

Numerical investigation on forming processes for the production of micro textured tappets

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List of variables, symbols and abbreviations

Symbol	Unit	Explanation
MPa	MPa	Megapascal
mm	mm	Millimeter
s	s	Second
deg	()	Degree
EU	-	European Union
CO ₂ /km	g	carbon dioxide per kilometer
R	Mm	Radius
ICE	-	Internal combustion engine
α	()	Die exit angle
IE	-	Indentation value
\bar{R}	-	Mean normal anisotropy
HAZ	-	Heat affected zone
BMF	-	Bulk-metal forming
SMF	-	Sheet-bulk metal forming
FEM	-	Finite elements analysis
LDR	-	Limiting Drawing Ratio
STR	-	Strip Reduction Test
ε_1	%	Principal strain in main direction 1
ε_2	%	Principal strain in main direction 2
ε_3	%	Principal strain in main direction 3
r_n	-	Normal anisotropy
Δr	-	Planar anisotropy
EDM	-	Electro-Discharge Machining
SF	-	Simufact Forming

EHL	-	Elastohydrodynamically lubricated contacts
MOP	-	Metamodel of Optimal Prognosis
DOE	-	Design of experiments
CAD	-	Computer aided design
HSS	-	High Speed Steel
EqS	-	Equivalent Stress (Von Mises stress)
MPS	-	Maximum principal stress
mps	-	Minimum principal stress
CH	-	Counterholder
.igs	-	2D/3D design exchange file (Initial Graphics Exchange)
.csv	-	Table file format (Comma separated values)

1 Introduction

Due to the increasing number of microtexturization applications such as improve prosthesis implants or reduce friction, the demand for a reliable, cost-effective manufacturing process that can implement this technology is rising steeply. [1,2]

In particular, due to the rising public concerns about environmental issue, laws regarding carbon dioxide emissions become stricter every year on. To meet this progressively stricter requirements, new ways of improving efficiency are being studied, mainly in the combustion engine department. In details, EU regulations set as target fleet-wide level for 2024 95g CO₂/km that in 2030 will be reduced of a further 15% in the following 5 years. [3]

In addition the ingoing energy and raw materials crisis is putting even more emphasis in these improvements since the aim is, not only to an improved efficiency, but also achieving it without the use of additional, more sought after or more expansive treatments.

Therefore the focus switched towards polluting wide spread technologies that have still margin of improvement, such as automotive or, more thoroughly, combustion engines. More specifically, the areas of main focus, are the one with higher friction losses such as the valve train.

Thus the valve train area has particular potential for optimization, as it accounts for up to one third of the friction losses in an internal combustion engine (ICE), depending on the operating state [4]. The friction metal on metal present between cam and tappet in the engine can be reduced only improving lubrication and therefore implementing some sort of texturization on the top of the tappet.

This lead to the deeper investigation of Sheet-Bulk metal forming and Bulk metal forming processes as fitting technologies in order to achieve microtexturization on the metal surface. These processes are able to bind the creation of functional part with the printing of textures, creating a really time efficient and thus cost-effective manufacture. However, the metal flow in these applications must be closely controlled in order to obtain tight tolerance and therefore consistency in the result [5]. In fact, even a slight variation in microtexture profile makes the stamping useless and unfit for the application.

In order to meet the aim of this research, after a first evaluation of the testing process, the investigation is based on production simulation and consequentially a tensions distribution, metal flow and shape comparison in order to identify the main factors that influence the production and their interaction with the result.

To meet these requirement would be also necessary to better comprehend the Sheet-Bulk metal forming, since this new technology merges the benefits of Sheet forming, such as cheap working material and low tensions involved, with the Bulk forming ones, as tight tolerances and ability to produce really small features like texture.

2 State of art

Metal forming is an important family of manufacturing processes, it includes Bulk Metal forming, Sheet Metal forming and Powder Metal forming. In general, it starts with a raw material (like billets or sheets) and turns them into near net-shape products in a cost-effective, fast and with tight tolerances way.

Forming is achieved through plastic deformation in which the physical shape of the material is permanently deformed to its final form through the use of very high loads. Therefore, the machinery involved are expensive, large and heavy, able to withstand not only very high loads but also capable to do it repetitively, in order to maximize the economy of scale and therefore compensate for the expense of the machine tools.

2.1 Bulk Metal Forming

The Bulk forming technologies are characterized by the three-axial tension state with high loads and important deformation ratios. They start from a billet of material and reach the final product through plastic deformation, passing the shape of forming die and punch to a billet. Thus the final product has high tensile strength and proper tolerances, requiring few or no subsequent processing.

However, the high loads involved are challenging an effective economy of scale due to high tools wear and longer cycle time in the manufacturing process.

2.1.1 Extrusion

The extrusion process consist in forcing the material out of a opening, gathering the shape of it. Therefore, it is particularly useful to create long objects shaped only along the profile.

2.1.1.1 Forward extrusion

In the forward extrusion the direction of the force is the same as the extruded workpiece.

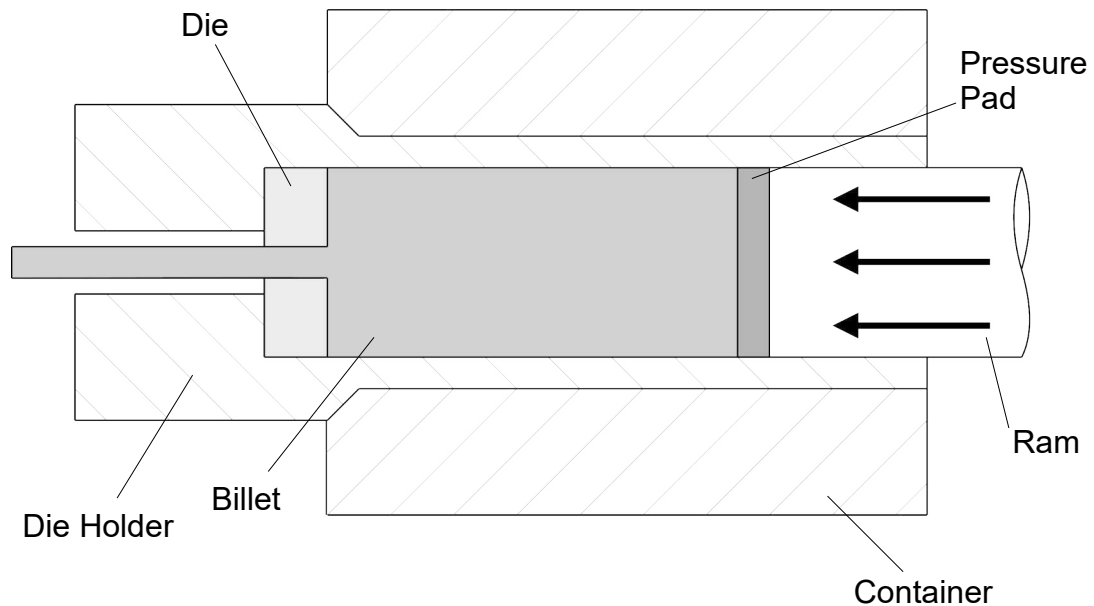


Figure 1: Illustration of Forward Extrusion operation

The billet is presented as a rod surrounded by a container liner and forced inside a die shaped as the final product. The movement is generated by the pressing stem (also called Ram) advancing until the whole billet is extruded, therefore, compression tensions are generated inside the material, making it particularly sensitive to friction, increasing substantially the force necessary for the process.

