Original scientific article

Received: Mar 07, 2017
Accepted: Apr 20, 2017
DOI: 10.1515/rmzmag-2017-0006

Reliability of system for precise cold forging

Zanesljivost sistemov za precizno preoblikovanje v hladnem

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Abstract

The influence of scatter of principal input parameters of the forging system on the dimensional accuracy of product and on the tool life for closed-die forging process is presented in this paper. Scatter of the essential input parameters for the closed-die upsetting process was adjusted to the maximal values that enabled the reliable production of a dimensionally accurate product at optimal tool life. An operating window was created in which exists the maximal scatter of principal input parameters for the closed-die upsetting process that still ensures the desired dimensional accuracy of the product and the optimal tool life. Application of the adjustment of the process input parameters is shown on the example of making an inner race of homokinetic joint from mass production. High productivity in manufacture of elements by cold massive extrusion is often achieved by multiple forming operations that are performed simultaneously on the same press. By redesigning the time sequences of forming operations at multistage forming process of starter barrel during the working stroke the course of the resultant force is optimized.

Key words: cold foring, process reliability, product accuracy, tool life, FE simulation

Povzetek

Prispevek podaja vpliv raztrosa glavnih vhodnih parametrov preoblikovanega sistema na natančnost izdelka in vzdržljivost orodja pri hladnem preoblikovanju v zaprti matrici. Za postopek nakrčevanja v zaprti matrici je bila izvedena prilagoditev glavnih parametrov procesa na maksimalne vrednosti, ki zagotavljajo zanesljivo proizvodnjo preciznega izdelka in optimalno vzdržljivost orodja. Kreirano je bilo operacijsko okno z maksimalnim raztrosom vhodnih parametrov za postopek nakrčevanja v zaprti matrici, ki zagotavlja želeno natančnost izdelka in optimalno vzdržljivost orodja. Prilagoditev vhodnih parametrov je prikazana na izdelavi kroglaste glave homokinetičnega zgloba v masovni proizvodnji. Visoko produktivnost izdelkov lahko dosežemo z več stopenjskim preoblikovanjem na isti stiskalnici. Z rekonstrukcijo časovnega zaporedja poteka preoblikovalnih operacij pri večstopenjskem preoblikovanju pesta zaganjalnika lahko izvedemo optimizacijo poteka rezultante sil.

Ključne besede: hladno preoblikovanje, zanesljivost procesov, natančnost izdelka, vzdržljivost orodij, simulacija z MKE

Introduction

When designing the cold forging manufacturing process, the forging process can be taken as a complex system that includes implicit interactions between the workpiece, tool and press influenced by tribological and environmental conditions. The centre of the system is the forging process that enables to shape the workpiece of simple initial shape into final product of complex shape and accurate dimensions next to good surface conditions. Response of the system is desired system function or the product of desired geometry and dimensional accuracy, respectively, the tool life, etc [1,2]. It must be emphasized that parameters of random and systematic deviations enter the forging process, and they consequently cause deviations of the product dimensional accuracy and of the tool life, and thus they cause the unreliability of process [3,4].

Reliable production of mechanical components by cold forging can be achieved with designing such a manufacturing process that enables production of components with required quality at minimum production costs which are in cold forging most often related to the service life of tools. Figure 1 schematically presents the forging system into which the parameters enter with random and systematic deviations. The system response represents a desired function or, in our case, the process operating window where the quality of product and the tool service life are in the limits of desired and permissible scatter, respectively [5].

High productivity in manufacture of elements by cold massive extrusion is often achieved by multiple forming operations that are performed simultaneously on the same press. By the help of FE we can control the material flow and load for individual stage already in the planning stage and in this way try to optimize the process. However, we have no insight into the entire forging system, where during the process elastic deflections and rotations of the press ram occur due to eccentric load, which is caused by the resultant force of forging operations during the working process. The main motivation is to plan a reliable multistage process that assures production of accurate cold forged parts. By redesigning the time sequences of forming operations at multistage forming process during the working stroke the course of the resultant force is optimized.

The article analyses the influence of scatter of principal input parameters of the forging system on the dimensional accuracy of products and on the tool life for closed-die forging process. The input parameters that most strongly influence the scatter of process response have been identified. By the help of the adjustment of basic input parameters of the production process to maximal values of deviations the production process is positioned into operating window that enables reliable achievement of the desired system function. Application of the adjustment of the process input parameters is shown on the example of making an inner race of homokinetic joint from mass production. An example from the regular mass production is represented to demonstrate prediction of tool loads and optimization of the resultant force.

