RESEARCH ON THE FACTORS OF INFLUENCE IN THE DIMENSIONAL AND FORM PRECISION OF STAMPING PROCESSES

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Abstract.*Mechanical assemblies are composed by components joined through the contact of finished surfaces. The assembly tolerances of these assemblies are obtained from the chain dimensioning of the accumulated tolerances of the respective components. Among the manufacturing processes of metallic parts which allow finished dimensions are mainly the machining and stamping ones. Other processes, like sintering, can also generate finished surfaces but, most of the time, demand additional adjustments by machining. The compliance with the tolerances of a stamped part specified on an engineering drawing depends, in principle, on the tooling design. However, due to the progressive and unavoidable tool wear effect, mainly in the cutting process, product dimensional tolerances may vary up to the allowed limits specified in design, after which the tool must be either reworked or replaced. In contrast, in the forming processes, the recurring concern in the dimensional and form tolerances treatment is springback effect, resulting mainly from the characteristics of the worked material. The objective of this work is to identify and analyze the factors that influence the dimensional and form tolerances in the cutting and forming stamping processes, in order that they can be used in specific studies related to both the product and tooling designs, and be used as indicators for the improvement of these processes as well, aiming in this case, mainly the economic aspect.*

Keywords: *stamping, precision.*

1. INTRODUCTION

Mechanical assemblies are composed by components connected through the contact of finished surfaces. The dimensional precision of these assemblies are determined by their dimensional tolerances, which are function of the chain dimensioning of the accumulated individual tolerances of the respective components and are subject to functional constraints (Umaras, 2010). The individual tolerance ranges of each component, therefore, play an important influence in the assembly. Amongst the manufacturing processes that generate finished dimensions, the machining and the sheet stamping are considered. Other processes which are also able to provide finished dimensions, like sintering, generally demand further adjustments by machining processes. In this work, the factors that influence dimensional and form tolerances in the sheet stamping processes are specially discussed, in order to allow their use for:

- helping designers on the manufacturing concerns related to the part;
- process planning;
- tooling design;
- supporting on analyzes of production problems.

The aim of this work is to approach, in a pragmatic and synthesized way, the main factors that affect the dimensional and form tolerances in the stamping processes, since a comprehensive presentation of the subject is composed by several items of complex development, impracticable in this text. The stamping processes of cutting and forming are considered, which present diverse factors and treatment: in the first one, which may be divided in two categories - punching and blanking, due to its lower complexity, factors are presented directly with the applicable suggestions for their control. Regarding the forming processes, the factors influencing the final result of the fabricated part are listed, since they are very useful in the development of the simulation models input data and as suggestions for production problems corrections as well.

In this work are treated specially the forming processes by stamping, which present greater economic interest in the Industry and the higher complexity. Other processes, like bending, spinning and drawing are not treated due to the different approach regarding the factors influencing the dimensional tolerances. The single point incremental forming process (Micari *et al.*, 2007) is also not treated, due to its still restrict application, mainly for prototyping.

Currently, finite elements analysis (FEM) techniques support the tooling design. Before this possibility, the tooling design was made by a try-and-error approach. So, the use of the factors of influence described in this text, in conjunction with the FEM techniques, can avoid the consumption of time and other resources during the design and the pre-production phases.

The results of the forming processes are related to the product quality: absence of cracks, wrinkling and, mainly, to the springback behavior, that affects the part dimensional and form precision and so, meets the aim of this work. The springback influence is illustrated through experimental results extracted from the researched literature.

The presented concepts can be used in the tooling and process design and in the product design as well, as warnings to designers on the difficulties in the compliance with restrict specifications concerning tolerances.

According to Shey (1983), 70 to 80% of the overall volume of metals currently used in several fields of application is transformed from laminated metals and, a large amount of this volume, represented by thin sheets - with thicknesses under $5\ mm$ - is processed by a variety of techniques named sheet metalworking processes. So, it can be seen clearly the importance of these processes. Steel plates are materials commonly used for stamping, due to their feature of producing parts with high degree of dimensional precision and good surface finish. Stamping processes are widely used due to their high productivity, low assembly costs and due to the high resistance to low weigh ratio (Park *et al.*, 2006).