In addition, a dummy block can be placed between the ram and the workpiece (used to avoid the extrusion of the last part of material since it is full of oxide and impurity, so only when the material is low quality).

2.1.1.2 Backward extrusion

In the forward extrusion the direction of the force is the opposite as the extruded workpiece.

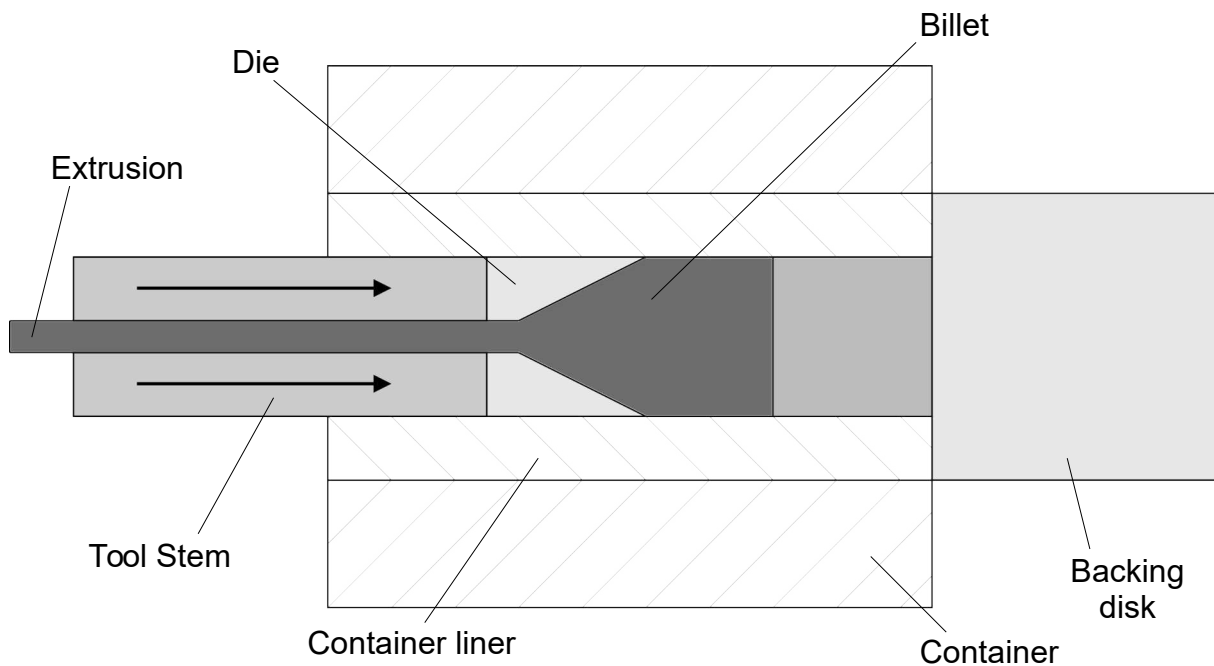


Figure 2: Illustration of Backward Extrusion operation

The process is analogous to the forward extrusion with the difference that the moving part becomes the tool stem. The main limit is that geometries must be simple because the stem needs an opening of the same shape as the final product.

2.1.1.3 Cold extrusion

Cold extrusion is developed recently due to his demanding mechanical requirement. However, thanks to the hardening process, not only it deforms the billet, but also improves his mechanical proprieties. In fact, it alters the grain dimension determining a increase in the tensile strength. Furthermore, thanks to the reduced spring-back effect, due to the low temperature, surface finish is more accurate and so are the tolerances.

In addition, there's no need to warm up the workpiece, decreasing the manufacture costs and improving production rate, which decrease it even more.

In contrast, the augmented tensions involved are reflected on the dies, rising their cost and enhancing the need for lubricant (usually in the solid state), crucial to avoid is the stick-slip situation that leads to the bamboo cane defect.

2.1.1.4 Hot extrusion

On the other hand, sometimes hot extrusion is the only way to go, since lots of metals can be extruded only in hot environment, such as titanium, refractory alloys or high alloyed alloys. In addition, temperature helps to decrease flux tensions when needed, improving flow of harder metals.

On the other hand, high temperatures means high die wear rate and also formation of oxide. The oxide layer is particularly challenging since, when it breaks, it interposes itself in the inner material ruining the homogeneity (usually oxide does not weld with the base material, becoming an impurity) and decreasing mechanical proprieties. Furthermore, since is a high temperature process, all the usual problems of hot working come out, such as grain accretion, distortions during the cooling down and residual tensions inside the workpiece, since the cooling down process can't be perfectly matched in every part of the material, creating cracks on the surface or, even worse, in the inner parts.

2.1.1.5 Chevron cracking

The most typical defect that happen during extrusion is the Chevron cracking.

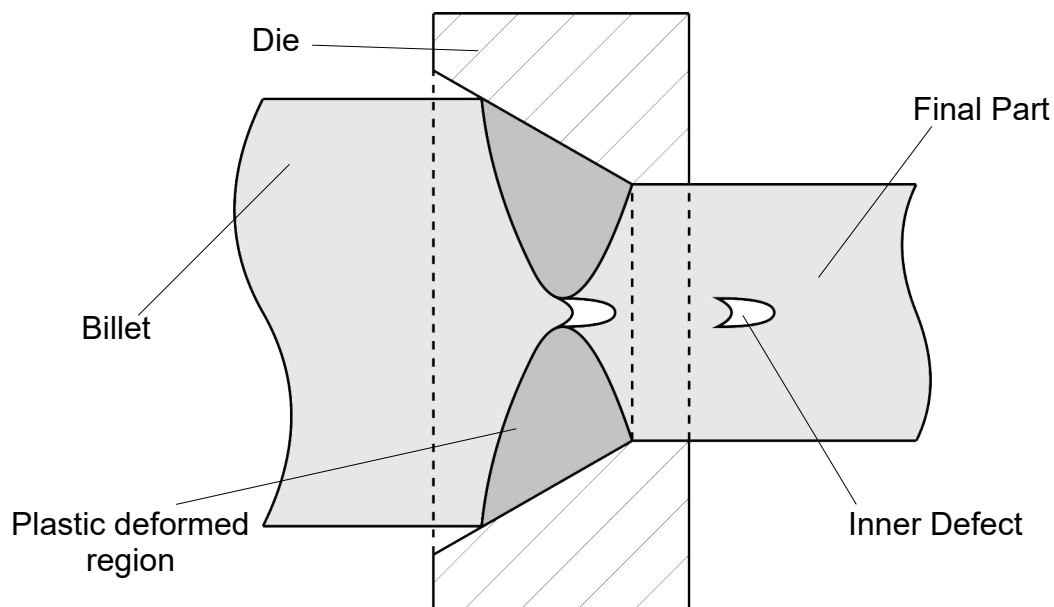


Figure 3: Chevron Cracking formation during extrusion

It develops when the inner part of the workpiece does not plasticize and consequentially traction stresses are developed when it is released. This situation initially lead to decreased mechanical properties, than can collapse and generate inner defects, which in the worst scenario could lead to defects in the inner region, determining a particularly dangerous situation since those are hard to spot.

2.1.1.6 Process parameters

The main parameter that rules the process is the die exit angle (α), since it influences extrusion force and material flux which afterwards determine the mechanical proprieties of the final product. Usually it can be determined by calculating the ideal deformation force required (constant with α), the required force for the redundant deformation work (linear with α , the bigger the angle, the more spring-back effect

there will be) and the force required to overcome friction (logarithmic with α , the bigger the angle the less friction there is).

