Comments on the cold metal forming processes stability control

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Abstract

Nowadays different components must be produced in very narrow tolerances, the number of non-satisfying ones is limited to some tens parts per million, the final goal is oriented towards zero-defect production. To fulfil these preconditions the forming processes must be well understood. The paper discusses a possibility to improve and stabilize the quality of products by permanent process stability control and by positioning these processes in stable parts of technological windows. To find optimal solutions a combination of carefully selected experiments, analysis of successful production cases and tests in the virtual environments is highly recommended.

To the discussion on process stability control some examples from sheet metal and bulk metal forming will be presented.

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Keywords: Cold forming; Accuracy; Process stability; Deep drawing; Bulk forming

1. Introduction

Different forming technologies are nowadays widely applied in mass production of mechanical components for needs of transportation, electronics, household appliances, etc. In order to reduce costs, manufacturers are trying to minimize additional machining and therefore to implement net shape forming technologies [1]. However, net shape forming is profitable only if the process is efficient and stable.

When planning forming technologies and especially net shape forming, one should consider the fact that forming tools are never the exact negative of the part to be produced. The difference between the tool and the part shape occurs due to heat generation and transfer as well as elastic response of the whole metal forming system (part/tool/machine).

The control of part-tool shape differences is nowadays one of the most important tasks because the manufacturers are required to react quickly to the market demands. The traditional approach based only on experience and trial and error methods are too costly and time consuming. Research reports addressing these problems suggest that the right solution is a combination of group technology laws based on the similarity principles and parametric analyses obtained from successful technological processes. As numerical methods are becoming increasingly reliable tools for solving complex non-linear problems, the knowledge obtained from earlier experience can be used for the fine tuning of computing codes.

In general, the parameters affecting the metal-forming system can be divided into the following major groups:

- input material with its micro- and macro-geometry, mechanical properties;
- tools with their shape, surface quality, rigidity, sensitivity to heat transfer and thermal dilatation, wear and load resistance;
- the forming machine with its kinematics, stiffness and sensitivity to heat transfer;
- the tribological system with tool/part interface, lubrication and friction;
- the forming process with strain, strain rate and temperature distribution inside the part, contact surface expansion.

When analyzing a real industrial problem, it is necessary to consider the permissible fluctuations of previously described parameters and to evaluate their impact on the final properties of the part.

Forward rod extrusion is very often used in cold forging, therefore the accuracy of the outgoing rod is the indicator of process quality. Fig. 1 shows the complexity of the problem, where the outgoing rod diameter depends on thermo-elastic deformations of the die and heat generation during drawing and stress relaxation after leaving the die outlet.
2. Cold bulk forming

2.1. Thermo-elastic response of the system

During cold metal and especially steel forming processes the tool loads are extremely high and nearly all of the forming work is transformed into the heat. For this reason the fluctuation of incoming material properties can have a severe impact on the outgoing part shape accuracy.

According to VDI recommendation, a flow curve for cold forging steel 16MnCr5 (0.16% C; 1.15% Mn; 0.95% Cr) can lie inside the interval

\[ \sigma_{f, \text{min}} = 780 \varphi^{0.176} \text{N/mm}^2 \] (1)

\[ \sigma_{f, \text{max}} = 900 \varphi^{0.155} \text{N/mm}^2 \] (2)

If at the same time the cold drawn incoming rods lie in the tolerance field of IT 11, it means that diameters (as shown in the example below) have fluctuations of:

\[ d_{0, \text{nominal}} = 15 \text{ mm}, \quad d_0 = 15 \pm 0.06 \text{ mm} \]

\[ d_{0, \text{nominal}} = 40 \text{ mm}, \quad d_0 = 40 \pm 0.08 \text{ mm} \]

Stresses affecting tools can be described as:

\[ \sigma_d = A \sigma_f = A C \varphi^n \text{N/mm}^2 \] (3)

where the flow stress follows the power law and the process parameter A for cold forward extrusion is not above 6 [3].

The specific forming work transferred into the heat is:

\[ w = B w_{\text{id}} = B \frac{n}{n+1} C \varphi^{n+1} \text{J/mm}^3 \] (4)

and B lies between (1.5...2.5).

Both parameters can be evaluated more precisely by implementing adequate FEM codes and knowing all influential parameters as presented by Ishikawa et al. [4].

The effects of above discussed fluctuations are given in Fig. 2. In Fig. 2a, the changes of flow stresses \( \sigma_f \) influencing the elastic response of the system are shown, in Fig. 2b the impacts of the same parameters fluctuations to the ideal forming work \( w_{\text{id}} \) transferred into heat are presented. Both figures represent two
cases, \( G \) is a process with small plastic deformations, \( H \) with remarkable greater ones.