Reliability and robustness of the process

One of the main goals of the forging process is to produce components with required quality. The quality of the production process should be designed already in the stage of development and designing new products. In industrial production process, periodic control of the production process is necessary. Monitoring and control of the production process is achieved by statistical process control (SPC) that determines the process capability to produce quality products. Product is supposed to be of good quality if its dimensional tolerances are in a certain tolerance interval, determined by the upper (*USL*) and the lower (*LSL*) specification limit (Figure 2). Important standpoint of the SPC is to determine the process capability indices that show the capability of the manufacturing process to produce quality products. Statistical distribution of measured product dimensions is represented by normal frequency distribution curve – Gaussian distribution. Position and spread of the normal distribution is defined by the mean value, μ , and standard deviation, σ. The process capability indices, C_{p} and C_{pk} are defined as:

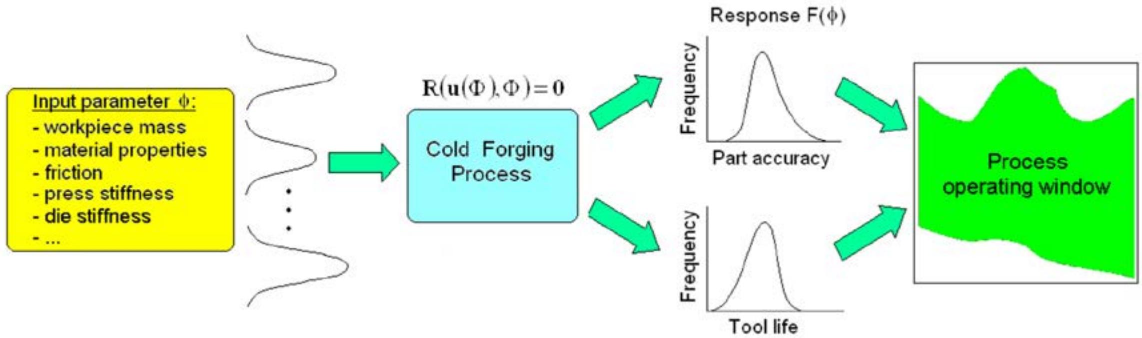

Figure 1: *Scatter impact of input parameters of the forming system on the accuracy of products and tool life.*

$$C_p = \frac{USL - LSL}{6\sigma} \quad (1)$$

and

$$C_{pk} = \min\left(\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right), \quad (2)$$

where C_p index gives the ratio between the size of tolerance range and the 6σ tolerance interval of the production process, while C_{pk} index gives the position of the tolerance interval of the production process or the centricity of the process, respectively. Full line in Figure 2 represents the 3σ process, for which the values of both indices, C_p and C_{pk},
are unity. The 3σ process represents the interval in which 99.73 % of all the results is expected to be, i.e. 2700 defective products per million. Dashed line in Figure 2 represents the robust 6σ process with 99.9999998 % efficiency, i.e. 3.4 defective components per million, for which $C_p = C_{pk} = 2$ [6]. The main aims of the 6σ method are the following: to increase the satisfaction of customer, to improve the process capability, to improve the efficiency of company, to achieve advantage against rival companies, to operate with the least defects, to increase the yield, and to reduces the variability of processes. Implementation of the 6σ method can be achieved by various methodologies, two of them are widely acknowledged and standardized: DMAIC (Define-Measure-Analyse-Improve-Control), and DFSS (Design For Six Sigma) [7]. The main difference between the two methods is that the first one is used for improving the existent products and processes, while the second one

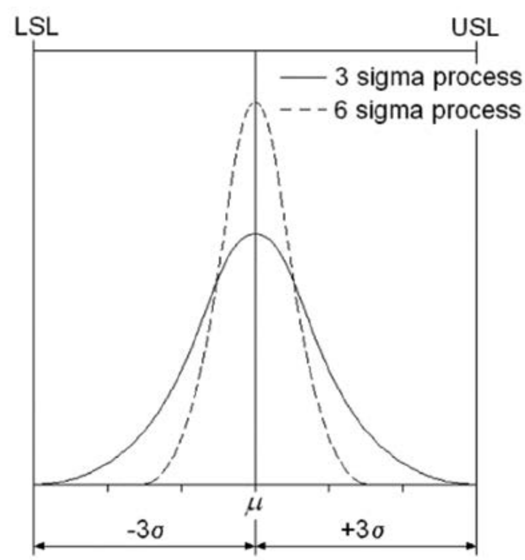

Figure 2: *3σ and 6σ process.*

is used in designing and development of new products and processes.

Optimization of the production process based on the reliability and the robustness usually takes place along the path shown in Figure 3. At first, it is assured that the distribution curve position of our process is inside the ± 3σ interval. In the optimization, based on the reliability, the mean value of the distribution function is shifted towards the centre, i.e. optimal values for a certain objective function are sought. The reliability is related to the probability of occurrence of a defect. The aim of the reliability based optimization is that response of our system is in the region in which the probability of a defect occurrence is minimal.

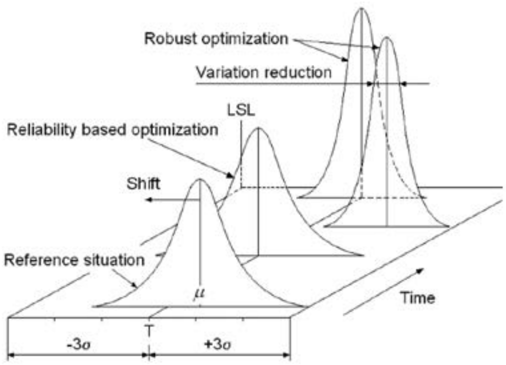

Figure 3: *Process optimization based on the reliability and robustness.*

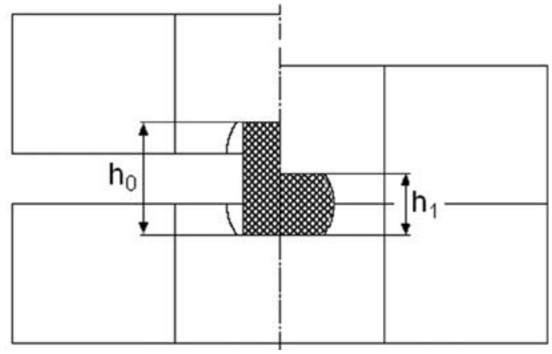

Figure 4: *Closed-die upsetting process, value of relative deformation $\varepsilon_h = 0.45$.*

