Influence of process chain on fold formation during flange upsetting of tubular cold forged parts

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Abstract

The present paper analyses a multi-stage cold forging process focusing the final upsetting stage regarding to annular fold formation during upsetting. Recent numerical and experimental investigations showed that annular folding is not only affected by geometrical instability of tubular parts or buckling respectively but also by high local strain hardening effects interacting with forging temperature, specific material flow and surface quality of inner lateral surface of the tubular part. Depending on mentioned influencing factors three different mechanisms or kind of folds respectively have been determined and analyzed. It has been shown, that annular folding occurs at related free upsetting heights ($h_s/OD_o$) hitherto known as uncritical if strain hardening of semi-finished tubular part is considered. A newly developed semi-empirical fold criterion for prediction of fold of 2nd-order has been implemented into commercial code DEFORM™ and assessed using experimental data.

Keywords: Cold forging; Flange upsetting; Tubular parts; Annular folding

1. Introduction

Flange upsetting of tubular parts -typically used as transmission components- is suitable for structural and work material lightweight design as well as material efficient production processes. Dieterle (1975) reported that one

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process limit in flange upsetting of tubular components is the formation of an annular fold mainly affected by geometrical parameters related to free upsetting height \(h_s/\phi D_o\) of specimen depending from diameter ratio of tubular part \(\phi D_i/\phi D_o\) (Fig. 1 (a)) leading to instability occurrence of the tubular part or buckling respectively. A classification of flange upsetting of tubular parts regarding to guidance and clamp as well as different working diagrams taking geometrical effects of tubular semi-finished parts into account have been published by him.

Such observations have been confirmed by Rudolf et al. (2010) and Schiemann et al. (2011) for additional materials and structures. A two stage upsetting process has been proposed by Schiemann et al. (2013) to prevent buckling of tubular semi-finished part in the first stage by using conical shaped dies and to extend process limits with regard to \(h_s/\phi D_o\). Although buckling has been prevented in the first upsetting stage using conical shaped dies, annular folding occurs anyhow during second upsetting stage. This has been shown for different work materials. An extension of forming limit by 30 % only was possible by an intermediate annealing treatment. Based on this numerical and experimental investigations Schiemann et al. (2013) classified three different kinds of folds. Fold of 1st-order due to instability occurrence and buckling of tubular part and is affected mainly by geometrical parameters of billet. This kind of fold can be predicted by numerical methods with high accuracy. Fold of 2nd-order is affected by high local strain hardening effects interacting with forging temperature, specific material flow and surface quality of inner lateral surface of the tubular part and is not predictable with high accuracy by numerical methods, as reported in Schiemann et al. (2013). Minor folds of 3rd-order occurs if fold of 1st-order and 2nd-order have been preventable due to unavoidable reduction of inner lateral surface during upsetting.

Different modes of buckling during lateral extrusion of tubular parts have been reported by Arentoft et al. (1995) and e.g. Balendra et al. (2004). To prevent buckling they used a mandrel forming a double frustum of a cone and a pre-forming ring leading to an inward material flow of the tubular part in the first operation sequence. In the second operation sequence radial outer flange is forged by radial extrusion. Lopes et al. (1998) investigated this two stage operation sequence and reported the occurrence of a dead metal zone inside the mandrel cavity causing a flaw failure starting at the inside of the tube. Numerical and experimental investigations have been conducted using commercial pure aluminum. Gouveia et al. (2000) analyzed ductile fracture criteria and its suitability to predict failure for different workability metal experiments and other applications. In case of double-sided radial extrusion of a tubular flanged component the occurrence of the previously described flaw at the inside of the inner flange cannot be predicted and quantified numerically using the fracture criteria of Cockcroft and Latham and Oyane. This is reducible to the high compressive hydrostatic stresses being found in investigated deformation zone.
Recent investigations on workability limits during forging of tubular flanged parts explicitly disclosed that annular folding also is affected by high local strain hardening and continuous reduction and the structure of inner lateral surface of tubular parts if buckling does not occur or can be prevented. Therefore forming history of the tubular semi-finished part (Fig. 1 (b)) and its effect on fold formation will be taken into account analysing and predicting fold formation during flange upsetting in this contribution.