The results clearly show that the process is expected to be more stable, if deformations are greater. On the other hand, when considering that fluctuations of both material parameters are similar to those in the daily practice, the changing of the forming properties are affecting the process stability much more then the fluctuation of the incoming rod diameter.

Fig. 2 presented only changes of incoming material properties. To transfer these into the forming system is a much more complex task. The part accuracy depends on its elastic and thermal relaxation after forming as well on elastic deformation and thermal diletation of the tool (Fig. 1). The thermo-elasto-plastic problems of the tool and part system can be more precisely evaluated by using adequate FEM codes [4]. However, the problem of heat generation and transfer is still unsolved because of insufficient or unreliable heat transfer coefficients. According to Lenard and Davies [5], coefficients depend on mechanical events, thermal balance and boundary conditions.

Under stationary production conditions the temperature field is rather stable, its impact on the process can be controlled. The temperature field variation in non-stationary production (due to start with cold tools, unperiodic work and unpredicted stops) affects the process much more. Therefore, the quality of the process outputs varies accordingly until thermal equilibrium is reached [6].

2.2. Process stability

When designing the cold forming process it is preferable do make it as stable as possible. As an example, the process stability evaluation was made for rod drawing. By analysing experiments, some interesting results were obtained related to the differences between the rod and die geometry.

It is evident in Fig. 3 that in particular areas the process is rather stable, locally insensitive to the small changes of incoming rod diameter \( d_0 \). These phenomena can be explained with the fact that the thermo-elastic system rod/die reached the optimum.

Since the process is closely related to the forming stresses and work, a generalised description can be given in the following form:

\[
F = f_1(AC\varphi^n p_i) - f_2\left( B \frac{n}{n+1} C\varphi^{n+1} p_j \right) \tag{5}
\]

where process parameters \( p_i \) and \( p_j \) are related to elastic deformations and thermal diletations, respectively.

By taking all parameters as being constant, the optimum can be reached if:

\[
\frac{\delta F}{\delta \varphi_e} = 0 \tag{6}
\]

and consequently it follows to:

\[
\varphi_{opt} = f_3(n) \tag{7}
\]

which means that the optimal deformation or reduction at rod drawing depends on strain hardening (defined with a coefficient \( n \)). This statement was confirmed by experiments with two different strain-hardening coefficients \( (n_A = 0.18 \) and \( n_B = 0.21 \) (Fig. 3).

In cold forging of steels the temperature increases of several hundred degrees are not infrequent [6]. When the workpiece is heated as a result of friction and forming work generation, the heat transfer warms also tools being in contact with the deformation zone. The thermal state of the assembly part/tool lies somewhere between two extreme thermodynamic states: in the adiabatic case there is no heat transfer from workpiece to the tool, in the isothermal case the assembly temperature is uniform. In the real cold forming process there are some similarities, at the early beginning with the adiabatic case, while later on, when the process becomes stationary and the heat transfer stabilised, the thermodynamic state looks like polytrophic.

A simplified presentation of the discussed phenomenon is given in Fig. 4a where a steel rod drawing through a steel or carbide die is discussed. The cold die has an inner diameter of 30 mm. After a customary reduction the rod is heated by 200 K. Regarding the die materials and thermodynamic state four extreme situations can be identified. The ideal combination is drawing in the steel die under isothermal condition. When using the carbide die the drawing process should be redesigned otherwise the rod geometry would be affected.
In the normal practice the shape accuracy of cold drawn products could be said as time dependent. It starts as adiabatic, then polytrophic and finally close to isothermal. In this final state the process could be defined as under the control. If during the process the incoming rod parameters are fluctuating (incoming rod diameter and flow stress), this could again affect the outgoing rod geometry. The schematic presentation of combined effects of both parameters fluctuation as well as the process start is presented in Fig. 4b.

To perform a sensitivity analysis of a complex cold bulk forming process, numerous material and process parameters should be considered. Some of the first results were published by Doltsinis and Rodič [7] where the isothermal and non-isothermal deformations were discussed in connection to the process sensitivity.

2.3. Manufacturing sequences and the shape accuracy

Manufacturing processes are nearly always composed by several sequences not being of the same origin. Cold rod drawing starts from warm rolled bars being later heat and surface treated. After finishing those pre-treatments, the drawing is performed in several steps until the final shape is obtained. The orientation of rods during multi-step drawing has among other parameters important influence on their shape accuracy which has been reported by Kocanda and Wanheim [8].
Fig. 6. Rod diameter fluctuations in a correlation to their orientation during multi-step cold drawing.

To get additional information to this phenomena, special sets of experiments were performed. The study started with hot rolled bars, prior one cold drawing operation rods were heat and surface treated at steel works. In a continuation rods were drawn in three steps where their orientation was strictly controlled (Fig. 5).