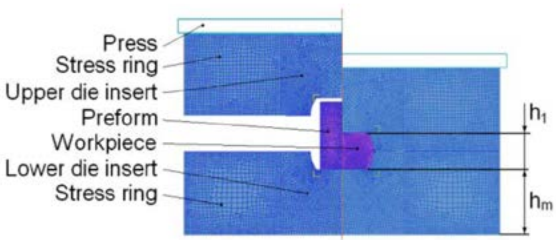

Figure 5: *FE model of closed-die upsetting process.*

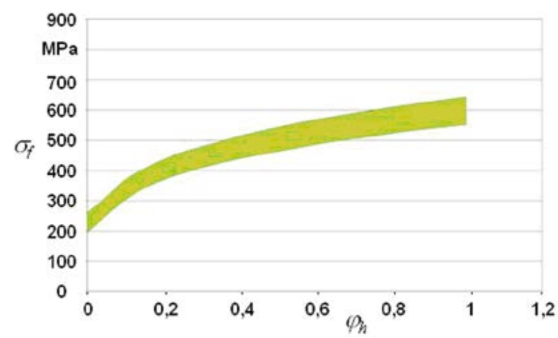

Figure 6: *Scatter of flow stress QSt 32-3 steel [8].*

QSt 32-3	R_p [MPa]	C [MPa]	n	$\varphi_{h\,max}$
Average	224.8	593.1	0.2552	1.1099
St. dev.	17.5	19.9	0.0188	0.0872
Min	196.8	551.9	0.2149	0.9591
Max	262.3	643.0	0.2957	1.2567
Max %	16.70	8.41	15.90	13.23
Min %	12.42	6.95	15.79	13.59

Figure 7: *Variables in mass production conditions for QSt 32-3 steel [8].*

In the Taguchi's robust process optimization, as described Yang and Haik [7], first the variability of the system response is reduced. This is made in such a way that the variability of those input parameters are reduced which influence the distribution scatter. Lower variability of the response means higher quality of products and lower production costs. The next step in the robust optimization is to shift the mean value of the distribution with reduced variability towards the desired mean value, T (Figure 3). Focussing on those process parameters that have important influence on the distribution mean value and the minimal influence on the distribution scatter enables to shift the distribution towards the desired value, T.

Created an operating window for closed-die upsetting process

Closed-die upsetting process was analysed to evaluate stochastic interactions (Figure 4). Workpiece mass and flow stress, friction as process parameter, and press stiffness were chosen as the principal parameters of the forming system. QSt 32-3 steel (according to DIN standards) with flow stress scatter was used as the workpiece material (Figure 6) [8]. The flow stress curve was determined with the Hollomon function $\sigma_f = C.\Phi^n$. The data for the material constant, C, logarithmic deformation, Φ, yield stress, R_p, and hardening exponent, n, are given in Figure 7 [8].

Blank mass, yield stress, and material constant were chosen on five levels, while the hardening exponent and friction were on the nominal level, and stiffness on the low or high level. Values for single levels of parameters are given in Fig-

Input parameters	Min. (-2)	Low (-1)	Nominal (0)	High (1)	Max. (2)
Mass (g)	305	307.75	306.5	307.25	308
Yield stress (MPa)	200	215	230	245	260
Material constant (MPa)	552	574.5	597	619.5	642
Hardening exponent (/)	0.255	0.255	0.255	0.255	0.255
Shear friction factor (/)	0.12	0.12	0.12	0.12	0.12
Press stiffness (MN/mm)	1.8	/	/	/	3.0
Press stroke (mm)	180	180	180	180	180
Die interference (%)	0.6	0.6	0.6	0.6	0.6
Heat transfer coefficient (N/mm/s/°C)	5.8×10^{-6}	5.8×10^{-6}	5.8×10^{-6}	5.8×10^{-6}	5.8×10^{-6}

Figure 8: *Process parameters and their levels, material of the blank is QSt 32-3.*

				Process responses			
	Parameter levels			Low stiffness (-2)		High stiffness (2)	
Run	Mass	Flow stress	Friction	h_1	$\sigma_{ef\,(max)}$	h_1	$\sigma_{ef\,(max)}$
1	0	0	0	26.53	825	26.51	916
2	-1	0	0	26.51	867	26.45	987
3	-2	0	0	26.49	913	26.43	1040
4	1	0	0	26.57	1010	26.53	1230
5	2	0	0	26.60	1240	26.56	1540
6	0	-1	0	26.52	832	26.49	930
7	-1	-1	0	26.49	856	26.45	992
8	-2	-1	0	26.47	912	26.42	1040
9	1	-1	0	26.58	990	26.56	1340
10	2	-1	0	26.63	1310	26.59	1940
11	0	-2	0	26.52	839	26.48	935
12	-1	-2	0	26.49	860	26.44	1040
13	-2	-2	0	26.46	904	26.42	1010
14	1	-2	0	26.55	892	26.54	1140
15	2	-2	0	26.62	1270	26.59	1910
16	0	1	0	26.54	908	26.51	1040
17	-1	1	0	26.51	863	26.47	915
18	-2	1	0	26.47	914	26.43	976
19	1	1	0	26.57	990	26.54	1650
20	2	1	0	26.63	1230	26.59	1730
21	0	2	0	26.55	944	26.52	1070
22	-1	2	0	26.52	848	26.47	883
23	-2	2	0	26.48	905	26.44	1110
24	1	2	0	26.56	948	26.54	1390
25	2	2	0	26.65	1340	26.60	2060