In addition, extrusion ratio, diameter of the circumscribed circle and form factor (complexity index) need to be taken in account during the design of the dies since they have an wide relevance on the tribological level indeed. If the resulting friction of the process results to high, is required to change the extrusion process or increase the temperature of the billet.

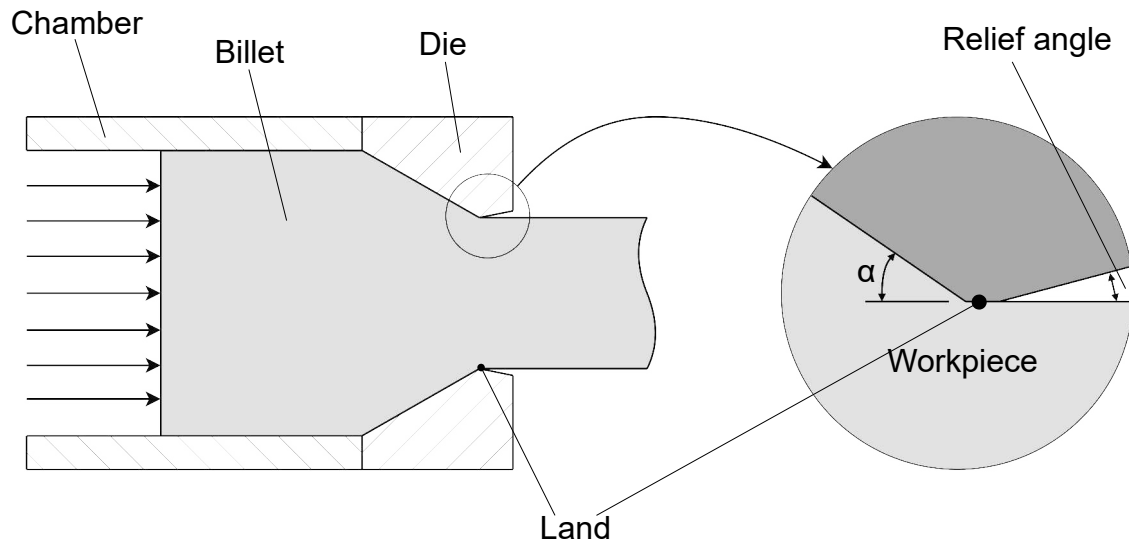


Figure 4: Die exit angle illustration

Therefore, the last parameters of the machinery are the temperature of the billet (to facilitate the deformation), the velocity of the stem and lubrication, all influencing the overall tribological condition.

2.1.2 Forging

Forging is a manufacturing process which aims to produce a near net-shape part from a billet of raw material through the use of mallets or hydraulic presses. The process involves extremely high compressive forces.

2.1.2.1 Process description

Firstly, the semi-finished product is prepared and cleaned, then warmed up and if necessary, removed the flakes. Consequently, the dies need to be warmed up and lubricated. Then the real forging process starts, composed by multiple dies one slightly different from the other, the dies are pushed one against each other with the workpiece in the middle that, given the pressure, gains the shape of the die. After the forging process the final part is separated from the flash, cleaned and checked dimensionally.

In case the forging process is conducted with “Impression die forging”, where the die are closed even on the sides, the die needs room for the waste flesh that later can be cut. The dimensioning of the space for waste needs particular attention, since it influences the dimensions, thickness and mechanical proprieties of the finished part. The main advantage of this process is the better control of the material flux and therefore the micro structure of the billet, leading to an improved (compared to other processes) mechanical resistance and fracture toughness. From the commercial point of view, the process is also very efficient on the use of material since the final product is near net shape (low buy to fly ratio). In addition, the process can deliver geometry complex enough for most of the applications.

The disadvantages of the process belongs to the cost of the dies and machinery. As a matter of facts, the forces developed in the process are extremely high, needing costly dies and expansive presses and thereafter qualified personal to operate them.

2.1.2.2 Process parameters

In addition to all the usual parameters (press force, press velocity, strength of the material...) is important to consider the draft angle, since is always required for extraction of the workpiece even though the original geometry do not account for that. The smaller it is, the easier the extraction but will result in an altered geometry and vice versa, turning in a trade-off balancing act.

Furthermore, during the die designing, the complexity of the shape in relation to the material deformation speed sensibility needs to be taken in account, in order to achieve the full filling of every detail in the die. The fittings must be large enough to accommodate the material without crack generation or instability, bringing uneven deformation.

2.1.3 Coining

The coining process is a variation of the forging where the three-dimensional state of stress happen only on a thin layer in the workpiece’s surface. The process provide a near-net shape product without the necessity of further processing also surface finish related.

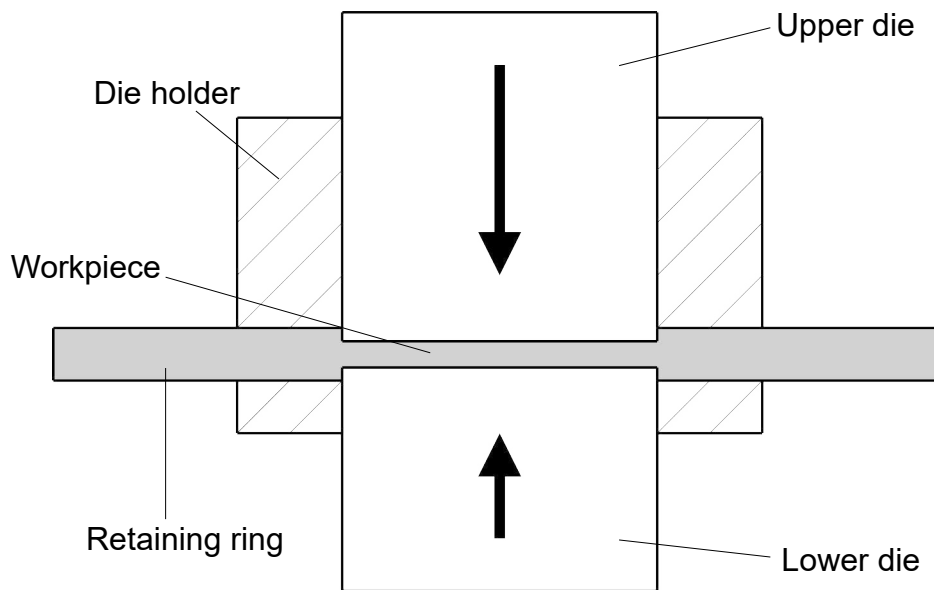


Figure 5: Illustration of Coining operation

2.1.3.1 Process description

Coining is a metal forming process where a workpiece, usually a disk, is compressed between two dies, meanwhile is positioned and kept in place by a collar [6]. All the steps involved are analogue to forging, but with different parameters and forces involved, in coining however, the dies are closed until the end without any flash creation. The filling of the engravings develops really high contact pressure that helps the coining process to happen. The pressure leads to a complex material flow during the process that makes it difficult to simulate. The pressure is really high since in the final stages the dies are completely closed. In addition it is mainly carried out cold since the deformation involved are really modest and therefore all the steps to remove the oxide layer are not necessary.

2.1.3.2 Process parameters

The main process parameter is the final coining force which determines filling of the dies, final shape and thickness of the product.

