even an overcompensation with a resulting, negative value of $\varepsilon_{long}$ is aimed for. On the other hand, an excessive compression might result in irreversible wrinkles along the specimen and therefore acts as a boundary condition for the process window.

3. Necessity of a pre-forming operation

In order to avoid excessive thinning or even material failure during the forming operation, a longitudinal feeding and thus compressive strain along the axis of the part is intended. Under non-tempered conditions and thus low friction impact, a feed movement of the sealing punches is performed parallel to the ramp up of the media pressure. Within hot forming conditions, there are two major obstacles which prevent this change in strain state. The friction of a heated austenite blank towards the forming die ranges between 0.3 and 0.45 [1] and therefore predominantly leads to a sticky contact behaviour. In parallel, the axial compression of the profile tends to get unstable due to the lowered strength and potentially inhomogeneous temperature distributions. Due to this lack of process repeatability, axial feeding is not applied to HMGF processes on industrial scale. To provide an alternative solution, the preceding material distribution by a cold preforming operation is proposed. Due to the significantly lowered friction conditions at room temperature and homogeneous stress distribution, a controlled compression is achievable. Geometrically, a macroscopic material movement into the subsequent forming zone is intended. For the considered profiles and pipe-type components, this can be achieved by an upset bulging process.
The ends of the specimen are restricted in radial movement by outer and potential inner active parts, which are approaching each other along the compression stroke $\Delta l$ as shown in Figure 3.

![Figure 3. General process scheme of the bulging process.](image)

To maximize the compression effect and prevent remaining humps on the component afterwards, the compression should be equivalent to the expected longitudinal strain as described in the previous chapter. The description of this intention in longitudinal strain delivers:

$$
\varepsilon_{\text{pref}} + \varepsilon_{\text{long,cyl}} = \varepsilon_{\text{pref}} + \ln \left( \frac{l_0 + 2(r_1 - r_0) \left( \frac{1}{\sin \phi} - \frac{1}{\tan \phi} \right)}{l_0} \right) \cong 0
$$

(7)

$$
\varepsilon_{\text{pref}} = \ln \left( \frac{l_0}{l_0 + \Delta l} \right) \cong -\varepsilon_{\text{long,cyl}}
$$

(8)

$$
\Delta l \cong 2(r_1 - r_0) \left( \frac{1}{\sin \phi} - \frac{1}{\tan \phi} \right)
$$

(9)

Aiming for even higher expansion ratios and therefore higher circumferential strains, the longitudinal strain is not only compensated by the preceding longitudinal compression, but even exceeded by higher initial compression strokes.

4. Upset bulging of specimen

The upsetting process is utilized to provide a preform containing a longitudinal compression and radial expansion according to the desired final shape. Following this approach, the material distribution along the longitudinal axis is crucial for the further HMGF process in terms of macroscopic material flow and thus friction effects on the wall of the forming cavity. The parameters defined by the selected pipe material are inner and outer diameter and thus wall thickness. The initial length of the specimen and compression stroke $\Delta l$ are varied within the trials in order to observe the geometric forming result. The process layout is shown in Figure 3. The restraining forming tools (Figure 4) are equipped with a radius depending on the material thickness $R = 2 \times s_0 = 4.0 \, mm$ and therefore the effective buckling length is the sum of the initial distance between those dies plus two times that radius. A repeatable compression stroke can be ensured by distance blocks of height $h = l_0 - 2R - \Delta l$. 


a) press ram, performing compression stroke $\Delta l$

upper die, guidance is realized by press equipment

lower die, fixed in position

press bed with mounted base plate

b) guide / positioning pin, ensures correct alignment of die segments

lower die with $R = 4.0 \text{ mm}$, symmetric on upper and lower side

specimen of diameter $d_0 = 2r_0 = 40 \text{ mm}$ and initial thickness $s_0 = 2 \text{ mm}$

not included: distance /stroke limiter blocks of height $h$

**Figure 4.** preforming tool mounted in press (closed state) a) and detailed review of tool components (opened state) b)

For the cylinder-shaped forming feature, a material distribution with two wave-shaped material depots close to the conical transition zones will minimize the longitudinal material flow during the HMGF process and does therefore provide the optimum result with regards to a uniform wall thickness distribution. Unfortunately, the axial force during the bulging process does not monotonically increase with ongoing compression stroke. As soon as the wave-shaped material depot is formed towards a half circle section, axial force decreases and the wave tends to close in a wrinkle. Due to the small bending radii, this cannot be flattened again during the HMGF process and needs to be avoided. The solution to this concern is a supporting die which limits the radial expansion of the wave-shaped material depot and therefore prevents it from flipping over and collapse. As a result, a pattern of two or even more symmetrical material depots could be achieved. The bulging process is described in [2] more in detail.

5. **Numerically assisted process design and prototyping**

The overall process chain was elaborated by means of a 3D finite element model undergoing the preforming operation, austenitization in the furnace and subsequent tempering in the handling process and finally the combined forming and quenching operation. The bulging process itself was calculated utilizing the finite element software QForm available at B-TU Cottbus. Based on an application-related selection of input parameters, the following result matrix could be achieved.
Figure 5. Parameter matrix of initial length and diameter of supporting tool leading to different shapes of the material depot in the subsequent forming zone.