Figure 9: *Results of FE simulations for the product height, h_1(mm), and maximal effective stress in the lower die, $\sigma_{ef\,(max)}$ (Mpa), for low and high level of stiffness and for various levels of parameters for mass, workpiece flow stress, and friction.*

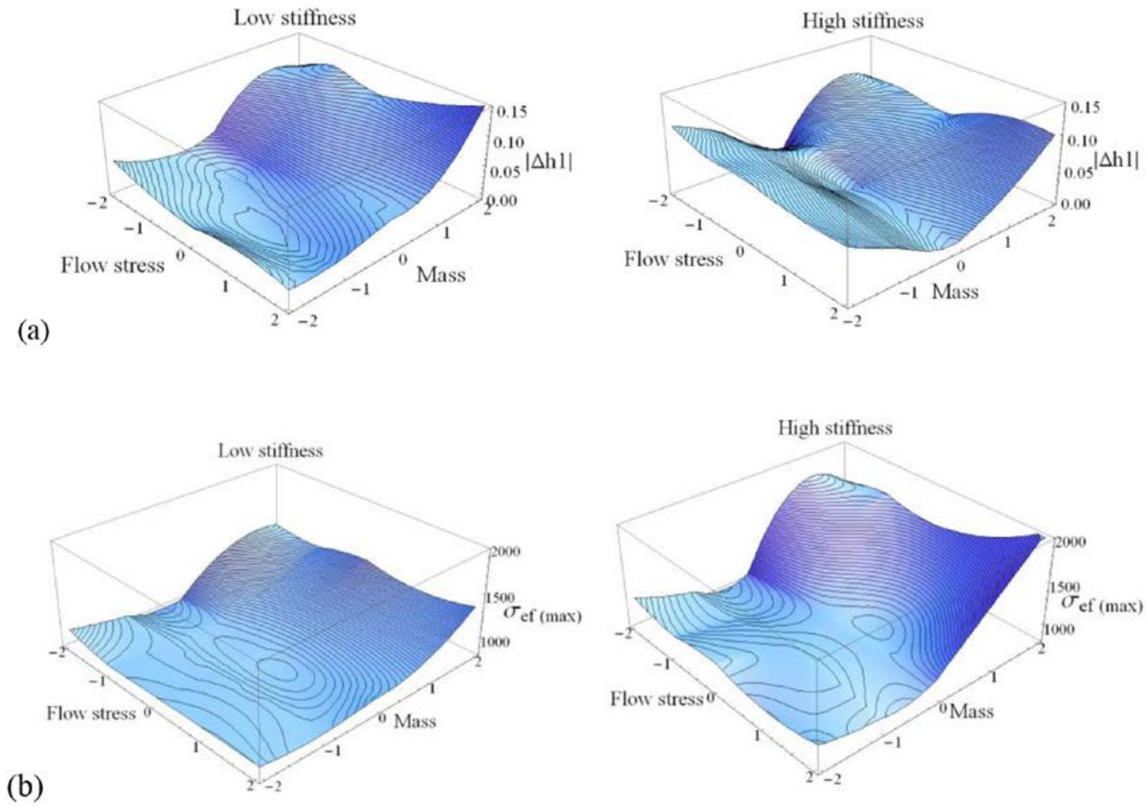

Figure 10: *Influence of the scatter of mass and flow stress input parameters on the (a) dimensional accuracy of product, $|\Delta h_1|$, and (b) on maximal effective stress in the die, $\sigma_{ef(max)}$, for various press stiffness conditions in the closed-die upsetting process.*

ure 8. Friction parameter was chosen only for the nominal level since friction in the closed-die upsetting process had small influence on the accuracy of products and tool life [4]. Figure 8 presents also die interference, and heat, transfer coefficient. Stiffness on two levels was chosen as input parameter of the vertical mechanical press with nominal force of 6.3 MN [9]. The low stiffness value is valid for soft press while the high value corresponds to stiff press.

DEFORM 2D Ver. 9.1 program with the integration of press stiffness in modelling the process was chosen for numerical simulations. The workpiece in our analysis was taken as coupled thermo-elastic-plastic body, and the tool as thermo-elastic body. Thus heat transfer from the workpiece to tool was taken in account. Friction conditions between the workpiece and the tool were modelled by shear friction law. FE model for the closed-die upsetting process (Figure 5) was designed to adjust the essential input influential parameters to maximal values that enable reliable production of dimensionally accurate products at the optimal tool life. Plan of the test with 25 FE simulations for various parameter levels for mass, flow stress, friction, and stiffness with the results for the product dimensional accuracy, and the effective stress in the lower die is given in Figure 9. Final value of the product height was h_1 = 26.5 mm with tolerance ± 0.1. Effective stress in the lower die is chosen as the damage indicator for prediction of the tool service life.