The growing market demand for quality has leading the Automotive Industry to a continuous development of its stamping processes, mainly applied in vehicle bodies, where dimensional precision and surface quality requirements are doubtless important: most of the modern vehicles present, in their bodies, a range between 100 and 150 different stamped items, varying from small and simple, to panels of high complexity (Majeske and Hammett, 2003).

2. INFLUENCE OF THE EQUIPMENT ON PRODUCT PRECISION

The specified precision of a stamped part, determined by its dimensional and form tolerances on detail drawings, must be accomplished by the manufacturing process, where two types of equipment are used: presses and dies. The presses are flexible production equipment that may be used for manufacturing several different items through the shift of dies. The dies are dedicated equipment, they produce specific items. These two types of equipment are influenced by factors that can affect the tolerances of the parts manufactured by them, mainly:

- Fits between columns and bushings;
- Clearances between moving parts;
- Stiffness.

The fits between columns and bushings are discussed in specific works, like Umaras (1979). The effect of the clearances between moving parts may be considered together with the stiffness since, during the force application, the clearances have to be removed before any elastic strain takes place. In a press, the stiffness may be defined by the ratio between the increment of an applied force and its resulting elastic deflection (DIN55189, 1988a,b). In its main axis, the following equation holds:

$$C_{zz} = \frac{\Delta F_z}{\Delta_z} \tag{1}$$

where C_{zz} is the linear stiffness in the z axis of the press, ΔF_z is the increment of the vertical force, and Δ_z is the vertical elastic deflection of the press. Other equations for the angular stiffness in other main directions are also defined (DIN55189, 1988a,b). Based on these concepts, the overall equipment stiffness may be calculated, as shown in some works (Chodnikiewicz *et al.*, 1994, 1997; Chodnikiewicz and Balendra, 2000). The greater the stiffness, the greater is the resulting stamped part precision.

3. THE CUTTING PROCESS BY STAMPING

The cutting by stamping is typically a shearing process, accompanied by a small plastic deformation. It is related in some way to the machining process (Shey, 1983) and consists on the separation of the worked plain material by conjugated counterparts of a tool (generally a punch and a die). The main factors affecting the part precision are related to the dimensional tolerances:

- Clearance between punch and die;
- Cutting speed.

Figure 1 defines the components of the punching process, used for making holes in parts and or producing small parts like washers. The blanking process is used for greater parts. The clearance increases with the punch wear along the time use. Consequently, the tool wear process is an indirect factor that affects the stamped part dimensional precision. The cutting speed is relevant for press ram (or stroke) velocities between 10 and $15\ m/s$ and may not be considered in general stamping applications due to the requirement of special equipment, like huge presses or accelerator devices mounted on conventional ones.

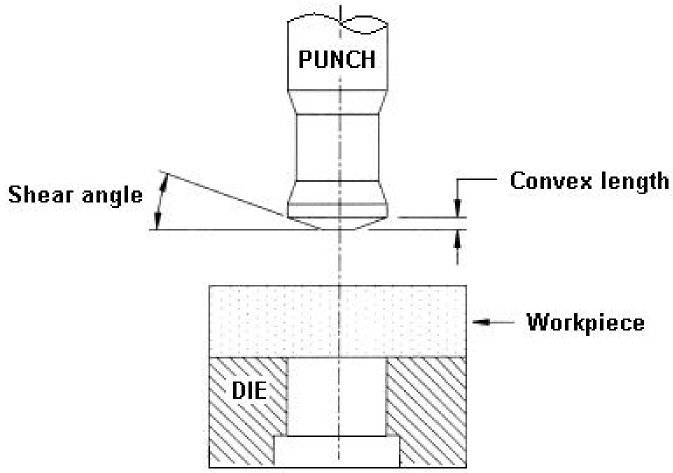

Figure 1. Punching process components and shear angle definition.

3.1 The shearing mechanics

In order to obtain a better understanding of the metal cutting process, an overview on the shearing mechanics is necessary (Shey, 1983; Owens *et al.*, 1981; Popat, 1989; Popat *et al.*, 1989). Fig. 2(a) illustrates the metal cutting process, which involves the following steps (shear angle = 0^o is considered for simplification):

1. At the moment that the tool contacts the material, a process of elastic deformation is started. Its magnitude is function of the material elastic properties, the geometry of the cutting zone and, when applicable, the restraint imposed to the material displacement (as the restraint provided by lateral blank holders);
2. After a critical penetration, a plastic deformation (or a slight extrusion) begins. It is dependent on the clearance between the counterparts and the material ductility. Cracks are generated in the worked material at the region of contact with the punch and die edges;
3. Further, the cracks propagate until a complete cut. The separation happens when the cutting force reaches its maximum. The force maximum value is slightly dependent on the clearance and does not depend on friction;
4. The part must be pushed farther to be removed from the cutting zone. At this stage, the force decreases considerably and depends on the friction between the worked material and the punch side surface.