The stroke is deeply linked with the final coining force, since one determines the other. The force vs. die stroke curve exhibits the characteristic behaviour of closed-die forging: in the first part it is almost flat and low until the filling of the engravings start, subsequently the material is squeezed and the force increases exponentially.

The process finishes when the force or the stroke reaches a predetermined maximum in which the relief coin features are completely filled with sharp corners and optimum surface finish (Figure 6). In addition the strokes involved are low. [6]

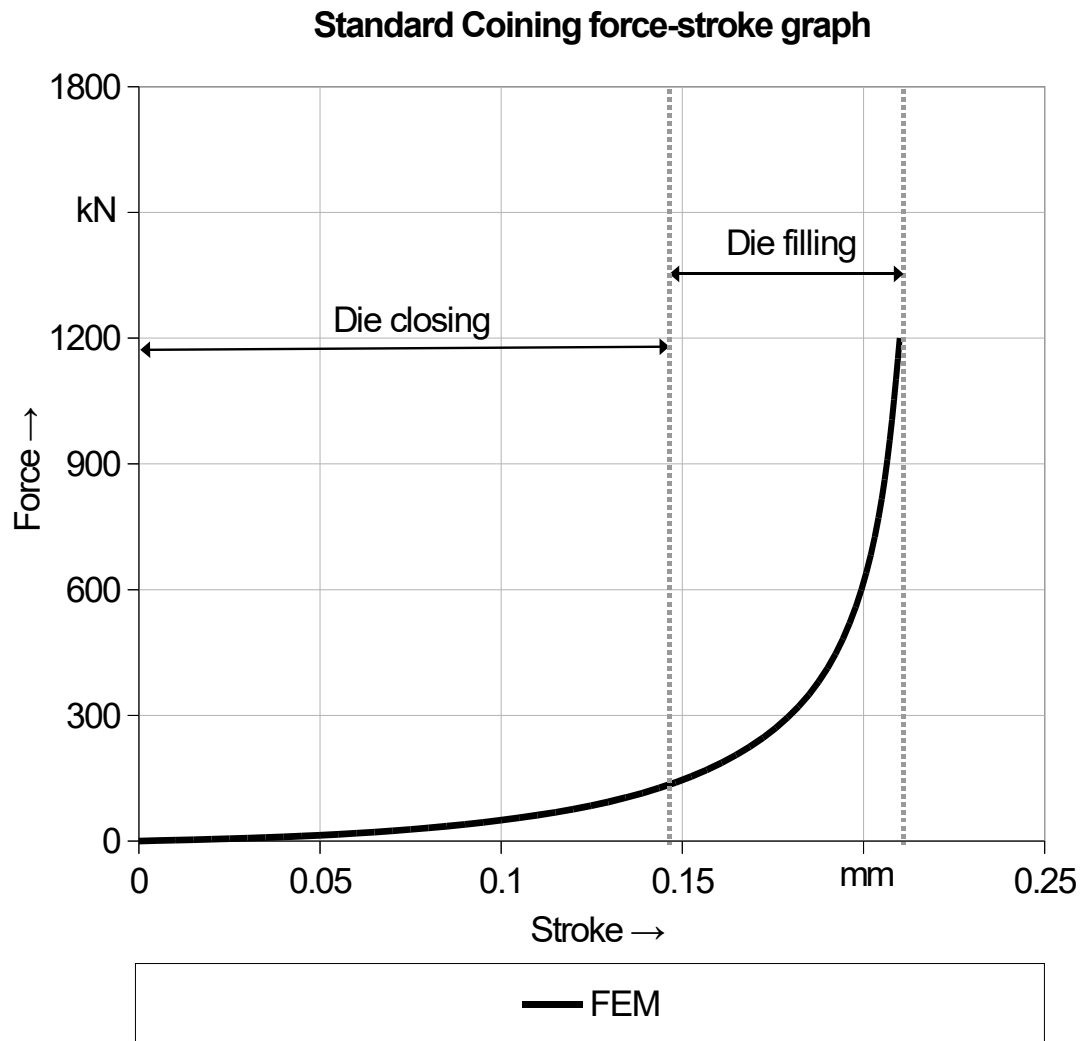


Figure 6: Evolution of the force with die stroke in Coining

Other parameters, involved in determining the final product, are related mainly to the geometry of the dies (as surface roughness and shape complexity), as a matter of fact the surface finish of the dies reflects the one of the final product. Accordingly, there isn't any single geometry factor that can drive the final product quality, but it is a set of parameters (undercuts, draft angles, features...) that must be taken in account all at once. Therefore the only way to have a clear picture of the final result is to use a FEM simulation and evaluate the output result.

2.1.4 Rolling

The rolling process is used to modify thickness or profile of beams, slabs and sheets of metal.

2.1.4.1 Process description

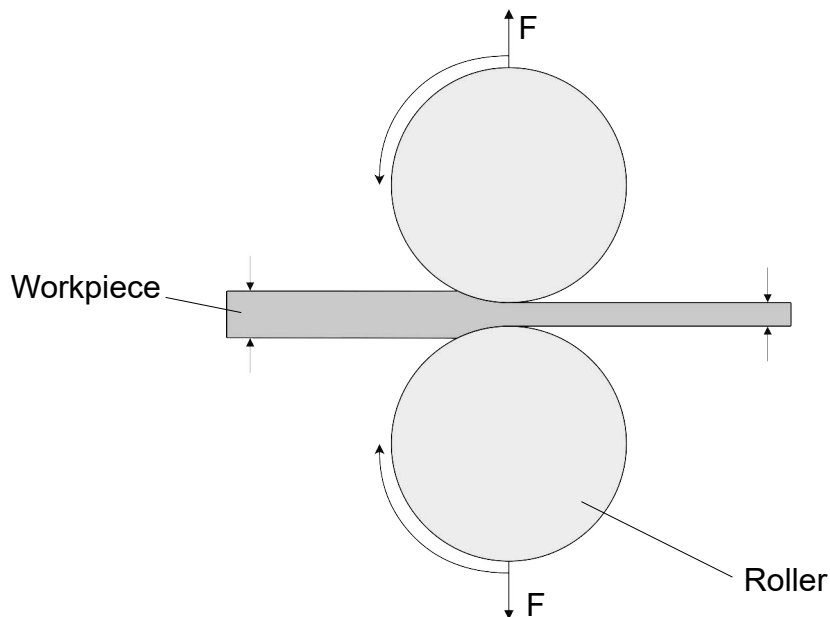


Figure 7: Illustration of Rolling operation

A semi-finished material (ingot or continuous casting bar) is warmed up and homogenized (if necessary), then it is laminated in a machinery composed by two rollers usually opposed (but it may be possible to have four rollers in order to deform the side parts of the material) that brings the material near the final shape. Afterwards, during the cooling down (if it is hot rolling), a heat treatment is applied, and a second cold lamination brings the shape to its final thickness.

2.1.4.2 Cold rolling

Cold rolling usually takes place when: lower deformation are involved (between 50% and 80% of the initial thickness), cold hardening is necessary, high quality surface is required and excellent tolerances are demanded.

In addition, cold rolling usually requires only one set of rollers since the reduction of thickness (only if it is compatible with the force exerted by the machinery) takes place in one single step (including also hardening during the process) and does not require any cooling at all, reducing cost overall.