Based on the results in Figure 9, the influence of scatter of both the essential mass and the flow stress parameters on the dimensional accuracy of products and on tool life was analysed for the closed-die upsetting process for various press stiffness conditions (Figure 10 (a,b). Mass on the maximal level reduced h_1, the product height accuracy in the soft press and increased the effective stress in the lower die in the stiff

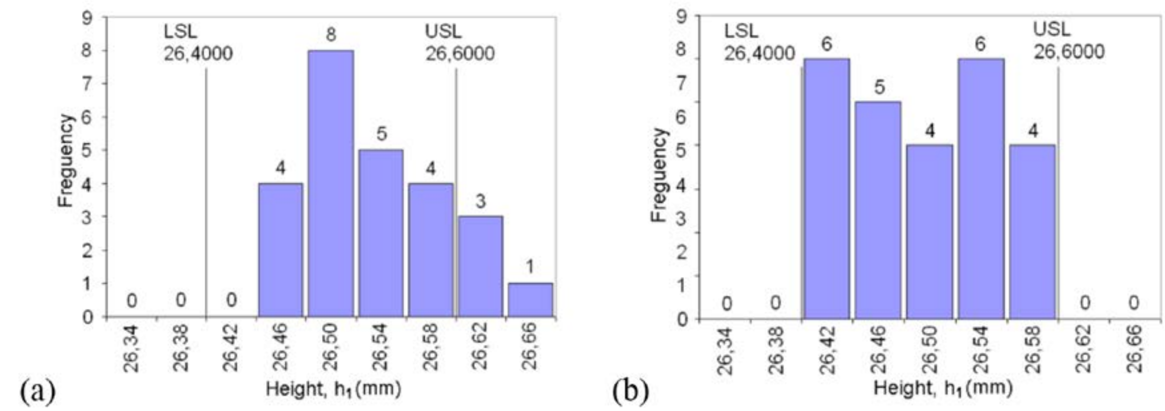

Figure 11: *Frequency histogram of product height tolerances, h_1, for various press stiffness conditions, (a) soft press, (b) stiff press.*

press. For the flow stress, it was characteristic that mainly values on the maximal level in combination with the mass on the maximal level influenced both, the dimensional accuracy of a product and effective stress in the die for both press stiffness conditions.

Stiff press enabled better centering of the process from the viewpoint of h_1, product height tolerance, as shown by graphs in Figure 11 (a, b). Scatter of h_1, product height, was in the tolerance interval ± 0.1 mm for stiff press (Figure 11 (b)) but this was in no way suitable for the process reliability in the industrial production process. With the robust optimization the variability of the distribution of h_1, product height tolerance, could be reduced. In other words, robust production process ensured products with narrower tolerance [6]. A production process that should ensure the product height h_1 with tolerance ± 0.06 mm was chosen. This meant that scatter of the product height tolerance would be inside the ± 4σ process mean value, σ was the standard deviation of the process. Effective stress in the lower die was estimated not to exceed the value of 1650 MPa. The desired values of the output process characteristic could be achieved with the adjustment of scatter of input process parameters, such as mass and flow stress. In this way the feasible region that ensured to achieve ± 0.06 mm tolerances for the product height in the press with the stiffness on the low level was determined in Figure 12 (a1). The feasible region was determined within the limits from (-2) level to (2) level for the flow stress, and from (-2) level to upper tolerance constraint for the scatter of mass. There was no limitation for the feasible region of the effective stress in the die (Figure 12 (b1)) since the desired value of 1650 MPa was achieved in the whole region of scatter of mass and flow stress. Intersection of the feasible region for the product dimensional accuracy and the maximum effective stress in the die results in the process operating window for which the product tolerance and tool service life constraints form the bounds (Figure 12 (c1)). In the case of the softer press, the reduction of mass scatter, mainly in its maximal level, ensured achieving of dimensional accuracy of product and desired tool life. Flow stress of material could remain in the expected limits of scatter.

For stiff press, the feasible region for desired dimensionally accurate product was determined with the adjustment of mass scatter by upper and lower tolerance constraints as shown in Figure 12 (a2). Reduced scatter of mass both, on the maximal and on the minimal level ensured the accuracy of product height in the ± 0.06 mm limits. Reducing scatter of mass values on the maximal level by maximum tool stress constraints enabled to create feasible region for the effective stress in the die (Figure 12 (b2)). Intersection of both feasible regions gave the operating window for our process for stiff press, as shown by the green region in Figure 2 (c2). Stiff press ensured higher reliability of the production process since better centering of the process in the respect to achieve desired value was enabled in this way.