### Nomenclature

| Abbreviation | Definition |
|--------------|------------|
| BCE          | backward cup extrusion |
| $D_o$        | outer diameter of tubular part |
| $D_i$        | inner diameter of tubular part |
| FEA          | finite element analysis |
| $h_f$        | flange height after final upsetting stage |
| $h_0$        | height of tubular semi-finished part |
| $h_s$        | free upsetting height of a double clamped tubular part |
| $K_1$        | material coefficient |
| $K_2$        | material coefficient |
| $m$          | strain rate exponent |
| $n$          | strain exponent |
| $v$          | material coefficient |
| $R$          | max. initial element radius |
| $r$          | min. initial element radius |
| RMS          | root mean square |
| $T$          | absolute temperature |

2. Process flow for manufacturing a tubular flanged part

2.1. Experimental procedure

Experimental investigations have been conducted on a mechanical knuckle joint press (May Press) having a press capacity of 6000 kN. Used tool set for the experimental tests for backward cup extrusion is depicted in Fig. 2 (a). Press force has been measured by a load cell and ram distance by a position sensor. Part temperature has been measured at top of cold forged cup or at outer diameter of flange using a thermocouple (welded) for validation of numerical model. Due to the fact, that no transfer system was used, tools have been changed after backward cup extrusion and 1st upsetting stage. In any case experiments have been conducted starting at room temperature.

Three different process routes (Fig. 2 (b)), starting from different semi-finished parts and continuing with single stage or double stage upsetting, have been investigated. Semi-finished tubular parts for Route 1 and Route 2 have been manufactured by BCE using tool set depicted in Fig. 2 (a). Different heights of semi-finished tubular parts for Route 1-a-b means, that after BCE process parts have been annealed for recrystallization objectives, pressed in 1st stage and then directly pressed in 2nd stage without intermediate annealing treatment. For Route 3 tubular parts have been machined with highly specified surface qualities at inner lateral surface for investigation of influence of surface structure and quality on fold formation.

Steel alloys have been shot blasted, phosphated and lubricated with soap for BCE and etched, phosphated and lubricated with MoS2 prior upsetting. Geometrical and experimental conditions for experimental investigations are summarized in Table 1.

After cold forging parts have been analysed in order to measure fold depth (if existing) and fold angle. For this purpose specimen have been cut at their longitudinal axis, fold endangered area has been embedded, grinded and
polished. Afterwards fold depth and fold angle have been measured and development of fold of 2nd-order has been analysed using flow patterns.

![Fig. 2. (a) Tool set for BCE and (b) experimentally investigated process routes.](image)

Table 1. Geometrical and experimental conditions of experimental investigations.

| Route | OD₀ (mm) | h₀ (mm) | OD₁/OD₀ (-) | hₛ/OD₀ (-) | Materials |
|-------|----------|---------|-------------|-------------|-----------|
| 1     | 36       | 38, 43.4, 45.2 | 0.5          | 0.5, 0.65, 0.7 | 1.7139, 1.7321 |
| 2     | 36       | 38       | 0.5          | 0.5         | 1.7139, 1.7321 |
| 3     | 36       | 43.4     | 0.5          | 0.65        | 1.7139, 1.7321 |

Uniaxial compression tests for cold and hot workability of investigated alloys have been carried out at three different strain rates (\(\dot{\varepsilon} = 0.04, \dot{\varepsilon} = 1, \dot{\varepsilon} = 25\)) using a Gleeble 3800°C and initial temperatures of specimen between RT and 500°C. Material model according to Molinari and Clifton (1983) (Eq. (1)) has been fitted with experimental derived workability data using the RMS method. Calculated material parameters are shown in Table 2.

\[
k_f = K_1(K_2 + \phi)^n \phi^m T^{-\theta},
\]

(1)

Table 2. Parameters for used material model.

| K1 (MPa) | K2 (-) | n (-) | m (-) | \( \theta \) [K] |
|----------|--------|-------|-------|-----------------|
| 1.7139   | 8226   | 0.005 | 0.21  | 0.009           |
| 1.7321   | 6407   | 0     | 0.18  | 0.004           |
|          |        |       |       | 0.34            |

2.2 Numerical procedure

Software that has been used for numerical investigations of described processes was commercial code DEFORM™ V10.2. Due to the fact, that fold of 2nd-order is not predictable using FEA a fold criterion has been developed by the authors and implemented into DEFORM™ using the usrmsht subroutine. This subroutine has access to many internal variables of DEFORM™ code and is utilized at the beginning and end of each time step. Developed fold criterion (Eq. (2)) takes the influence of strain hardening, surface reduction, temperature and surface texture into account and \( F \) is handled as an accumulated state variable in the simulation. Current fold value
\( F_i \) consists of fold value \( F_{i-1} \) at previous step and change of \( dF \).