In spite of the benefits, the main disadvantages of cold rolling are the really high forces involved (increasing the cost of the machinery and decreasing the quality of the tolerances due to rollers barrelling) and the traction tensions that can develop inside the material, spoiling mechanical proprieties and increasing the chance of inner defects.

2.1.4.3 Hot rolling

Hot rolling usually takes place when: a rolling forces reduction is required, big reduction of the thickness are carried out, a recrystallization of the grain is necessary (the hot environment triggers a dynamic recrystallization process) or hardening is not pleased.

On the other hand a friction increase needs to be taken in account (due to the oxide layer formed on the surface), requiring additional rolling force, and therefore a necessity to cool the rollers. In addition, high temperatures render handling of the material problematic, needing additionally heat protection for workers.

2.1.4.4 Process parameters

The main independent variables are: roller velocity, draft (thickness reduction), initial thickness and width of the blank, material tensile strength, temperature and lubricant. In addition, there are some dependent variables that is necessary to consider during the design of the rollers: deformation force and power, exit speed, final temperature, maximum draft and contact length.

However, the study of force distribution, and therefore the tribological aspects, is critical to avoid the central flexing (camber) or flattening of the rollers and consequentially spoiling the tolerances, increasing the forces involved (more contact patch) and uneven surface.

Furthermore, if the process aim is to create a profile shape (E.g. structural profiles like H section), the rolling is divided in more steps in which every feature is created.

2.1.5 Formability

Formability is the capacity of the material to undergo deformation during a bulk metal forming process.

The index is measured through a compression test and a hot torsion test. The compression test is conducted on a cylindrical billet without any lubricant, using high reduction ratios in order to make clear the barrelling condition. Once the process is done, all the deformation defects are judged, such as superficial cracks (which underline the limit of deformability), compression instability, folds or internal cracks. The main parameter to assign the index are the superficial cracks but also the others are used in the judgement.

The hot torsion test instead, is used to assess the formability in hot conditions, the specimen is twisted until breaking, the number of twists required is the value of the index. The test is repeated multiple times at different temperature in order to generate a plot of the formability against temperature.

2.2 Sheet metal forming

The sheet metal forming process is characterized by biaxial tensions, mainly traction stresses.

The starting material is presented in the shape of blank with high surface-thickness ratio, or rather sheet of metal, therefore every thickness variation is due to blank ironing, according to the Poisson's effect. However, this is only a secondary result and needs to be mastered since can lead to necking or fracture.

2.2.1 Deep Drawing

Deep drawing is a sheet metal forming process by which a sheet metal blank is slightly clamped along its perimeter by a blank holder and radially drawn into a forming die by a punch [7].

In the Deep drawing process, unlike in the Ironing one, the thickness remains theoretically constant, since the shaping process occurs only thanks to recall of material.

2.2.1.1 Process description

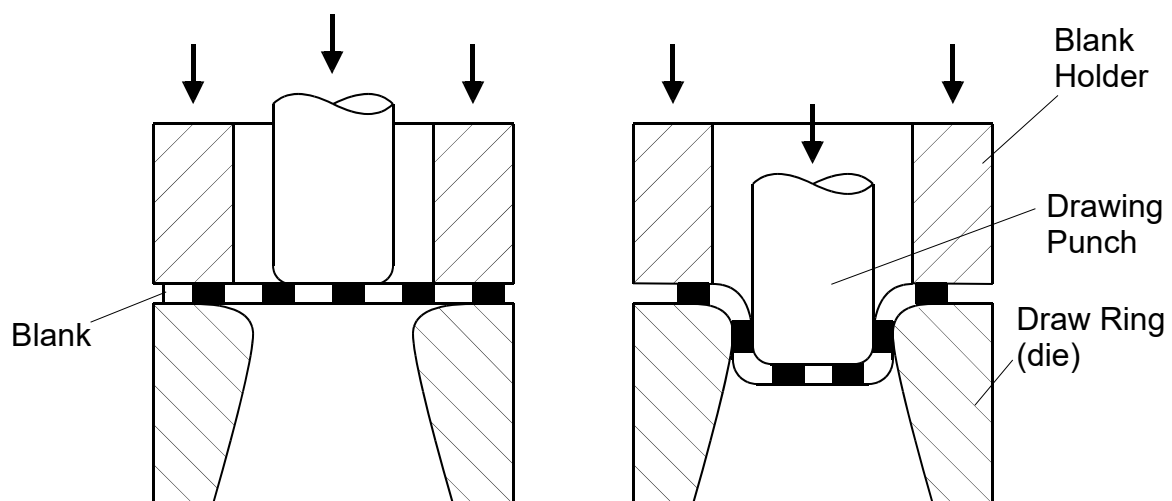


Figure 8: Deep Drawing functioning illustration

The Deep Drawing process manage to create simple geometry parts starting from cheap sheets of metal. It starts with the fixing of the sheet of metal to the die through the blank holder. Once the blank is set in place, the punch begins to deform it until the final product is generated. Normal compression pressure applied by the blank holder induces retracting force into the blank by friction and prevent wrinkling in the

flange area. Basically the forming process starts only when biaxial forces are applied to the bottom area of the workpiece by the punch.

During the forming process, hardening of the walls occurs thanks to deformations involved, for that reason the amount of blank holder's pressure is a crucial parameter in terms of thinning of the material side walls.

Subsequently the punch is retracted leaving the final product free from the die and ready for cutting away sheet's excess parts.

On the surface traction stresses are developed whereas unintentional compression stresses appear tangentially to the punch surface.

The machinery involved is essentially composed by three parts: deep drawing punch, draw ring or forming die and a blank holder [7].

2.2.1.2 Process parameters

The main parameter that influences the quality of the drawing is the Blank holder's pressing force. If it's too high, the sheet may crack or fracture, if too low wrinkles may spoil the surface making the whole workpiece unusable, therefore a balancing act is necessary based also on the other parameters. It's set usually between 1 and 1.5 the ultimate breaking tensile stress of the sheet's material.

Furthermore clearance between punch and die is key: if it's too large the deformation process became ineffective leading to poor tolerances of drift from nominal geometry, if too tight the sheet is cut, it's usually set between 1.07 and 1.14 times the sheet thickness.

Lubrication needs to be adequate in order to avoid defects on the surface or excessive die wear.

In addition the usual geometrical parameters are needed: punch diameter, sheet thickness, sheet diameter. Moreover the forming die entrance radius and the punch exit radius must be controlled, especially the exit radius, since it leads to fractures if too tight and wrinkles if too slack.

Finally, the punch force became a dependent variable driven by the required force to circumferentially compress the sheet of metal, the force require to overcome friction and the force required to bend the blank related to forming die's and punch's fillet radius. Some empirical formulas are available to correlate all these factors to the actual force required.

2.2.1.3 Limiting drawing ratio

The Swift test is used to assess the LDR index of various materials. It is defined as:

$$LDR = \max \left(\frac{\text{Blank diameter}}{\text{Punch diameter}} \right)$$

Since in a Deep drawing process the fracture happens through thinning of the side wall, LDR identifies it's the maximum that the ratio can be with the sheet of metal still intact. LDR so is defined as the ratio between the two diameters when fracture

happens. Whenever the value of the ratio exceed LDR, the drawing force became greater than what side wall can withstand leading to fracture.

In addition, LDR can be useful to estimate the Mean Normal Anisotropy (\bar{R}), since a correlation among them exists.

2.2.1.4 Swift test

The Swift deep drawing cup test is a method used for the determination of forming properties of a specific sheet of metal/alloy.