After performing drawing experiments rods diameters were evaluated, results presented in Fig. 6 are confirming the importance to control rod orientation during multi-step operations. The total variation of diameters lies between 11% of IT 7 for the first and to 20% of IT 7 for the last operation which has to be respected. If rods are later on cut to slugs for subsequent cold forging operations the orientation loss could again affect the shape accuracy of cold forged components.

3. Deep drawing sensitivity analysis

When designing the sheet metal deep drawing process, a variety of questions should be answered (initial blank geometry, tool loads) and thereby several problems avoided (fracture, sheet thinning, necking, wrinkling, final part geometry).

Contrary to the cold bulk forming, shape inaccuracies caused by stresses and the heat generation can be neglected, which means that reliable sensitivity analysis can be performed using commercially available FEM codes.

The process and influential parameters when drawing cylindrical cups is presented in Fig. 7. The parameters can be divided into the following groups:

- material properties,
- blank dimensions,
- process parameters,
- tool geometry.

The technological window assuring stable production is usually limited by fracture, wrinkling and thinning. A very important question to be answered here is therefore how sensitive the process is to the fluctuations of its parameters.

Since it is very difficult to change the material properties during the running production, the only possible means to be used for successful problem solution are the blank, process and tools. For an adequate answer a sensitivity analysis should be performed.

Contrary to experimental sensitivity analysis, where it is nearly impossible to vary only one parameter, the numerical methods are the most suitable tool. The results of performing several sets of calculations [9] clearly indicate that fluctuation of the incoming sheet thickness has the greatest impact on the part thickness fluctuation. Due to the danger of thinning or fracture, the anisotropy and strain hardening should be taken into account very seriously. As tools were presumed to be manufactured in very small tolerances, the effect of the tool shape fluctuation is nearly negligible.

To extend the above stated results to more complex parts, the analysis of wall thickness distribution in corners of a rectangular box was performed. Fig. 8 shows firstly that the impacts of anisotropy (Fig. 8a) and strain hardening (Fig. 8b) were different for thickening or thinning respectively, and secondly that the particular process is more sensitive to the anisotropy than to strain hardening fluctuations.

4. Direct process stability control

Metal forming process stability evaluation should be performed in the process designing phase where it is much more easier to change some material or process specifications. In this phase numerical methods can be a very useful means to study the effects of unplanned or unpredicted changes (material or tool quality) on the final product quality in advance, before taking decisions or performing process modifications. Numerical methods can also help to perform backward computing to redefine the forming processes, always targeting centres of stable technological windows.

The modern market driven economy is under severe pressure concerning costs. On the other hand, product should be more and more precise with narrowed tolerances. To fulfill all stated
demands it is not possible only to narrow the incoming material and process specifications but it is much better to implement a kind of an adaptive and in a process integrated control.

Metal forming processes are known as very unsuitable for on line and in real time adaptive control as there are only few process parameters which could be controlled. When forming wire or sheet strips, the straightening after unrolling is the first forming operation. By adequate positioning of straightening rollers mechanical properties of incoming materials can be affected [10]. If there is a good correlation between mechanical properties of the incoming material to the outgoing parts accuracy, this can be used for an adaptive process control.

A special EUREKA project [11] studied an idea of controlling the quality and stability of a wire bending process by linking it to the wire straightening operation. For this reason the wire straightening system was equipped with sensors to measure rolling forces, data were then transferred to the original mathematical model which later on automatically gave instructions to reposition the rollers (Fig. 9).

The experimental evaluation of the redesigned wire forming process confirmed (Fig. 10) the idea which was later on slightly modified and integrated into the production [12].

5. Conclusion

To analyse a cold forming process in a view of the accuracy of the formed part and the stability of the process, one should consider the system response of the tool-workpiece and taking their interaction into account. The physical phenomena governing the process are among the most complex ones and are characterised as highly non-linear thermo-elasto-plastic problems.

The paper discussed needs to perform computer metal forming process stability and sensitivity analysis before taking final decisions, before starting the tool production. The process sensitivity analysis is a very important tool for the technology designers as it ranks parameters with accordance to their impacts on the process. The virtual process analysis offers also a possibility for positioning processes into stable technological windows which is almost impossible to be done by conventional try and error methods.

As nowadays numerical methods are still not efficient enough to model multi-step forming operations in regards to parts orientation, to model cyclic loading with small elasto plastic deformations, the industry as well researchers should still use carefully planned real experiments and physical modelling, to study their technologies and search there for similarity rules which could later on be extrapolated to similar problems. Finally an idea of developing process control systems capable to react nearly in the real time was presented. Such approach is very promising as it offers a possibility of zero defect production without significantly increased process and materials costs.

References