When cutting is done with less than optimum clearance, a secondary shearing takes place (as illustrated in Fig. 2(b)). Consequently, a second peak in the force-displacement curve happens. The force magnitude depends on the friction developed on the tool side surface. Special processes such as precision blanking, can ensure significant better dimensional accuracy, perpendicularity and surface finishing. In the precision blanking a specially shaped blank holder imposes compressive stresses on the cutting zone (as illustrated in Fig. 2(c)). This arrangement delays the crack start and ensures that the whole thickness is plastically sheared.

In normal conditions, surfaces cut by stamping are neither perpendicular nor smooth. The finish can vary from $R_t = 3$ to 6 μm and $R_t = 0.1$ to 2 μm in the transverse and parallel punch movement directions, respectively (Shey, 1983). The Standard DIN 6930 (DIN6930, 1989) presents accepted values for general stamping cut and form tolerances. Fig. 3(a) illustrates the actual size of the dimension to be considered in a stamped part, i.e., the length or diameter specified in its detail drawing. Fig. 3(b) shows the form deviations of a part stamped by cutting. The form deviations are not considered in Fig. 3(a) as they become important only for parts with determined aspect ratios (actual size/sheet thickness), when the actual size approximates the material thickness.

3.2 The effect of clearance between punch and die

The clearance between punch and die is the main factor for compliance with the specified design tolerances. It must be considered in two ways:

- Its design value when the tooling is brand new and;
- Its value during the wear process.

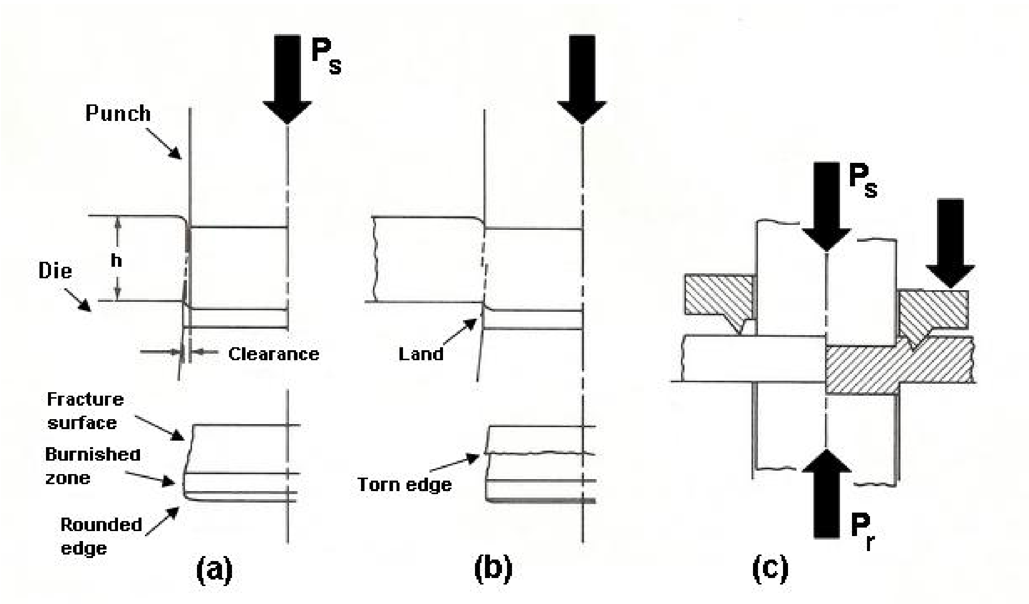

Figure 2. Schematic illustration of the shearing process (Shey, 1983).