It consists in deep drawing the blank into a cup of increasing blank/punch diameter ratio, until crack formation. Once cracks are formed the LDR of that specific combination material-geometry is determined.

2.2.1.5 Nakajima test

The Forming Limit Diagram provides a method to evaluate if the expected stress is compatible with a given sheet of metal [8]. Note how formability is a feature of the material and not of the process.

The shows the breaking point related to the two main deformation (expressed in percent), where the third one can be calculated through volume consistency.

The Forming limit diagram is determined through the Nakajima test.

The test consist in a pure ironing test, where a punch with hemispherical head, deforms a series of sheet of metal of different geometries (usually at least seven) until fracture occur. By varying the specimen width, different Deep draw and stretch forming conditions occur on the sheet metal surface (from a square geometry, to evaluate the regular biaxial deformation, to a strip one with simple tensile mono-axial load present). Thanks to this wide variety of geometry it's possible to evaluate from right to left all the ϵ_1 - ϵ_2 plane where the curve is built.

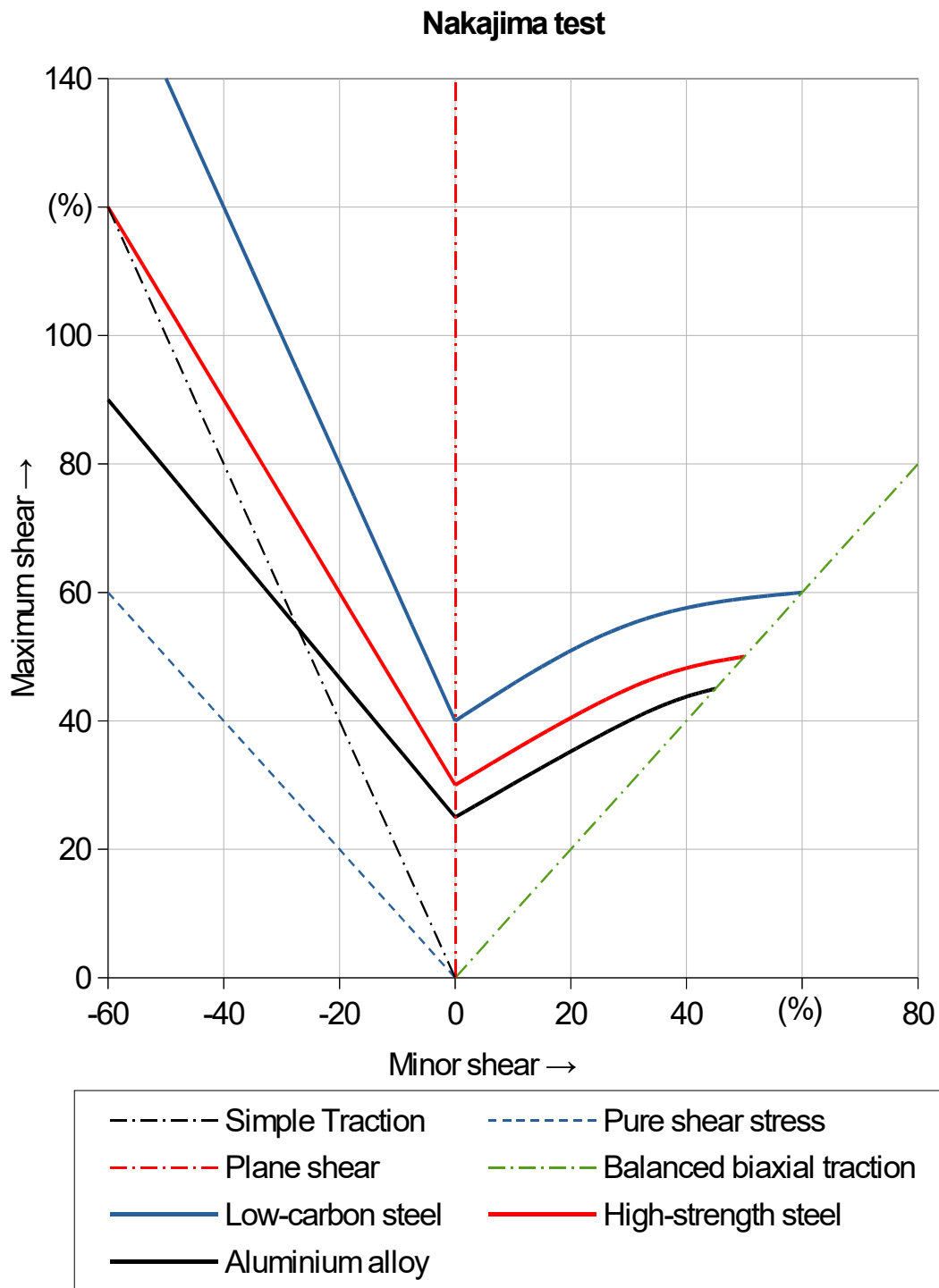


Figure 9: Forming Limit Diagram for Nakajima test

In order to evaluate the deformations afterwards, the surface of the workpiece is prepared silk-screening it with incremental diameters before the test.

The sheet of metal is kept in place from a blank holder then the test starts with the advancement of the punch. When the blank cracks the pressure is released and the deformation can be evaluated.

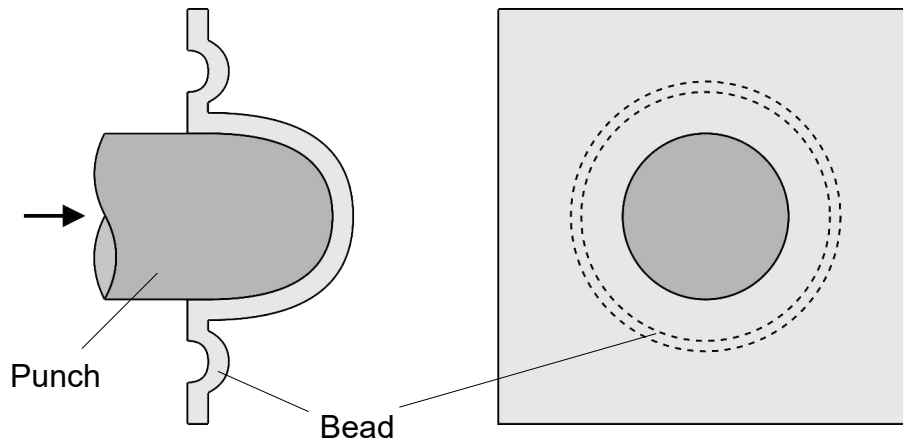


Figure 10: Illustration of Nakajima test execution on a specimen

Due to punch pressure, the circular marks turn into ellipses the main axes of which represent the strain on the surface in major and minor direction.

Afterwards all the data are measured, collected and presented in the aforementioned graph. In order to improve the measurements accuracy nowadays the data collection process is conducted through the use of 3D optical measurement systems.

The test is conducted in optimal lubrication condition since if the fracture occurs far from the punch the test is not valid.

2.2.2 Ironing

Ironing is a sheet metal forming process by which a sheet metal blank is blocked along its perimeter by a blank holder and radially drawn into a forming die by use of a punch, since the main feature of ironing is that the blank is locked, every increment in the surface of the blank comes at expenditure of the side wall thickness (reduction that in optimal conditions can reach 60%-70% [9] of initial thickness), due to mass conservation. Its most common purpose is to give the workpiece a constant thickness before other processing. The process is often used in combination with deep drawing, in order to give shape and thickness at the same time.

