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Flange upsetting of tubular components

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Abstract

The present paper analyses a multi-stage cold forging process focusing on the final upsetting stage design regarding to annular fold formation. It has been shown, that annular folding occurs at large upsetting heights (h_s/ØD_o) hitherto known as uncritical if strain hardening of semi-finished tubular part is considered. A short overview of the existing failure mechanisms during flange upsetting of tubular parts will be given in this paper and the numerical prediction of fold of 1st and 2nd-order will be discussed in more detail using a newly developed fold criterion. Experimental results of formation of fold of 1st and 2nd-order gained by used manufacturing sequences are shown which enlarge working limit diagram of double clamped upsetting of tubular components according to Dieterle (1975) significantly.

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

Nomenclature

BCE	*backward cup extrusion*	h_s	*free upsetting height of a double clamped tubular part*
ØD_O	*outer diameter*	*m*	*friction factor*
ØD_I	*inner diameter*	*m*	*strain rate exponent*
ØD_R	*diameter of raw part*	*n*	*strain exponent*
ØD_F	*flange diameter*	R'_a	*surface factor*
DK	*dissipation coefficient*	*RMS*	*root mean square*
dF	*change of fold value*	*T*	*absolute temperature*
F	*fold value*	α	*heat transfer coefficient*
FEA	*finite element analysis*	ε	*emissivity*
h_f	*flange height after final upsetting stage*	$d\psi_i$	*change of surface reduction*
$h_{0\text{-}2}$	*height of tubular semi-finished parts*	φ_v	*effective strain*
h_{IN}	*cup height*		

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 on process limit when flange upsetting of tubular components as formation of an annular fold mainly affected by geometrical parameters related to free upsetting height h_s/ØD_O of specimen depending on diameter ratio of tubular part ØD_I/ØD_O (Fig. 1) leading to instability occurrence of the tubular part or buckling respectively. A classification of flange upsetting of tubular parts regarding to guidance and clamp of tubular raw parts 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/ØD_O (Fig. 2). 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. Extension of forming limit by 30 % has been achieved by an intermediate annealing treatment. Based on such 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 is affected mainly by geometrical parameters of billet. This kind of fold can be predicted by numerical methods using commercial FE software. Fold of 2nd-order is affected by high local strain hardening effects interacting with forging temperature, specific material flow conditions 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 occur if fold of 1st-order and 2nd-order have been preventable due to unavoidable reduction of inner lateral surface during upsetting.

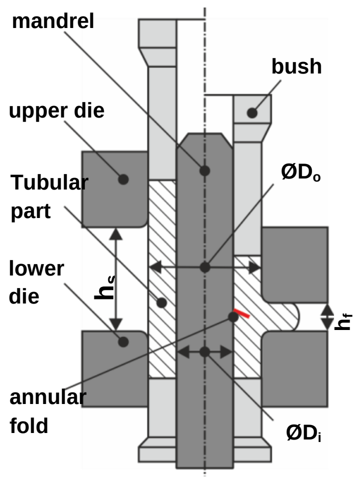


Figure 1 Process overview of single stage upsetting

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 numerically and experimentally using commercial pure aluminum and reported the occurrence of a dead metal zone inside the mandrel cavity causing a flaw failure starting at the inside of the tube. Gouveia et al. (2000) analyzed ductile fracture criteria and its suitability to predict failure for different forming processes 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 though when using the fracture criterion of Cockcroft and Latham and Oyane.

Recent investigations on workability limits during forging of tubular flanged parts explicitly disclosed forming or manufacturing history respectively of the tubular semi-finished part. Its effect on fold formation will be taken into account when analyzing and predicting fold formation during flange upsetting in this contribution using manufacturing sequence as depicted in Fig. 3. Moreover fold criterion for the numerical prediction of fold of 2nd-order proposed in Schiemann et. al. (2014) will be assessed using manufacturing sequence depicted in Fig. 3.