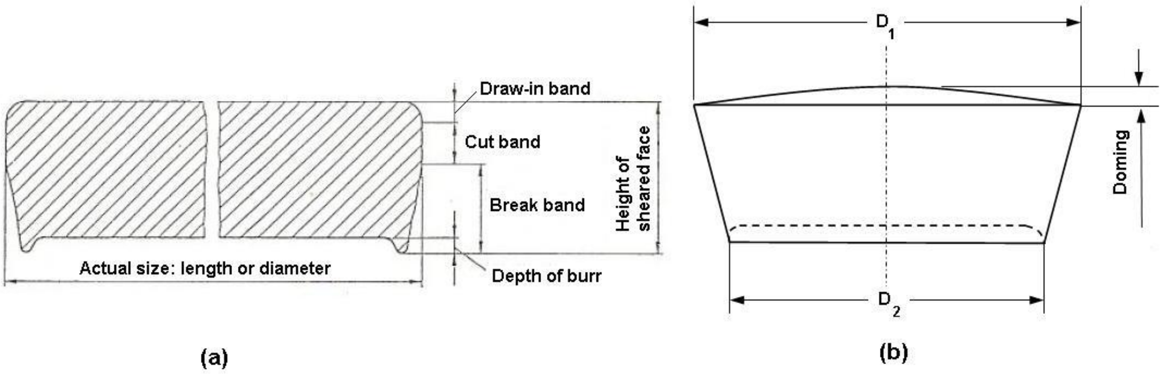

Figure 3. (a) Determination of the actual size of a stamped part (DIN6930, 1989). (b) Definition on form tolerance terms (Jana and Ong, 1989)

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Popat *et al.* (1989) investigated the punch-die clearance using FEM. They compared their results with experimental data and showed that the optimum punch-die clearance, additionally to the material thickness, is dependent on the local fracture strain of the worked material. In other terms, they concluded that the tooling design for stamping mild steel and aluminum should be different regarding the punch-die clearance for the same material thickness

3.3 The tool wear and its control

The tool wear is illustrated in Fig. 4 (shear angle $= 0^o$). The following parameters characterize the tool wear:

1. **Flank (or side) wear** determines the length to be considered when punch rework is executed. It is characterized by length L shown in Fig. 4 or by its corresponding side area. The flank wear is created by adhesion and abrasion and increases with the number of strokes. The increasing rate is higher when the clearance is smaller (see Fig. 5(a)). The wear length increases asymptotically to the maximum given by the punch penetration. A semi quantitative assessment is possible by inspecting the flank for scoring and pickup (Shey, 1983). Due to the adhesion of metal layers, the friction force increases progressively and leads the punch side face to produce micro-fractures (Luo, 1997). Flank wear increases the clearance between punch and die and causes the internal diameter of the punched holes to become smaller. When internal diameter of the punched holes becomes too small, the punch reaches the end of its useful life;

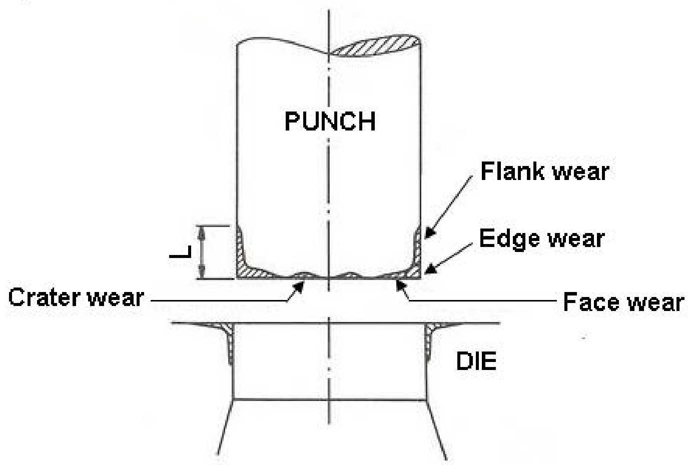

Figure 4. Tool wear at shearing process (Shey, 1983).