2.2.2.1 Process description

The process machinery is composed by a blank holder, which also has the function to keep the blank in tension to avoid wrinkles, a forming die and a punch which pushes on the sheet and therefore on the forming die.

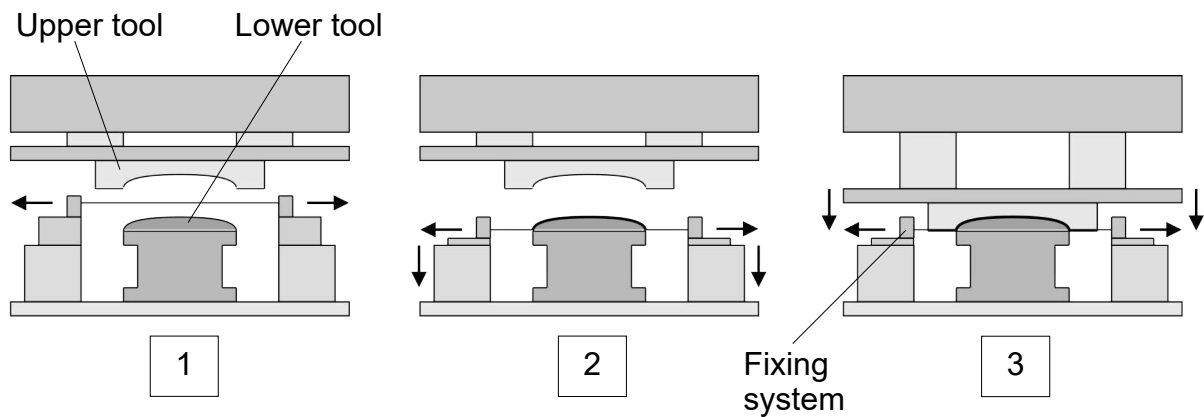


Figure 11: Illustration of Ironing operation

The pure ironing process starts with the clamping of the workpiece through the blank holder which consequentially lowers to the forming die and finally the punch irons the metal. The gains in surface are upset by a lose in wall thickness, unlike deep drawing.

2.2.2.2 Process parameters

The process parameters can be referred to the deep drawing once with the exceptions of geometrical quotes, theoretically the forces involved are traction that turn into compression in the inner part of the sheet.

In addition, the clamping force is no longer a variable since the only purpose of the blank holder became to lock the sheet in place, on the other hand the traction stresses imposed by the clamping mechanism before the ironing process become an important parameter to be studied, since it influences the whole forming.

2.2.2.3 Deep drawing – Ironing combination

The ironing method is rarely implemented by itself, nevertheless is really popular in combination with deep drawing complementing each other. As a matter of fact, deep drawing gives shape and ironing defines the thickness of the final workpiece.

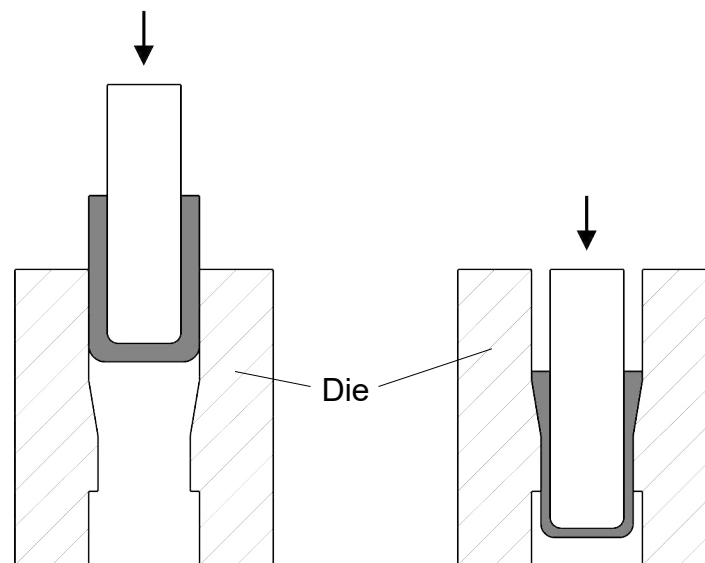


Figure 12: Illustration of Deep Drawing operation

The forming happens exactly as described in the Deep drawing section, but with the addition of a step in the forming die that thins the metal walls. For example this combination is used to produce beverage cans in a single step, starting from a simple sheet of metal.

The process start with a blank that is initially drawn into the forming die and consequentially the ironing process begins as soon as the metal sheet hits the forming die's step, since the diameter of the die is slightly bigger than the outer diameter of the cup, the walls undergo plastic deformation.

In addition, this particular type of ironing, since is considered as one of the most severe due to the occurrence of high localized pressures and large surface expansions [10], can be replicated by reducing the thickness of a plane strip and evaluate the capability of the material to withstand the conditions involved. This assessment can be made thanks to the Strip Reduction Test (STR) [10], which consists in a pure ironing simulative test where the specimen is reduced until fracture. Furthermore, the test replicate even the tribological condition, giving a clear picture of the situation simulating the whole manufacturing environment. The test is usually realized in order to validate a design.

2.2.2.4 Erichsen test

The Erichsen is a fast and cheap test used to evaluate the ironing capabilities of a particular sheet of metal under biaxial stress.

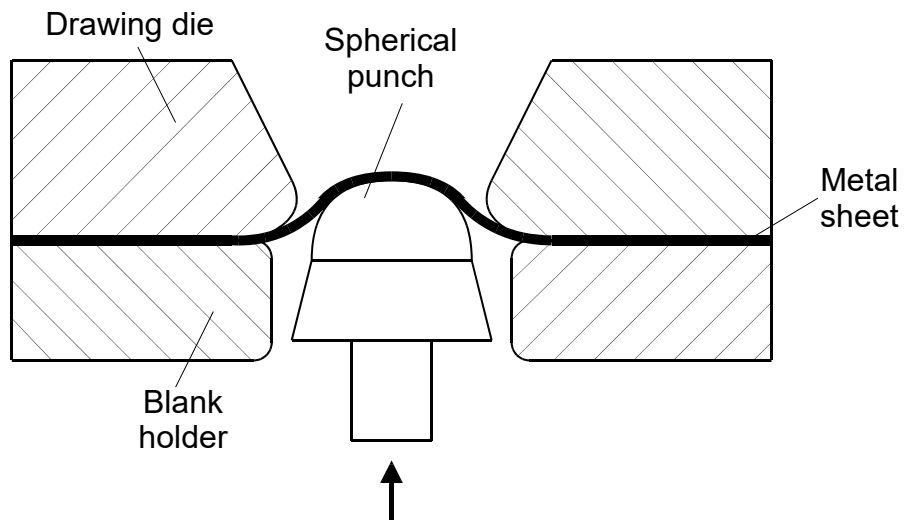


Figure 13: Erichsen test execution on a specimen illustration

The specimen is clamped between the sheet holder and the die, then formed with a hardened ball [11] connected to a punch.

Therefore the test starts with the progress of the punch until cracking occur. The distance travelled (in mm) by the punch before fracture is referred as “Indentation value” (IE) and represents an important quality feature of the tested sheet of metal.

Since is a very fast and useful test, it’s used for goods inspection or quality control due to evaluate easily the quality of the material.