2 Process flow for manufacturing a tubular flanged part

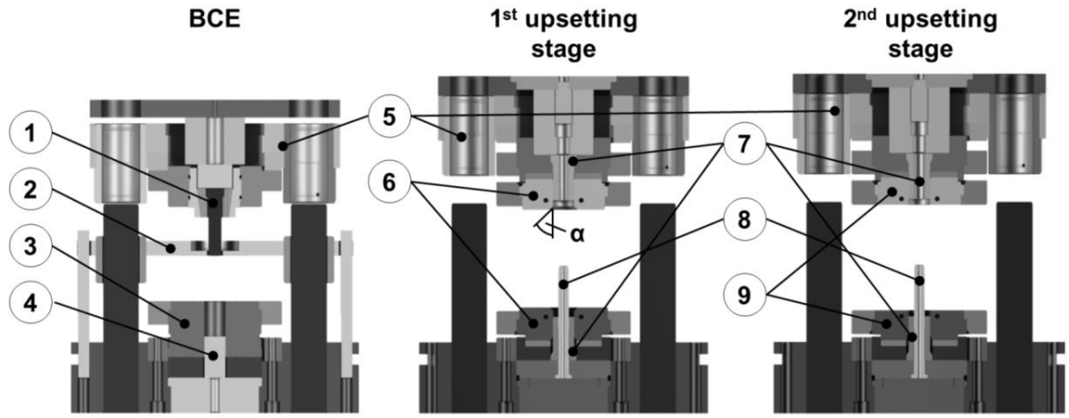
2.1 Experimental procedure

Experimental investigations have been conducted on a mechanical knuckle joint press having a press capacity of 6000 kN. Used tool sets for the experimental tests for backward cup extrusion, 1st and 2nd upsetting stage are depicted in Fig. 2. Press force has been measured by a load cell and ram distance by a position sensor. In some cases 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 in terms of material model quality. 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. Upsetting dies of 1st-upsetting stage are shaped conical with an angle of $\alpha = 45°$ for the prevention of buckling of tubular part at critical related upsetting heights $h_s/ØD_O$. For 1st and 2nd upsetting stage bushes (Fig. 2, No. 7) and mandrels (Fig. 2, No. 8) have been manufactured having three different diameters allowing the investigation of the diameter ratios $ØD_I/ØD_O$ = 0.4, 0.5 and 0.6.

Six different process routes starting from BCE and continuing with single stage or double stage upsetting have been investigated (Tab. 2, Fig. 3). Between forging stages annealing treatment and surface treatment has been performed in some cases for the investigation of effect of strain hardening state on fold formation. Double stage upsetting process has been used only in case of critical related upsetting heights $h_s/ØD_O$ (depending on used diameter ratio $ØD_I/ØD_O$). From manufacturing sequence depicted in Fig. 3 the possible parameter combinations lead to six different process routes (Tab. 2). Used parameters for heat treatment prior upsetting as well as surface treatment of raw parts for BCE or upsetting respectively are shown in Tab. 1.

Table 1 Parameters of heat and surface treatment

Work material	Heat treatment	Surf. treat. befoce BCE	Surf. treat. before upsetting
1.7139	6h at 650 °C	phosphated + soaped	phosphated + MoS_2
1.7321	4h at 680 °C	Phosphated + soaped	phosphated + MoS_2



1: Punch; 2: Stripper; 3: Die; 4: Ejector; 5: Tool rack with load cell, pressure plates and clamping rings; 6: Conical shaped upsetting dies (α=45°); 7: Bushes; 8: Mandrels; 9: Flat upsetting dies

Figure 2 **Tool sets for BCE, 1st and 2nd upsetting stage used for experimental investigations**

Table 2 **Indication of process routes depending from upsetting stages and intermediate treatment**

Process route	Annealing + Surf. treat.	1st-upsetting stage	Annealing + Surf. treat.	2nd-upsetting stage
1-a-a	yes	yes	yes	yes
1-a-b	yes	yes	no	yes
1-b-b	no	yes	no	yes
1-b-a	no	yes	yes	yes
2-a	yes	-	-	yes
2-b	no	-	-	yes

Tab. 3 shows numerical and experimental design table. Depending on diameter ratio $ØD_I/ØD_O$ different process routes as well as related upsetting heights $h_s/ØD_O$ have been investigated. Process routes consisting of the two stage upsetting process (Tab. 2) are only expedient if instability occurrence in single stage upsetting is noticeable. Some parameter combinations e.g. $ØD_I/ØD_O = 0.5$, Route 2-b, $h_s/ØD_O = 0.55$ hitherto have only been investigated numerically. Further experimental work will be done.