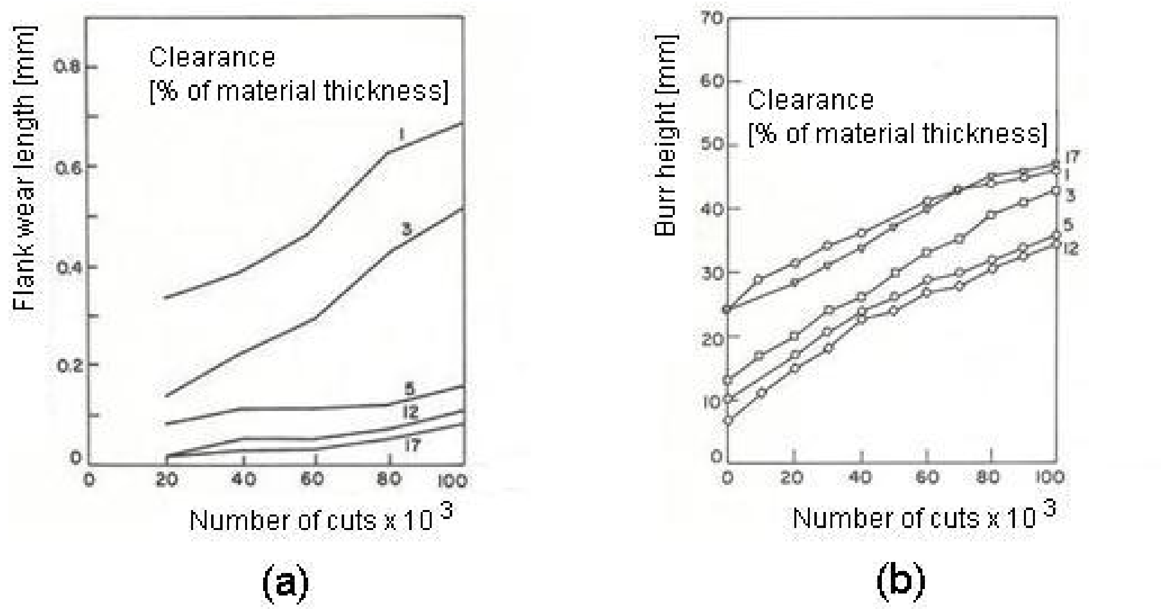

Figure 5. (a) Flank wear and (b) Burr height in function of punch-die clearance and number of strokes (Shey, 1983).

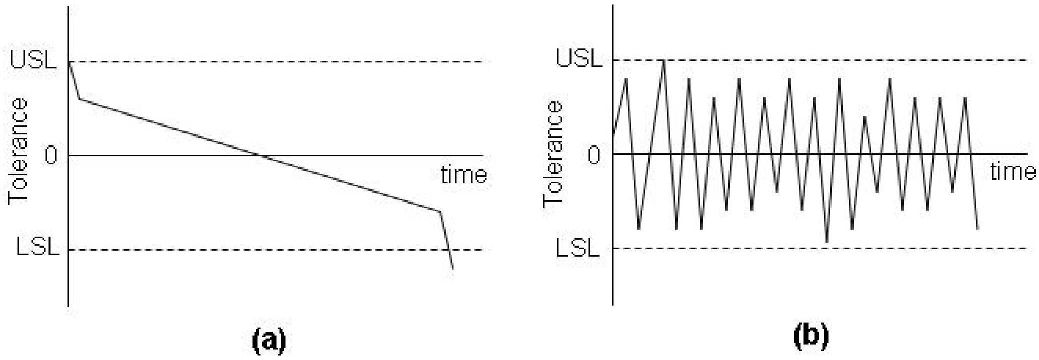

Figure 6. Tolerance variation vs. time: (a) Punched hole. (b) Drilled hole.

2. **Edge (or tip) wear** is important because it determines the burr height. It is very difficult to differentiate edge wear from flank wear (see Fig. 4). It increases with the number of produced parts and it has a minimum at some fairly generous clearance (Fig. 5(b) shows a curve with 12%). Excessive clearance (Fig. 5(b) shows a curve with 17%) leads to a large burr also, but only because the part is finally separated by tensile fracture, and not because of wear.

3. **Face wear** is mostly abrasive and increases linearly with the number of produced parts (Shey, 1983). It can result from micro-chipping: micro-crushes, fragments and breakage on the cutting edges (Luo, 1997). It is the cause of round and obtuse punch edges. It reduces the punch sharpness during shearing, and increases the deformation of punched workpieces. Burrs become large and the press noise level becomes very high (Luo, 1997).