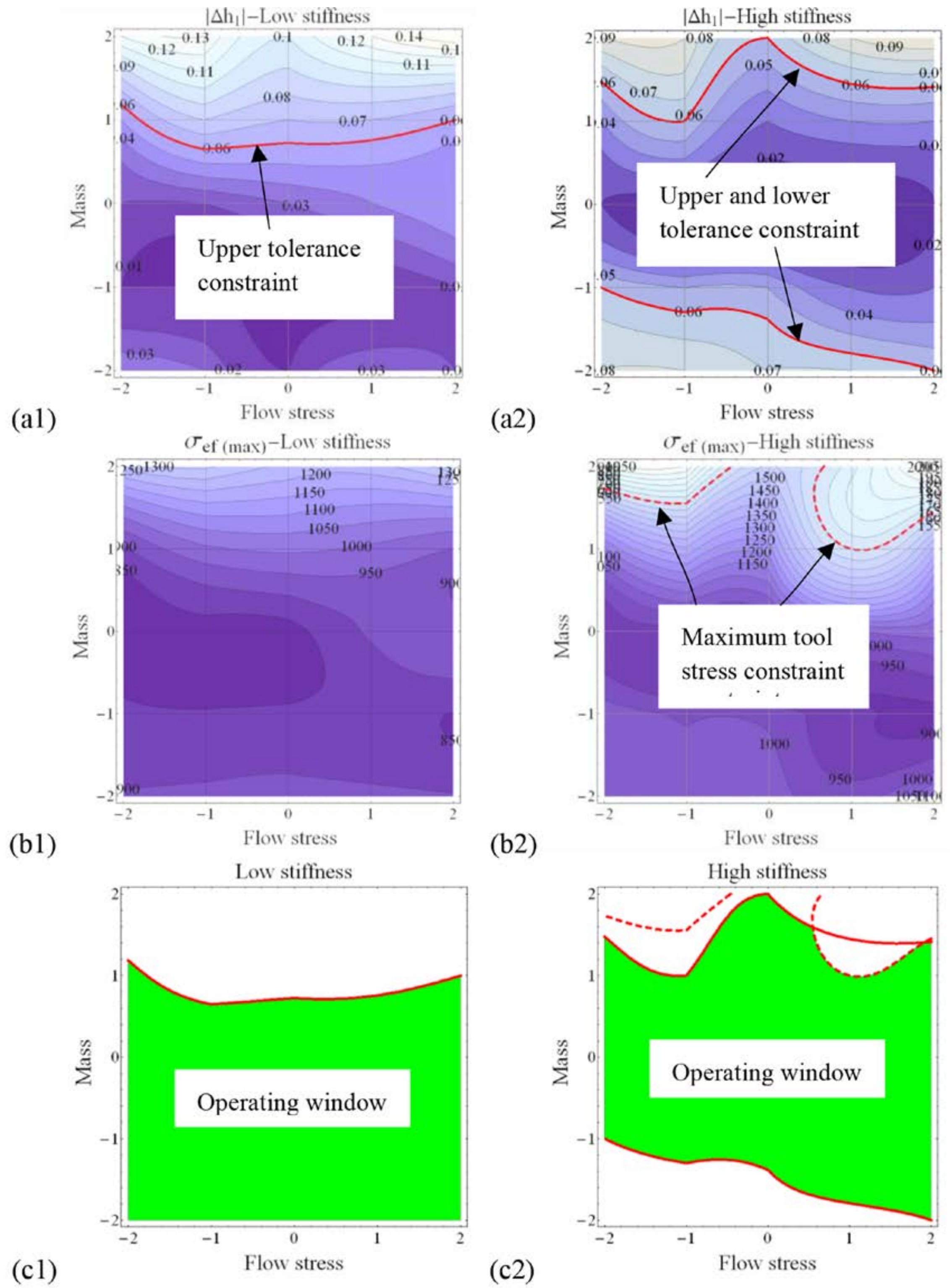

Figure 12: *(a1 and a2) feasible region for the product height (h_1) accuracy, (b1 and b2) feasible region for maximum effective stress in the die, ($\sigma_{ef\,(max)}$), and (c1 and c2) operating window for the closed-die upsetting process for low and high press stiffness.*

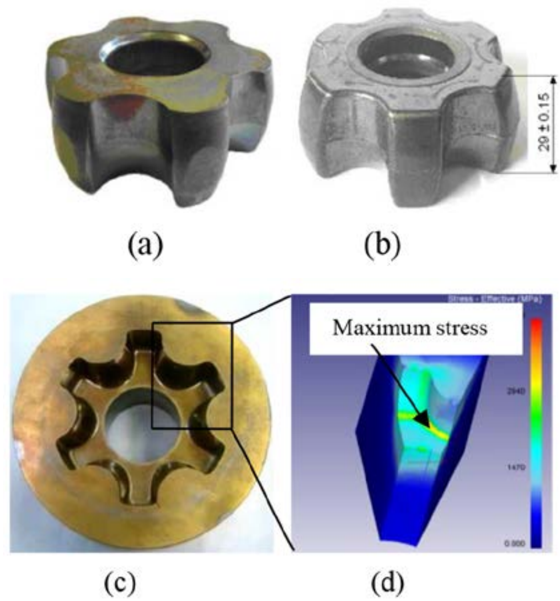

Figure 13: *(a) performed piece, (b) inner race of homokinetic joint, (c) lower die, and (d) effective stress in the lower die.*

Example of the parameters adjustment in designing process of manufacturing inner race

The principle of adjustment of principal input parameters can be applied in the calibration procedure for making the inner race of homokinetic joint (Figure 13 (b)). Product with nominal mass of 494 g was made of 16MnCr5 steel. Preformed piece (Figure 13 (a)) was previously heat-treated and surface-treated. Zinc phosphate as the main lubricant and the Na-soap were used for the surface treatment. The last operation in manufacturing of the inner race was the calibration process in the closed-die that ensured to obtain final product shape of specified dimensions. The aim of this process was to shape both face surfaces and the height of product in specified tolerances with the cold forging technology while still external grinding of sphere and intermediate grooves were needed to finish the product. The specified tolerance for the product height was ± 0.15 mm. In order to ensure the reliable production of the product for the whole series, the scatter of product height tolerance had to be in limits ± 0.1 mm.