\[
F = \sum_{i=1}^{n} F_i', \quad F_i' = F_{i-1} + dF_i, \quad dF_i = f(\varphi_{i,j}, d\varphi_{i,j}, T_{i,j}, Ra')
\]

(2)

where \( \varphi_{i,j} \) is the nodal equivalent strain value according to V. Mises, \( d\varphi \) is the change of surface reduction, \( T \) is the nodal temperature and \( Ra' \) is a scalar taking the surface roughness and the surface texture into account as it has a certain influence on temporal beginning of the fold. Change of surface reduction \( d\varphi \) at current step and for the nodes at surface is calculated by Eq. 3.

\[
d\varphi_{i,j} = \varphi_{i-1,j} - \varphi_{i,j}, \quad \varphi_{i,j} = \frac{A_i}{A_0} = \frac{(R_i + \tau_i) \ast \sqrt{(R_i - \tau_i)^2 + h_i^2}}{(R_0 + \tau_0) \ast \sqrt{(R_0 - \tau_0)^2 + h_0^2}}.
\]

(3)

where \( \varphi_{i,j} \) is the ratio of inner lateral surface of an element before \( (A_0) \) and after distortion \( (A_i) \) due to deformation. Change of fold depth is calculated following Eq. 4. No change of fold value \( dF \) occurs if nodal temperature \( T_{i,j} \) reaches recrystallization temperature \( T_R \) or strain value \( \varphi_{i,j} \) and the change of surface reduction \( d\varphi \) are zero.

\[
dF_i = (0.56 \ast \varphi_{i,j}^{0.2}, 1.22 \ast d\varphi_{i,j}) \ast Ra' = (0.56 \ast \varphi_{i,j}^{0.2} + 1.22) \ast d\varphi_{i,j} \ast Ra'.
\]

(4)

If a surface node reaches experimentally determined critical fold value \( F = 1.52 \) its pathway is tracked and fold is visualized by highlighting elements. Fold depth can be measured at any step using the integrated measurement tool. Factor \( Ra' \) has been determined as \( Ra' = 1; 1.02; 1.03; 1.05 \) for the four investigated different surface structures of inner lateral surface of tubular parts (Route 1 and 2: \( R_a = 0.21 \), Route 3: \( R_{a1} = 0.4, R_{a2} = 3.2, R_{a3} = 8 \)).

3. Results

3.1 Comparison of numerically and experimentally determined results regarding to fold of 2nd-order

Satisfying conformity between numerically determined fold depth as well as fold position and measured fold depth and fold position has been achieved using the proposed fold criterion (Fig. 3.)

![Fig. 3. (a) Fold depth and fold position predicted by FEA using Eq. 2 and (b) determined by microscopic analysis (1.7139, Route 3-b).](image)

From Fig. 4 (a) and (b) it can be seen, that fold depth strongly correlates with surface structure or surface quality of tubular part used for experimental analysis. Moreover no interdependence from work material can be derived comparing fold depth of route 3-b in Fig. 4 (a) and (b). Additionally accurate prediction of fold depth by FEA using the proposed fold criterion is possible. According to Dieterle (1975) part investigated in route 2-b reveal uncritical related free upsetting height \( (h_\varphi/OD_{h_\varphi} = 0.5) \) and annular folding should not occur. Fold depth of 278 µm at cold forged part using route 2-b underlines, that development of an annular fold is not only affected by geometrical parameters such as related free upsetting height, but also depends on forming history of workpiece.
Fig. 4. (a) Fold depth depending from process route, measured in longitudinal plane at a flange height $h_f = 9$ mm and predicted by FEA respectively for work material 1.7139 and (b) for work material 1.7321.

4. Summary and outlook

It has been shown, that annular folding is not only affected by geometrical instabilities as discussed in past publications. Accuracy of numerical prediction of fold of 2nd-order is possible and accurate using the proposed fold criterion. Fold depth hardly depends on work material but strongly correlates with structure of inner lateral surface of used tubes as well as forming history. Further investigations will focus on numerical prediction of fold of second order taking into account mentioned influencing parameters.

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