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Simulation of a Full Forward Extrusion Process from Metal Strip

Marion Merklein, Tommaso Stellin and Ulf Engel

Chair of Manufacturing Technology, University of Erlangen-Nuremberg, D-91058 Erlangen, Germany

Abstract. The interest on mass production of small complex metal components is currently fostered by fields like electronics and micromechanics. A possible approach is seen in a multi-step bulk forming process, limited among scaling problems by handling difficulties between the forming stages. A radical simplification of the positioning of the workpiece is seen in a process in which a metal strip acts both as raw material and support of the workpiece through the different forming stages. Within the study of this method, a full forward extrusion process from metal strip has been simulated with the goal of getting the basic knowledge about the strip behavior and process performance. The influence of the main geometric and tribological features has been evaluated designing a full factorial plan. The role of the radius of curvature of the tool edges and of the factor of friction have become the points of main interest in the optimization of the process.

Keywords: microforming, full forward extrusion, metal strip forming.

PACS: 81.20.Hy, 81.16.-c.

INTRODUCTION

The multi-stage cold forging of bulk microparts is a process with a high production rate potential, mainly limited by handling problems between the distinct forming stages. This has limited the mass-production to simple axisymmetric components, producible in a single step process [1, 2]. Research has also pursued the development and optimization of the micro-handling systems, to improve precision, speed and reliability during the workpiece mobilization [3, 4]. An alternative solution is seen in a bulk forming process inspired by sheet metal stamping, not requiring high performance tools like mechanical microgrippers. In this process called bulk micro forming from strip the material is formed off a strip, which acts at the same time as raw material and means of transportation between different forming stages. The study of the fabrication of a micro-billet by sheet extrusion has already been conducted by [5], analyzing the influence of different constraining conditions. In this work a one stage full-forward extrusion process from strip is studied. The analyzed process is simulated, implementing the considered material (OF-Cu copper) according to a continuum elastic-plastic model. A full factorial plan was designed in order to detect and chart not only the influence of the single parameter, but also the important effects of their interactions. As the prerequisite of this process is a high precision handling capability, the strip must be a reliable means of transportation and positioning.

PROCESS

The process which is analyzed in this study is a full-forward extrusion process. The particularity is that it is a no closed die process as most of the extrusions, because the raw material is a metal strip. The formed part must not be released and is carried through the different steps by the strip.

The tooling system is represented in this work by an upper and a lower punch (Figure 1a, b). The upper punch is full while the lower is acting as a die; they press locally the strip with the goal of obtaining a raw cylindrical geometry. This object is not a well defined shape because the interest lies on the varying of the performance, in relation to the modifications of the tool. The cavity of the lower punch should not stop the flow of the material, thus it is designed deeper than the estimated results of the extrusion.

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The final workpiece is not the only deformed material. Three different forming areas can be distinguished: the metal filling the die cavity, the compressed strip between upper and lower punch and the deformed strip around the punches (Figure 1b).

FIGURE 1. (a) Tooling system and strip representing the full forward extrusion process from metal strip; (b) Section of the formed strip before the forming process; (c) Section of the formed strip, with the three forming areas: metal filling the cavity (A), compressed strip between upper and lower punch (B), deformed strip around the punches (C).

Ideally the process should collect as much material as possible and favor the filling of the die cavity, but when the volume between the punches is reduced the material also flows outwards. The amount of material outside the punches should be reduced as much as possible, because it is detracted from the workpiece and furthermore the deformation of the strip adjacent to the tool edges is higher.

In the reality the strip length is not well defined, as the strip comes from a roll. However in the following full factorial analysis this dimension is reduced to a 40 mm long strip, pressed until 40% of its thickness. The axisymmetric modeling represents this process as an extrusion from a round metal sheet (where the diameter is 40 mm wide).

SIMULATION

The simulations are designed with the software Simufact, implementing the material characteristics as working with continuum. This study is focused on the full forward extrusion process of a 1 mm thick strip. However this model allows a further approach in which the geometric features of the simulations are proportional to the strip thickness. The results may then be used to extend the description of the process to different scales, even though not considering the micro-effects. The simulations are considered particularly meaningful in the relationships between the geometric features and in the way they differently influence the process. In order to evaluate it a 2^5 full factorial plan has been designed. Four tool design features and a tribological variable are the factors analyzed in the study, and for each of them are considered two values representing respectively a high and a low level. The geometrical features are displayed in Figure 2. All the 5 factors and their levels are listed in Table 1. In addition to the design parameters of the tools the fifth value is the friction factor, considering a good or a bad lubrication of copper.

TABLE 1. Levels of the factors. S = thickness of the strip (1 mm). Low and high level expressed in mm. $\zeta_i = X_i$ when $S = 1\text{ mm}$.