The calibration procedure in the closed die was similar to the closed-die upsetting process, therefore the workpiece mass, the workpiece

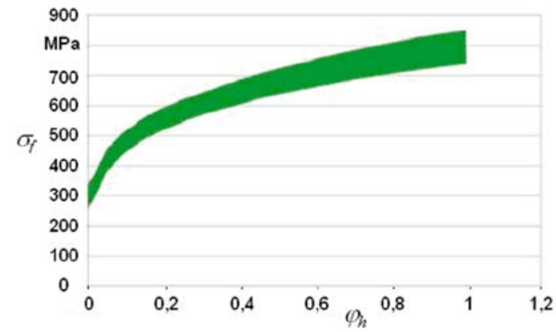

Figure 14: *Scatter of flow stress for 16MnCr5 steel [8].*

16MnCr5	R_p [MPa]	C [MPa]	n	$\varphi_{h\ max}$
Average	287.7	791.9	0.2212	0.9374
St. dev.	18.9	25.6	0.0200	0.0353
Min	261.4	739.2	0.1765	0.8636
Max	331.2	848.3	0.2522	1.0112
Max %	15.12	7.12	13.99	7.88
Min %	9.13	6.65	20.22	7.87

Figure 15: *Variables in mass production conditions for 16MnCr5 steel [8].*

flow stress, and press stiffness were chosen as the principal process input parameters. Scatter of flow stress and of variables for the 16MnCr5 steel is given in Figure 14 and in Figure 15, respectively. Scatter of the preformed-piece mass is influenced mainly by the variation of initial blank diameter. To achieve reliable production of a product, the adjustment of mass parameter to maximal scatter of ± 0.5 % of nominal value and adjustment of flow stress parameter to ± 8 % of mean value were needed. In this way the product height tolerance of ± 0.1 mm with the index of process centering C_{pk} > 1.67 was assured on the one hand and the tool life for 42,000 manufactured pieces as an average number on the other hand.

Change of the preformed-piece mass has influence on the scatter of product height and the fullness of the outer shape. Preformed pieces with the mass concentrated on the upper level give products with the height on the upper tolerance limit and vice versa. Flow stress has not such a pronounced influence on the product dimensional accuracy. For reliable achievement of desired product height accuracy, also elastic deformations of die had to be taken in account.

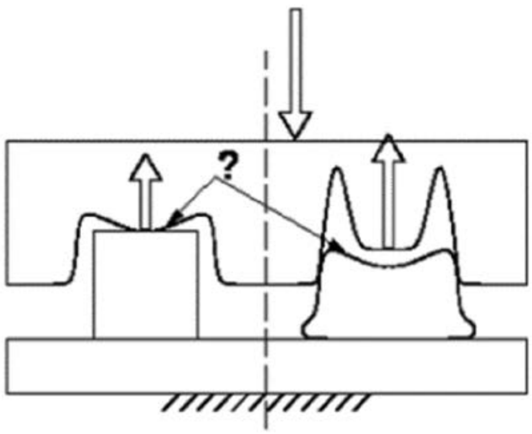

Figure 16: *An example of a two-stage forming process.*

Figure 17: *Clutch barrel of a starter.*

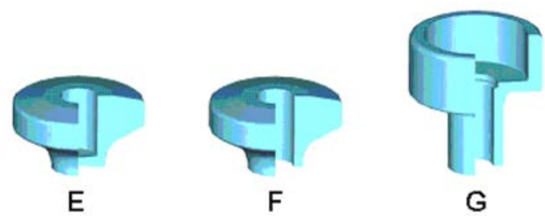

Figure 18: *A multi-stage forming process for manufacture of a starter clutch barrel.*

Figure 19: *Three-stage tooling for barrel production.*

Die was made of the ASP 23 steel with the hardness of 60 + 1 HRc (Figure 13 (c)). Suitable pre-stressing of the die, and forging in a 10 MN vertical mechanical press with vertical dynamic stiffness of 2.1 MN/mm enabled achievement of the specified tool life. Permanent plastic deformation and later crack appeared on the die bottom, as shown in Figure 13 (d). The adjustment of scatter of mass and flow stress parameters, the selection of suitable press stiffness, the design of the optimal die interference, and the selection of suitable material and of heat treatment process in making die assured reliable production of inner race for the whole series.

Optimization of the resultant force course for a multi-stage cold forging process

High productivity in massive production is often achieved by simultaneous implementation of more forming operations on the same press. The problem, which occurs in such situations, is schematically shown in Figure 16. In the illustrated case, first the forming process starts on the left side of the press axis, so that the resultant force equals the forming force of the first process. Later on, the second process is included, the maximum force of which is bigger than that of the first one. Consequently, during the process the resultant force moves to the other side of the press axis. The changing force torque causes relative rotations between the ram and the press table and performs asymmetry after the first process. These faults can increase in the stage of the process when the force torque changes the sign and the ram is unstable due to the clearance in the guiding elements.

The example in Figure 18 gives an analysis of a three-stage forming process used for manufacture of a starter clutch barrel (Figure 17), where operations E, F, and G are formed on the three-stage tool (Figure 19) at the same time.