The geometric result was exported utilizing a Nastran mesh description. By the subsequent heating up to austenite state well above Ac3 temperature, previous strain values and related hardening effects are reset and can be neglected. The wall thickness distribution was transferred by the volumetric elements. In an initial configuration as shown in Figure 6, a single material depot was generated by the combination of a short buckling length and compression stroke. The material thickness distribution was utilized for validation of the FE model and corresponds well to measurements from section cuts.

| Parameter                  | Preform result | Final result - longitudinal material movement in mm |
|----------------------------|----------------|-----------------------------------------------------|
| no preforming              | ![Image]       | ![Image] +5.0 -5.0                                   |
| Δl = 13 mm                 | ![Image]       | ![Image] +5.0 -5.0                                   |
| h₀ = 30 mm; R = 2 × s₀     | ![Image]       | ![Image] +5.0 -5.0                                   |
| Δl = 16 mm                 | ![Image]       | ![Image] +5.0 -5.0                                   |
| h₀ = 30 mm; R = 2 × s₀     | ![Image]       | ![Image] +5.0 -5.0                                   |

Figure 6. Preforming result and final material thickness distribution.
Even if the developed length in longitudinal direction is already contained in the preformed specimen and therefore no significant longitudinal strain was expected, the material distribution along the axis of the part does not correspond to the final shape. Under the aforementioned friction conditions in the HMGF process, only a minor longitudinal material flow was observed. As a result, the thickness distribution along the part axis still shows strong peaks with a maximum in the preformed middle section and still considerable thinning towards the conical transition areas. Heading towards a preform closer to the final shape, the buckling length was significantly increased towards the form feature length plus the desired compression stroke. By additional limitation of radial movement by the support die, two material deposits close to the conical transition areas could be generated. As Figure 7 illustrates, the preform represents the final shape more precise. Consequently, a homogeneous wall thickness distribution within the cylindrical area of the form feature could be observed.

### Optimized preforming parameters:

\[
\Delta l = 17.7 \text{ mm} \\
h_0 = 68 \text{ mm}; \\
R = 2 \times s_0 = 4 \text{ mm}
\]

Result of optimized preform:

- uniform material thickness along part length,
- no significant thinning, even in conical transition areas
- full contact to cavity in cylindrical area, sufficient cooling rate is achieved

![Figure 7. Simulation result of optimized preforming parameters and subsequent HMGF.](image)

6. **HMGF of preformed specimen**

The existing tool was initially designed for a pipe outer diameter of 44 mm resulting in a circumferential elongation of 27%. This can be achieved without a preforming operation. By reduction of the pipe diameter to \( d_0 = 2r_0 = 40 \text{ mm} \), the circumferential elongation develops towards 40%, which is no longer feasible without preforming and repeatedly results in a provoked rupture of the pipes. In a further experimental setup, a feeding motion was tested but did result in either a crumpling of the pipe ends or collapse of the pipe in the middle section. Accordingly, a preforming of the pipe is mandatorily required. The preformed specimen are heated up in a furnace at \( \theta_{furn} = 950^\circ C \) for a period of \( t_{furn} = 300 \text{ s} \). The transfer operation was performed manually, but still in a repeatable manner. Thus a transfer time of \( t_{transfer} = 5.0 \pm 0.5 \text{ s} \) was ensured. Coming from the furnace, the forced convection due to the swift handling leads to a cooling rate of about 12 K/s, which further decreases with the temperature level of the part. Due to the wall thickness of \( s_0 = 2.0 \text{ mm} \) and the predominant radiation merely on the outside of the specimen, the cooling rate is comparatively low. From the insertion temperature of about \( \theta_{insert} = 890^\circ C \) the temperature further drops due to radiation and convection on the upper side and the loose initial tooling contact on the lower side of the part. Regarding a time period of \( t_{closing} = 2.5 \pm 0.5 \text{ s} \) for activation of the security curtain of the press and closing of the cavity, a starting temperature
of $\vartheta_{\text{start}} = 840 \pm 25^\circ C$ is achieved on the part. The utilized forming tool is shown in Figure 8, where the expansion in the middle area to $d_1 = 2r_1 = 56 \text{ mm}$ is obvious.

![Figure 8](image_url)

**Figure 8.** Successful HMGF process with expansion from $d_0 = 40 \text{ mm}$ to $d_1 = 56 \text{ mm}$. Preform shown on the left, finally achieved component on the right.

7. **Characterization of the manufactured components**
During the experimental trials, the optimized preforming proved robust in terms of feasibility. An interesting side effect in this case is the middle area of the preformed part which still is about 2 mm less in diameter and therefore does not yet get in direct contact to the die during the inserting of the part. Within CMM measurements, the shape of the cylindrical form feature was within a tolerance of $0/-0.05$ from reference. Section cuts did show a complete martensitic transformation in the cylindrical section. Due to the lack of contact in the conical transition zone, a slight drop in micro hardness was observed in that area. If required, this can be achieved by an adaption in tool design.

8. **Summary and outlook**
Hot metal gas forming (HMGF) is a process well suitable for a variety of high-strength and lightweight pipe-typed or even profile components. Previously, the limitation in component design was severely restricted by the feasible circumferential elongation in the various sections along the components axis. Due to the challenging tribological conditions within the HMGF process, a notable axial feeding is not possible in particular within an industrial process environment. By an innovative preforming step based on a tool-supported bulging operation, significant material resources can be moved into the subsequent forming zone. By this precedent axial material feed and compression, the axial elongation portion is lowered. As a benefit, extraordinary circumferential strain values can be achieved. So far, the methodology has been applied on cylindrical form features. A transfer of the approach towards non-rotational, but arbitrary regular shaped cross sections is ongoing.

**Acknowledgments**
The content presented within this paper was funded within IGF 21359N.

**References**
[1] Müller R and Mosel A 2014 Characterisation of Tool Coatings for Press Hardening *Adv. Mater. Res.* 966–967 259–69
[2] Alimov A and Haase R 2022 Upset bulging as a preforming operation for hot metal gas forming of 22MnB5 tubes *IOP Conf. Series: Mat. Sci. and Engineering*