Luo (1997) studied the effect of punch shear angles (see Fig. 1) and concluded, through experiments with two different shear angles, that:

- A shear angle of 12.5^o produces higher punch flank wear, leading the tool to have a shorter life;
- When the shear angle is 20^o, the face wear is predominant and the tool's life is longer;
- Shear angles of 20^o create better edge straightness;
- Shear angles of 20^o produce punched holes with larger eccentricity. Possibly, because the face wear is irregular when the edge is straight, leading to asymmetric loads;
- Shear angles of 20^o produce higher plastic deformations in punched holes and higher burrs in the removed slugs.

Singh (1992) evaluated by FEM different geometries of punch tips. Results for the convex tip shapes seems to be in accordance with the ones obtained later by Luo.

During tooling design, in order to compensate the tool wear along its life, generally the punches are made at their maximum material condition (MMC) leading the stamped part to be specified at least material condition (LMC). For example, the punched hole has its diameter defined according to the upper specification limit (USL) when the tool starts its operation. In cutting processes, the lower specification limit (LSL) is never reached. This procedure contrasts with the one used in machining processes (drilling), where nominal tolerance condition (approximately at mid range between LSL and USL) is used and is the standard for statistical process control (SPC). The tolerance stack-up calculation for mechanical assemblies is affected by this fact. Fig. 6 illustrates the tolerance variation in time for punched and drilled holes.

The tool's life generally follows a Weibull distribution, i.e., it has a normal distribution with a finite lower limit: after a stage of rapid initial wear, wear progresses at a lower steady rate until a phase of rapid wear sets in again. At this point the part becomes unacceptable: the part conforms to the worn punch and a burr develops. Therefore, the punch's life is usually defined by the maximum tolerable burr height. However, wear cannot be judged from absolute burr height alone, because this is also dependent on material properties. Burr height increases with ductility and is thus generally smaller on cold rolled than on annealed material. Excessive face wear causes plastic deformation of the worked material before starting of the shearing process described in item 3.1, leading to a doming (Jana and Ong, 1989), or dishing (Shey, 1983), similar to illustrated in Fig. 3(b). So, when doming exceeds the flatness tolerance specified, the punch has reached a critical wear and must be reworked or replaced. The avoidance of the tool wear can be done at its design phase, by specificating appropriate materials and, during the process development, by selecting adequate lubricants:

Table 1. Factors of influence on the springback in the forming process by stamping

Factor	Feature
1. Tool geometry	• Radius/Sheet thickness ratio • Baushinger effect
2. Process parameters	• Blankholder pressure
3. Sheet material	• Type and parameters • Anysotrophy • Thickness • Strain hardening • Baushinger effect
4. Lubrication	• Type and quality of lubricant

- Tool material and hardness are important for resistance to the abrasive and adhesive wear, but some ductility is also important to prevent spalling. According to Shey (1983), the Rockwell harness is, if isolated, an inadequate measure of wear resistance. The hardness of the dispersed carbide phase must be also taken into account. Tools respond extremely well to surface treatments, doubling or even quadrupling their life. Treatments like hard facing with nickel-base alloys, boronizing, hard-chromium coating, and nitriding have shown adequate and TiC based treatments seems to be the most effective.

- According to Shey (1983), crack generation in itself is not affected by lubrication, but this does not mean, however, that lubrication is not important. In many instances, lubrication is essential if tool wear must be held to tolerable rates and to keep the surface quality of the cut at acceptable levels. The lubrication process initiates when punch hits the sheet and squeezes the lubricant film deposited over it. Most of the film squeezes out, but in doing so it also lubricates the face edge and reduces face wear. The squeezed-out oil is available to seep into the cutting zone, reducing adhesion on the punch flank. As the punch retracts, the oil lubricates the flank, reduces the retracting force, and minimizes scoring and adhesive wear, but also causes the part to stick to the punch face (Dannenmann and Sugondo, 1981). Generally, liquid lubricants of higher viscosity are used in the cutting process, compounded with extreme pressure (EP) additives, which are activated at high temperatures and with repeated contact. Aqueous lubricants are used for lighter duties. Liquid lubricants are helpful also in removing wear debris, which becomes a major cause of wear especially for larger clearances, and thus adhesive wear is less severe (Shey, 1983).