Factor	Description	Low Level	High Level
$\zeta_1 = X_1/S$	External diameter of the punches	4	6
$\zeta_2 = X_2/S$	Diameter of the die cavity	0.5	1
$\zeta_3 = X_3/S$	Radius of curvature of the outer edges	0.05	0.2
$\zeta_4 = X_4/S$	Radius of curvature of the inner edge	0.05	0.2
$\zeta_5 = m$	Factor of friction	0.1	0.3

FIGURE 2. Geometrical features of the tool system.

The process is modeled as axisymmetric, so a 2-dimensional simulation represents the whole extrusion. Even though the strip is designed as a prism with different depth, width and height, it should be rendered like a cylinder with the same height and a diameter as large as the width of the prism.

Each specific process, defined by the combination of all the factor levels, has been simulated and rated according to different performances of the process. The investigated performances are the material flow into the die, the maximum effective plastic strain, the stability of the strip and the applied load.

The first one is obtained measuring the distance between the lower point of the formed material in the die cavity and the contact surface with the upper punch. The effective plastic strain is directly obtained by the simulation program, such as the applied load. The stability of the strip outside the punches is not easy to define; the strip is bending upwards and downwards, with different curvatures. Referring to Figure 1c, the placement of the forming area C which drives the movement of the strip is hardly predictable. As the extrusion process is not symmetric with respect to the horizontal axis of the sheet, the plastic strain is not symmetric as well. During lateral flow it is the strain gradient which is causing the vertical movement of the strip. There is a higher effective plastic strain ($1 \div 1.5$) along the extrados of the curved strip, while in the intrados it is about the half. To identify the tendency in each simulation, the evaluation has been determined by measuring the distance along the x axis between higher point of the strip and contact surface of the upper punch, with the strip bending upwards, and between lower point of the strip and contact surface of the lower punch, when the strip is bending downwards. As a specific reason of the different bending directions is hard to be identified, these measures are used in the analysis as modulus.

RESULTS

According to the full factorial plan evaluation as described in [6], the effect of each factor and also the interactions between them have been calculated. The results are reported in Table 2 and Table 3. Each factor has its own impact on the different performances of the process, and a trade off has to be determined.

A larger external diameter of the punches improves the material flow in the die cavity. At the same time the effective plastic strain grows, the strip is very unstable and the required applied load is much higher because of the increasing of the contact area. Therefore this factor has to be reduced as much as possible. A larger diameter of the die cavity helps its filling, reduces the instability of the strip and the applied load. On the other hand it is the parameter that most raises the effective plastic strain.

The radius of curvature of the punches outer edges has a good impact in almost all the process performances. Obviously it favors slightly the flow of the material outside the punches, reducing the material in the cavity, but the strain value is lower and it has the best impact in reducing the load and stabilizing the strip. The radius of curvature in the lower die involves a great reduction of the strain. It also lets the material easily flow in the die cavity and reduces the load of the machine. The bending of the strip is not reduced by increasing this parameter. The finishing

of the punch edges has basically a good influence on the process performance. The geometry of the die cavity insertion is rather limited by the workpiece final shape, depending on how it is removed from the strip.

The factor of friction performs an unexpected influence on the process, improving the overall performance to the detriment of applied load. In a normal bulk forming extrusion process it would be expected as one of the most constraining factors. This particular process may be defined as open-die, so a bigger factor of friction would hold the material back between the punches. This control of the strip is also stabilizing the material close to the die cavity, reducing the strain value and highly incrementing the flow into the die. Unfortunately in micro-scale the friction between raw material and tool is greater, and this effect is predominant in the die cavity. During the experimental phase the lubrication will be a very important aspect, especially the location of the lubricant. The sliding must be facilitated in the die and not between the punches.

TABLE 2. Effects of each factor in relation to each process performance.

Factor	Material Flow in the Die (mm)*	Effective Plastic Strain (max.)	Movement of the Strip (mm)*	Applied Load (kN)*
$\zeta_1=X_1/S$	0.223	0.155	2.23	30.8
$\zeta_2=X_2/S$	0.321	0.964	-0.332	-1.68
$\zeta_3=X_3/S$	-0.038	-0.594	-0.44	-3.86
$\zeta_4=X_4/S$	0.368	-2.72	0.297	0.372
$\zeta_5=m$	0.486	-1.07	-0.121	7.13

**absolute values for $S = 1 \text{ mm}$*

TABLE 3. Effects of the interactions in relation to each process performance.