After cold forging parts have been analyzed in order to measure fold depth (if existing) and fold angle. For this purpose specimen have been cut along its longitudinal axis, fold endangered area has been embedded, grinded and polished. Afterwards fold depth and fold angle have been measured and development of fold has been analyzed using flow patterns. Uniaxial compression tests for cold and hot workability of investigated alloys have been carried out at three different strain rates ($\dot{\varphi}$=0.04, $\dot{\varphi}$=1, $\dot{\varphi}$=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)) for the work material 1.7139 and material model according to Shirakashi (1970) (Eq. (2)) for the work material 1.7321 have been fitted with experimental derived workability data using the RMS.

$$k_f(\varphi, \dot{\varphi}, T) = 8225 * (0.005 + \varphi)^{0.21} * \dot{\varphi}^{0.009} * T^{-0.4} \quad \textbf{(1)}$$

$$k_f(\varphi, \dot{\varphi}, T) = 908 * \varphi^{0.2} * \dot{\varphi}^{0.003} * e^{[-0.0007*(T-299.15)]} \quad \textbf{(2)}$$

In both cases validation of material models or derived coefficients respectively has been done comparing numerically and experimentally determined load stroke and temperature stroke data considering elastic losses of tools and used press. High quality of prediction of load and temperature depending on stroke at seven discrete points also has been achieved.

Table 3 Numerical and experimental design table

$ØD_I/ØD_O$	Route	$h_s/ØD_O$ [-]													
		0.45		0.5		0.55		0.6		0.65		0.7		0.75-0.85	
		FEM	EXP	FEM	EXP	FEM	EXP	FEM	EXP	FEM	EXP	FEM	EXP	FEM	EXP
0.4	2-a	not expedient						x		x		x		x	
	2-b							x		x		x		x	
0.5	1-a-a	not expedient								x	x		x	not expedient	
	1-a-b									x	x	x	x		
	1-b-b									x	x		x		
	1-b-a									x	x		x		
	2-a			x	x	x		x		x		x			
	2-b			x	x	x		x		x		x			
0.6	2-a	x		x		x		x		not expedient					
	2-b	x		x		x		x							

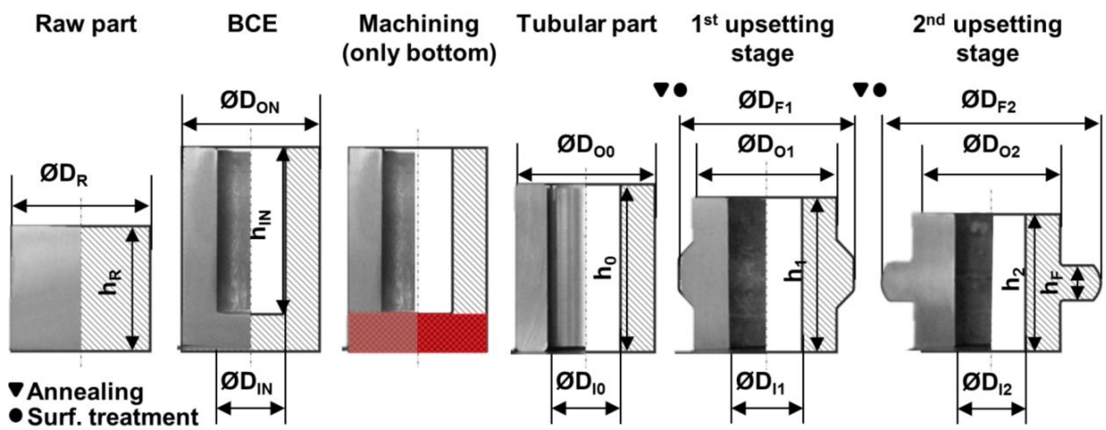


Figure 3 Numerically and experimentally investigated manufacturing sequence

2.2 Numerical procedure

Software that has been used for numerical investigations of described processes was commercial code DEFORM™ V10.2 and model parameters used for numerical investigations are shown in Tab. 4.

Due to the fact, that fold of 2nd-order has not been predictable using FEA or available damage criterions a fold criterion has been developed by the authors Schiemann et. al. (2014) and implemented into DEFORM™. Developed fold criterion (Eq. (3)) takes the experimentally determined influencing factors strain hardening, surface reduction of inner lateral surface, temperature and surface texture into account. F is managed 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. If a surface node reaches experimentally determined critical fold value $F_{Krit} = 1.52$ its pathway is tracked and fold is visualized by highlighting corresponding elements. Factor R_a' has been determined as R_a' = 1.01; 1.02; 1.03; 1.05 for the four investigated different surface structures of inner lateral surface of tubular parts (Schiemann et. al. (2014)).