3.4 The effect of cutting speed

The high cutting speeds may also be considered an important factor on improving dimensional and form precision in the stamping cutting process, as already cited at the beginning of this section. Jana and Ong (1989) describes an alternative equipment - an accelerator device - to cope with the heavy investment issue. They found by experiments that:

- Both doming and edge taper, defined by $ET = D_1 - D_2$ in Fig. 3(b), reduced for mild steels when cutting speed varied from 0.13 to 10 m/s;

- Doming and edge taper increases with the punch to die clearance, for low and high speeds;

- At high speeds, an improvement on the surface finish of the cut face was observed, regardless of the punch to die clearance. The secondary shear phenomenon (Fig. 2(b)) does not occur at high speeds.

4. THE FORMING PROCESS BY STAMPING

The dimensional and form precision in the forming processes by stamping is affected mainly by the springback effect that, due to its complexity, is considered in this section. Nowadays, the use of FEM in sheet forming tools design is almost mandatory. Even though the expertise of the process specialists is high, the development by a try-and-error basis is impracticable, mainly due to time and tool costs reasons. Through FEM modeling, designers are able to define the tool geometry which compensates the springback displacement after part removal from the die. As the precision of the designed geometry depends on FEM input parameters and adopted model, tooling tryouts (validation tests) are necessary before its thermal treatment, in order that adequate adjustments can be done, assuring that the manufactured part complies with the specification. Table 1 summarizes the main factors influencing the springback in the sheet forming process.

The tool geometry and process parameters are variables that process designers can use to control the resulting part form tolerance. Sheet material and lubrication, however, are subject to variations during production and, due to this fact, are called as process noise factors (Donglai *et al.*, 2008). The following factors affect springback:

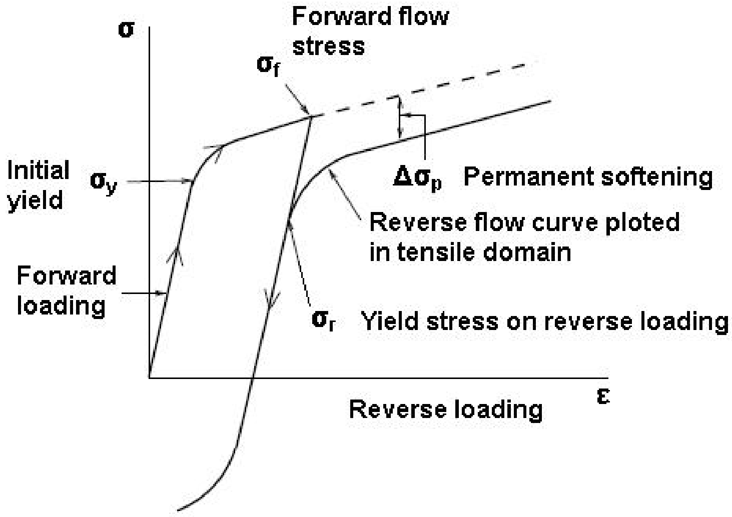

Figure 7. Schematic representation of the Bauschinger effect in a metalic sample (Guruprasad *et al.*, 2008).

1. The R/t ratio (R is the tool radius and t is the sheet thickness) influences the springback, as shown by Carden *et al.* (2002):
   - A reduction on springback is observed for values of $R/t > 5$, for steel HSLA (High Strength Low Alloy), steel DQSK (Drawing Quality Silicon Killed) and aluminum 6022-T4;
   - For steels HSLA and DQSK, the value $R/t = 5$ is a maximum inflection point, that is, for ratios $R/t < 5$ springback is reduced, reaching a zero value for $R/t = 2$. According to Carden *et al.* (2002), it seems to be possible the springback reduction through the use of reduced values of tool's radii. This observation is in accordance with Pereira *et al.* (2009), who studied in detail the mechanics of contact between tool radius and sheet material. They found that the sheet compression caused by the tool radii acts over the local yielding of the worked material. This feature, affecting springback, is also important in the prevention of the tool wear and can be applied in the simulation program and as setup adjustment alternative as well.
2. The Baushinger effect was firstly observed by J. Baushinger in 1881, being an important phenomenon which affects some ductile metals and some alloys under cyclic loading. It may be defined in the following way (Terada *et al.*, 2004): "a previous plastic strain with a certain sign (e.g. tension or compression) diminishes the material's resistance with respect to the next plastic strain with the opposite sign" (Fig. 7 illustrates the phenomenon). So, one can infer that the mechanical response of a material does not depend only on its current stress state, but also on its strain history (Xiang and Vlassak, 2005). The effect can be attributed as function of several parameters, like the variation of internal stresses distribution, strain rate, temperature and material internal texture and, additionally, to microstructure characteristics of intergranular displacement and precipitations (Jordon *et al.*, 2007). It occurs in several aluminum alloys, including the reinforced ones (Jordon *et al.*, 2007), austenitic stainless steels (Manninen *et al.*, 2009) and biphasic materials (Guruprasad *et al.*, 2008). In this way, when the sheet is submitted to reversions in the forming process, depending on the tool geometry, the change in the material strength due to the Bauschinger effect must be considered in the FEM, in order that the modeling approximates the actual condition. Chun *et al.* (2002a,b) describe the modeling of the factor in metallic sheets. Therefore, as the Bauschinger effect depends on both the material and on the tool geometry (when forming considers direction reversal), it is placed twice in Table 1;
3. The blank holding pressure (BHP) allows control of springback by means of stress control in the sheet and influences over the material parameters following described. Souza and Rolfe (de Souza and Rolfe, 2008) demonstrates, for a given model, that the springback decreased from 11 to 1 mm when BHP was increased from 6 to 12 MPa. Additionally, a tolerance in the value of the BHP must be taken into account due to the conditions of variability of the equipment;
4. Some material parameters exert influence over springback (de Souza and Rolfe, 2008):
   - Direct relation with yield strength: the lower the yield strength, the lower the springback;
   - Inverse relation, almost negligible, with the Young modulus.