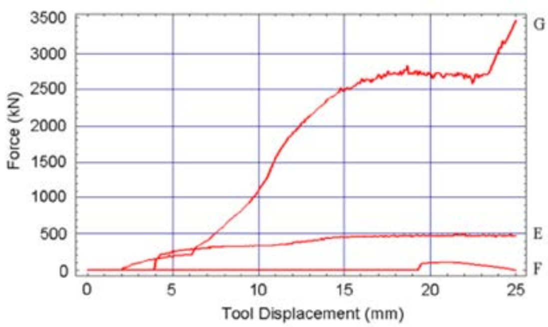

Figure 20: *Basic course of forming forces.*

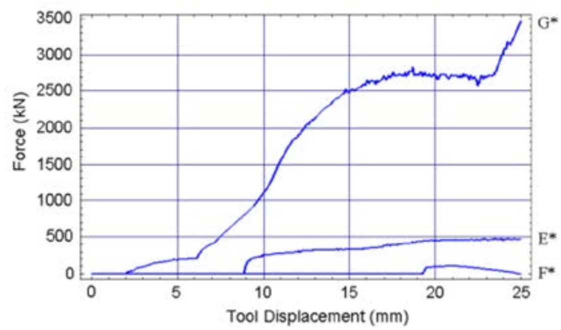

Figure 21: *Optimum course of forming forces.*

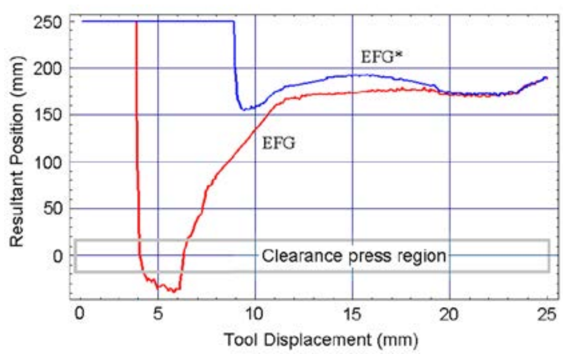

Figure 22: *A comparison of the resultant force course for a basic and optimized process.*

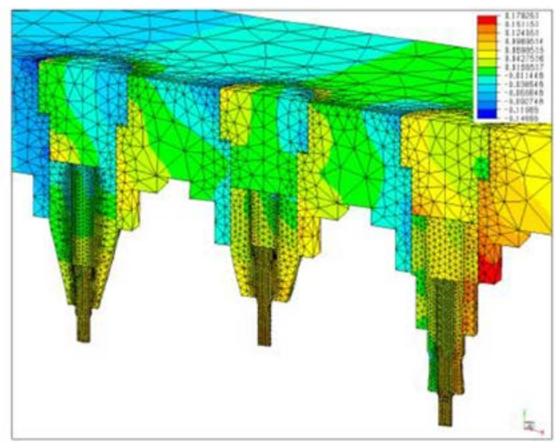

Figure 23: *A relative displacement between the upper tool and press bolster.*

Operation F is positioned in the centre of the press, whereas operations E and F are 250 mm left and right from the press centre.

The loading for individual operation is shown in Figure 20. The biggest loading appears in the last operation G, where the procedure of simultaneous backward and forward extrusion is performed. The resultant force course is shown in Figure 22, the curve EFG.

By the help of reconstruction of the beginning of the course of forming operations the forming force course and consequently the resultant force are changed [10]. A preform (Figure 18, operation E) is changed in a way that the beginning of the forming process E* (Figure 21) is delayed with reference to the course of E shown in diagram Figure 20. In this way, the force required for the process E* is always smaller than the force required for the process G*. Therefore, the course of the resultant force is always on the same side of the press centre (Figure 22, curve EFG*). Consequently, the resulting torque has the same sign during the entire movement of the ram. In this way we avoid a double ram transition through the unstable area that is affected by clearance in the press guiding elements. Thus we increase the reliability of the process considering endurance of vital tool parts and improve the possibility to reach narrower tolerances of a product. This method of resultant force optimization prevents the large portion of the horizontal displacement of the press ram in the clearance region (Figure 23) and, therefore, increases the dimensional accuracy of the clutch barrel as well as the tool- and press-service life.

Conclusion

A numerical-experimental approach for optimization of forming parameters for closed-die process in an operation window was presented, which ensures reliable achievement of the desired accuracy of a product at the optimum tool life. Application of the adjustment of the process input parameters is shown on the example of making an inner race of homokinetic joint from mass production. The press stiffness is an important parameter in the formed piece-tool-press parameter system, which increases accuracy of products and unfavourably influences the tool life, so it has to be taken into consideration when planning technologies for precise cold forging. The majority of the processes for manufacture of cold-extruded parts are carried out by a multi-operation forming on the same machine. For such forming process the resultant of forces of a multi-stage process was optimized which consequently reduced the variations of elastic displacements and rotations between the ram and the press bolster. In this way, the reliability and accuracy of a multi-stage forming process was considerably increased.

Acknowledgements

The article was published in Conference Proceedings: New Developments in Forging Technology, Editor Prof. Dr. M. Liewald MBA, Institute for Metal Forming Technology, University of Stuttgart, Fellbach, Germany, 2011.

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