Factor	Material Flow in the Die (mm)*	Effective Plastic Strain (max)	Movement of the Strip (mm)*	Applied Load (kN)*
$\zeta_1 \zeta_2$	0.012	-0.248	-0.193	-0.247
$\zeta_1 \zeta_3$	0.011	-0.010	-0.051	-0.990
$\zeta_1 \zeta_4$	0.018	0.076	0.096	-0.113
$\zeta_1 \zeta_5$	0.186	-0.085	0.006	4.093
$\zeta_2 \zeta_3$	0.022	0.637	0.098	-0.180
$\zeta_2 \zeta_4$	-0.079	-0.655	-0.094	0.098
$\zeta_2 \zeta_5$	0.053	-0.102	0.481	-0.702
$\zeta_3 \zeta_4$	0.011	0.435	0.423	-0.075
$\zeta_3 \zeta_5$	0.004	0.489	0.006	-0.525
$\zeta_4 \zeta_5$	-0.012	1.04	0.053	0.028

**absolute values for $S = 1 \text{ mm}$*

The study of the combined effects has pointed out some interaction between the factors (Table 3). For the flow of the material in the die cavity, the only meaningful combination of factors is between the external diameter and the factor of friction. It has not a great influence but confirms the importance of the contact surface between punch and strip in order to hold it in the pressing area.

The analysis of the single effects showed that strain is higher respectively with higher external diameter and cavity diameter. Therefore the interaction of the cavity diameter with the radius of curvature of its edge points out that, when combined, also the first one has a good impact in the reduction of the strain value. The interaction of external diameter and cavity diameter has a slight influence in stabilizing the strip. As working with continuum it shows that the same geometry has a better control on the strip when it is thinner.

TABLE 4. Characteristic factor levels of the sample simulation ($S = 1 \text{ mm}$).

Factor	Level
$\zeta_1=X_1/S$	4
$\zeta_2=X_2/S$	1
$\zeta_3=X_3/S$	0.2
$\zeta_4=X_4/S$	0.2
$\zeta_5=m$	0.3

FIGURE 3. Distribution of the effective plastic strain in the chosen simulation (factor levels in Table 4).

In consideration of the above, a single simulation among those analyzed in this study has been selected. The factor levels are listed in Table 4 and the distribution of the plastic strain is seen in Figure 3. For a thickness of 1 mm the best choice is seen in a tool system with a 4 mm wide diameter. The inner diameter of the lower punch is 1 mm and the radiuses of curvature of the edges are 0.2 mm long.

Analysis of the material flow

In order to analyze the response of the raw material to different process configurations, a meaningful output of the simulations is the material flow. The copper is compressed by the punches and flows in two opposite directions: in the die and outside of the tooling system. The study of the flow lines clearly identifies and gives explicit information about the trend of the process. To understand the relationship between the material behavior and the parameters of the process, the effect of a different level of each factor is compared to the results of the simulation previously selected among the factorial plan. All the variations in the geometry influence the disposure of these lines, especially about the edge of the cavity. In Figure 4 the most meaningful graphical comparison between the reference simulation (factor levels in Table 4) and the extrusion process with same geometry and lower value of the factor of friction are shown.

FIGURE 4. Flow lines of: (a) chosen simulation (factor levels in Table 4); (b) simulation with the factor levels in Table 4 except for $m = 0.1$.

The reason of the better process performances with a higher factor of friction is easily seen in the vertical flow lines between the parallel faces of the tools. The friction force opposes the flow in the direction opposite to the die cavity and as result the volume flown in the lower punch is bigger.

A more complete analysis about the influence of the punch dimension on the material flow has been conducted, increasing the outer diameter of the tools. A linear increasing of this geometrical feature involves the increase of both the distance of the separation front from the center of the tool and the filling of the die.

Process design

This study outlines the design rules of a full forward extrusion process from metal strip. The factor levels in Table 4 define a tool geometry for a 1mm thick strip that represents a good trade off between the analyzed process performances. As this process finds its application just in a full step forming chain, the first goal is the reduction of the plastic strain. With different strip thicknesses the whole model can be scaled and ensures low plastic strains and a good forming potential. A tool-width bigger then 4S has to be supported by the need of a very high material flow in the die cavity, in fact an exponentially growing applied load and a more difficult control of the process outside the forming area have to be strongly justified. The radiuses of curvature of the tool edges can be directly related to each strip thickness, and eventually oversized when manufacturing limits occur. The inner diameter of the lower tool obviously depends from the specific extrusion process. Its interactions with other factors are not very critical, but a strong reduction of the ratio X_2/S should be joined with a bigger radius of curvature of the cavity edge, in order to reduce the raise of the plastic strain.

The ideal lubrication should consist in a concurrent containment of friction in the die cavity and a higher value in the parallel surfaces of the punches. When this is not possible, a higher overall friction between tools and strips is preferable, because the contact area inside the lower punch is limited if related to the overall contact surface. This configuration requires a higher applied load but anyway favors all the other process performances.

CONCLUSION

The study of the influence on the process performance of friction and of the main geometric features has pointed out the importance not only of the main dimensions of the tool system, but above all the impact on the process of the radius of curvature of the tool edges and friction. At the same time a well weighted trade off of the tools outer diameter is decisive. The filling of the die increases almost linearly, while the pressing surface is getting exponentially bigger and also the applied load. Basic rules in designing a full forward process from metal strip have so been defined, in order to lead a further more complex optimization study which considers the scale effect in microforming.

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