It is important to notice that the worked material yield strength variation may be considered a process noise, since it occurs: (a) in different batches, (b) at the same batch, and (c) even along the same sheet, where hardness varies from edges to center;

5. The anisotropic plasticity can be understood as the dependence between yield strength and material grain orientation (Firat *et al.*, 2008). In rolled sheets, this orientation is determined by the rolling direction, which must be considered as a modeling input constraint. Good designs specify, on stamped components detail drawings, the blank rolling direction in order that product performance characteristics are assured;

6. The sheet thickness presents direct influence over springback (de Souza and Rolfe, 2008) (the sheet thickness has direct relation with its bending moment). Consequently, the sheet thickness has a direct relation with springback. In this case, a tolerance range on the sheet thickness must be considered in function of the lot or production batch;

7. The material strain hardening rate is expressed by the n value, defined by the flow stress relation (Shey, 1983):

$$\sigma_f = K(\varepsilon_0 + \varepsilon)^n \tag{2}$$

where, σ_f is the flow stress, K is a material constant, $\varepsilon = \ln(t_0/t_1)$ is the natural (or logarithmic) strain, ε_0 is the strain at which plastic deformation starts, t_0 is the sheet thickness before deformation, and t_1 is the sheet thickness after deformation. de Souza and Rolfe (2008) show a direct relation between the material hardening properties with strain and the springback, similarly to the yield stress factor. They also studied the interaction of these two factors by means of design of experiments (DOE) and they stated that a direct relation with the springback is present. Oliveira *et al.* (2007) studied specially the work hardening in modeling for springback prediction. Hahm and Kim (2008) dealt with material hardening in different material directions in function of the rolling direction;

8. Results involving the effect of lubrication over the springback present divergences in the researched references. Lubrication, in general, presents little influence on springback. Some experimental results show a slight increase of springback with the increase of the friction factor and, in these cases, lubrication would be beneficial in reducing springback. de Souza and Rolfe (2008) established a direct relation between friction factor and springback, so lubrication has a positive effect on attenuating the problem. Lubrication is mainly effective at the tool radii, where occurs the more severe contact with the sheet, being important to prevent tool wear and to improve the surface finish quality of the formed material. Shey (1983) supplies an extensive description on the types and applications of lubricants in the cutting and forming processes of metals.

5. CONCLUSION

The dimensional and form precision of each component of a mechanical assembly play an important role in assuring that this assembly complies with its functional constraints. Therefore, the tolerances specified in the detail drawings of parts must be met by the production processes, as tight as possible. The aim of the present work is give a contribution to the design of stamped parts, by displaying an overview on the factors that influence the precision in the stamping processes by cutting and forming, in order to provide both tool and process developers with the parameters needed for compliance of the produced part with the specified dimensional and form tolerances and to warn product designers on the process limitations as well. The theoretical approach of the subject is ample and diverse, and can be found in better detail in the cited references.

6. ACKNOWLEDGEMENTS

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8. Responsibility notice

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