Table 4 Basic, tribological and thermal parameters of used FE-models

Object	Workpiece (BCE)	Workpiece (Upsetting)	Mandrel	Upper die	Lower die
Object type	plastic	elasto-plastic	rigid	rigid	rigid
No. of elements	5000	5000	-	-	-
Material data	Eq. (1) and (2)	Eq. (1) and (2)	-	-	-
Kinematic	-	-	-	MayPress	
α [kW/m²K]	11	11	5	5	5
m [-]	0.12	0.12	0.12	0.12	0.12
DK [-]	0.9	0.9	0.9	0.9	0.9
ε [-]	0.7	0.7	0.7	0.7	0.7

$$F = \sum_{i=1}^{n} F_i \ , \ F_i = F_{i-1} + dF_i, dF_i = f(\varphi_{v,i}^{n}, d\psi_i, T_i, R_a') \qquad (3)$$

Change of fold depth is calculated following Eq. 4. No change of fold value dF occurs if nodal temperature T_i reaches recrystallization temperature T_R or strain value φ_v and the change of surface reduction $d\psi$ are zero.

$$dF_i = \left(0.56 * \varphi_{v,i}^{0.2} + 1.22\right) * d\psi_i * R_a' \qquad (4)$$

3 Results

3.1 Annular folding depending on process route

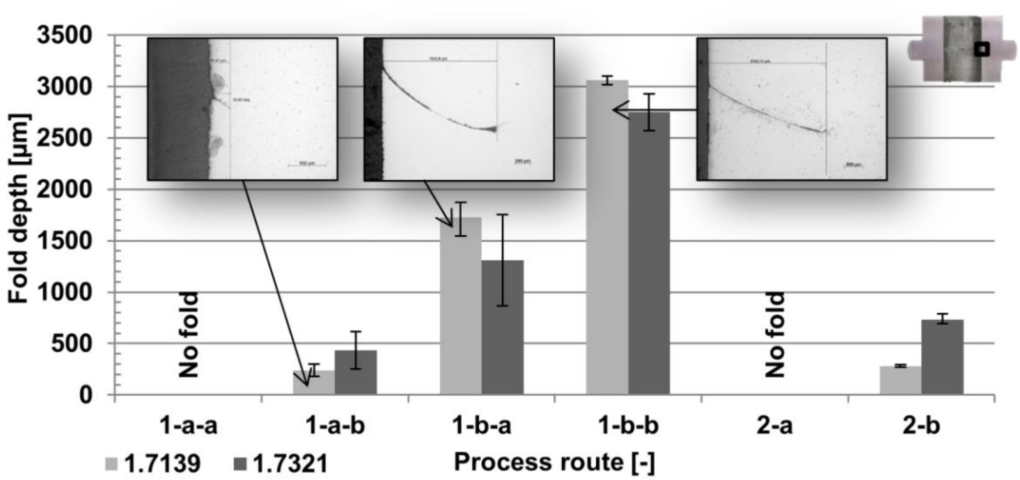


Figure 4 Fold depth depending from process route ($ØD_I/ØD_O = 0.5$, Route 2-b: $h_s/ØD_O = 0.5$, single stage upsetting; Route 1-x-x: $h_s/ØD_O = 0.65$, two stage upsetting)

Fig. 4 shows that fold depth or existence of an annular fold strongly depends on forming history or process route respectively. Using a suitable (Tab. 1) heat treatment process fold development can be suppressed e.g. in case of route 1-a-a or 2-a. It is noticeable that according to Dieterle (1975) process route 1 has a critical related upsetting height and instability occurrence is only preventable using the two stage upsetting process with conical shaped dies within the first stage. According to Dieterle (1975) part investigated in route 2-b reveal uncritical related free upsetting height ($h_s/ØD_o$=0.5) and annular folding should not occur. Fold depth of *278 µm* for work material 1.7139 or *729 µm* for work material 1.7321 respectively at cold forged parts using route 2-b do reveal such development of an annular fold which is not only affected by geometrical parameters such as related free upsetting height, but also depends on forming history of workpiece. This phenomenon has been observed by the authors also for the work materials 3.2315 and 1.0401. Moreover fold depth increases significantly using process route 1-b-a and 1-b-b.

3.2 Numerical prediction of annular folding

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. 5). It is remarkable that failure prediction of fold of 2nd-order occurring at process routes 1-a-b and 2-b is possible only using the proposed fold criterion (Eq. 3, 4) developed by the authors. For route 1-a-a and 2-a no annular folding occurs in any case.

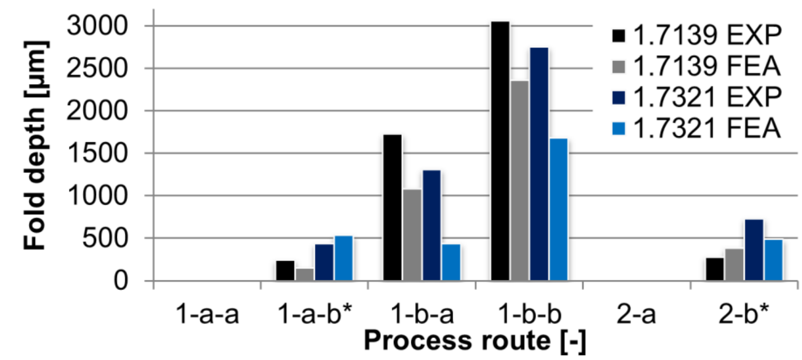


Figure 5 **Fold depth FEA vs. EXP depending on process route; *failure solely predictable when using proposed fold criterion ($ØD_I/ØD_O$ = 0.5, Route 2-b: $h_s/ØD_O$ = 0.5, Route 1-x-x: $h_s/ØD_O$ = 0.65)**

3.3 Working limit diagram

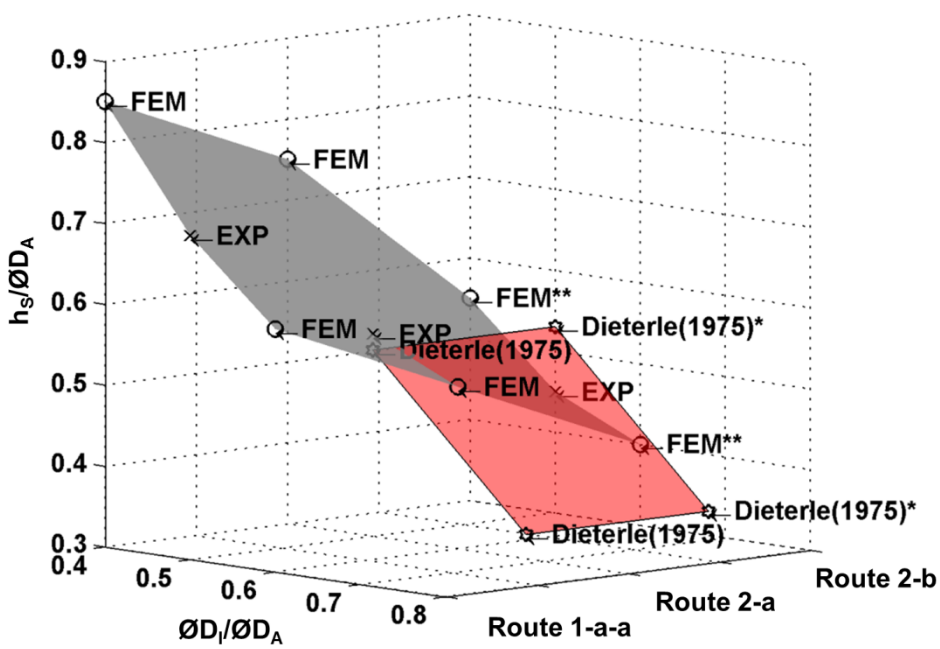


Figure 6 **New working limit diagram for 1.7139; related free upsetting height $h_s/ØD_O$ depending on diameter ratio $ØD_I/ØD_O$ and process route (**: solely predictable when using proposed fold criterion; *: extrapolated)**

Following the numerically and experimentally derived results a revision of existing working limit diagrams' needs to be done. For this purpose existing and material specific working limit diagram for the work material 1.7139 according to Dieterle (1975) has been extended taking also the forming history into account (Fig. 6). It can be seen that process limit of related free upsetting height can be extended significantly when using process route 1-a-a. Moreover significant drop of process limit occurs if route 2-b instead of route 2-a is used for the manufacturing of flanged parts from tubular components. Following these results it is not sufficient to take only geometrical parameters into account when an annular fold is unwanted.

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. Existence of an annular fold strongly correlates with forming history of tubular raw parts. Further investigations will focus on additional experimental validation of new working limit diagram also for different work materials.

5 Acknowledgements

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