2.2.3 Anisotropy

Due to their crystallographic structure and the characteristics of the rolling process, sheet metals generally exhibit a significant anisotropy of mechanical properties. This effect influences every sheet metal forming process since changes the outcome of every deformation processes. In fact, due to heat treatment, cooling down distortions or just fibre alignment, the plastic behaviour of a material changes from direction to direction leading to unexpected warps in the final product.

The variation of their plastic behaviour within directions is assessed by a quantity called Lankford parameter [12] or anisotropy coefficient. This coefficient is determined by mono-axial tensile tests on sheet specimens in the form of a strip. The normal anisotropy coefficient is defined by:

$$r = \frac{\varepsilon_2}{\varepsilon_3}$$

Where ε_2 and ε_3 are the two main strains (width and thickness direction respectively). Since r is a in-plane propriety, beforehand must be determined which is the rolling plane where the deformation will take place. Afterwards the two parameters to evaluate the warping will be: coefficient of normal anisotropy and coefficient of planar anisotropy.

In order to obtain the values of the coefficients, three bone shaped specimens (0° , 45° and 90°) must be cut from the initial metal sheet and evaluate the respectively coefficients r_0 , r_{45} and r_{90} .

Finally, the value of the coefficients can be found through the following formulas:

$$\text{Normal anisotropy: } r_n = \frac{r_0 + 2 \cdot r_{45} + r_{90}}{4}$$

$$\text{Planar anisotropy: } \Delta r = \frac{r_0 + r_{90} - 2 \cdot r_{45}}{2}$$

Once these coefficients are defined, the whole plastic anisotropic behaviour is defined.

2.3 Sheet-Bulk Metal Forming

In order to achieve weight-optimized design and manufacturing, the idea of combining the functional advantages of sheet metal forming with the manufacturing advantages of Bulk metal forming rose. The resulting forming process uses the fundamentals of SMF improving it through the addition of local three-dimensional stress and strain [13], obtaining the local adaptation and shaping of functional elements. Thus resulting in a near net shape product that can also be realised with high resistance steel sheets, blending shape and functionality.

2.3.1 Deep drawing/Extrusion process

The current implementation of the SMF is a Deep-drawing/Extrusion [13] blend where initially the deep drawing process gives the initial shape and the extrusion aim at increasing the thickness of the side wall, implementing the three-dimensional stress, where the final dimension may be greater than the initial thickness of the blank.

2.4 Microtexturization

The microtexturization technique consist of engraving texture on the material surface in order to change the tribological, structural and functional characteristics.

2.4.1 Microcoining

Microcoining is a deformation processing of metallic materials. It's considered a variation of closed die forging where only the surface is involved in deformation without meaningful metal flow and in three-dimensional stresses. It can be carried out equally in open or closed die in the same way of the coining process. [14]

The main characteristic of the forming technology is the exploitation of elastic spring-back (that in other situations is challenging), sure enough, since the elasticity of the material tends to decrease depth and width of the grooves, it makes possible to use bigger, and so easier to produce, dies or to produce tinier engraves on the

workpiece's surface after an accurate calibration. However, it introduces another variable to be taken in account: grain size [14].

In fact, open die coining designates that finer grains cause greater elastic spring-back and greater forming force influencing substantially the process as a whole.

On the other hand, when the process is conducted in closed die, the opposite behaviour can be appreciated: coarse grain demand greater forming force and cause larger elastic spring-back.

Consequently grain size takes a leading part in controlling of process parameter and needs to be taken in account during the design.

2.4.2 Laser ablation

Laser ablation is becoming a dominant technology for fast prototyping in lots of fields, such as: analytical chemistry [15] and microtexturing. The main application of this technology are to engrave thin layer of the surface vaporizing material, drilling holes, cutting sheets and surface material hardening.

The process consists in an intense burst of energy delivered by a short laser pulse is used to sample (remove a portion of) a material however, since laser pulses of nanoseconds damage the material, it's really important to calibrate the timing in the order of femtoseconds [16], since the laser's heat generate thermally haltered zone on the processing site.

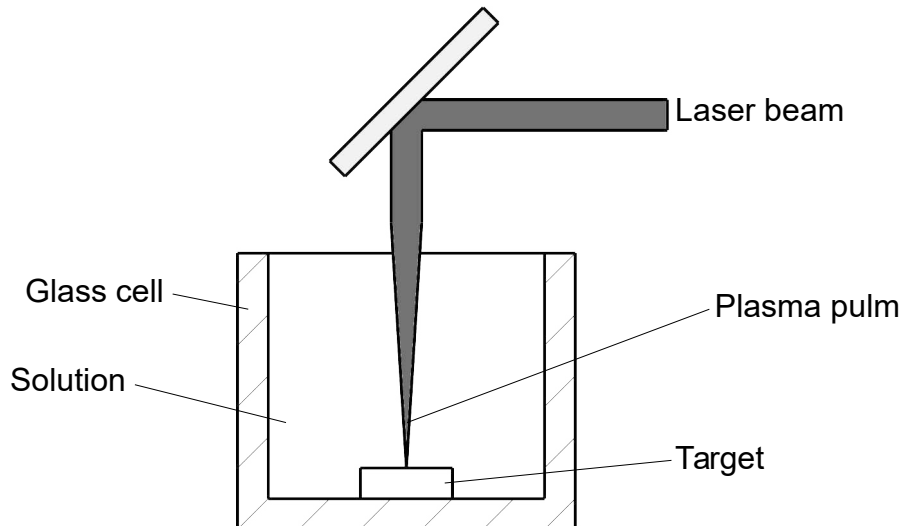


Figure 14: Illustration of Laser Ablation operation

The laser beam, originated from a high power source, is deviated and concentrated through a series of lenses on the target, thanks to the fast handling of the lenses and the limited exposure time the process of engraving a layer is fairly fast. However the

ablation depth is still really limited making the process not suitable for big material removal but optimal for cutting thin sheets.

In addition it can be used to manufacture hole with extreme depth over diameter ratio and diameter under 1 mm.

The main process parameters are light wavelength and exposure time. In fact the wavelength can determine which material will absorb the energy and sublimate making suitable for selective material removal, however the range where can be varied is really narrow for energy concerns, imposing need for calibration, furthermore reflective surfaces became hard to engrave making the process not optimal for certain materials.

The main disadvantage for for what our research is concern is the lack of mass production opportunity and so really high production cost.

2.4.3 Chemical ablation

Chemical ablation can be included in the removal manufacturing category. It consist in an chemical attack with an appropriate reagent to remove little quantity of surface material from a component.

The process requires a workpiece without any internal tensions and cleaned from any foreign substance. Subsequently masks are applied to the parts where the ablation is not desired and then the chemical reagent is added. When the desired result is obtained the reagent is removed and the piece washed in order to suddenly stop the reaction.

The main process parameter is the time given to the reaction to occur, which determine the depth of the engrave and therefore the shape of the final part.

The main advantages are the low initial costs, the reaction can occur in a wide surface at the same time reducing process time and enable mass production and there's no residual stresses or thermal tensions.

On the other hand the requirement for the starting material are strict and it's impossible to realize sharp edges and therefore undercuts.

2.4.4 Electro-Discharge Machining (EDM)

The process consist in the cavity creation through the discharge of an electrical charge between the workpiece and an electrode which melts the surface eroding the base material. It's mainly used in 3D shape creation or in the processing of high hardness material that cannot be done in other ways, in addition it can also be used to create holes in a single pass.

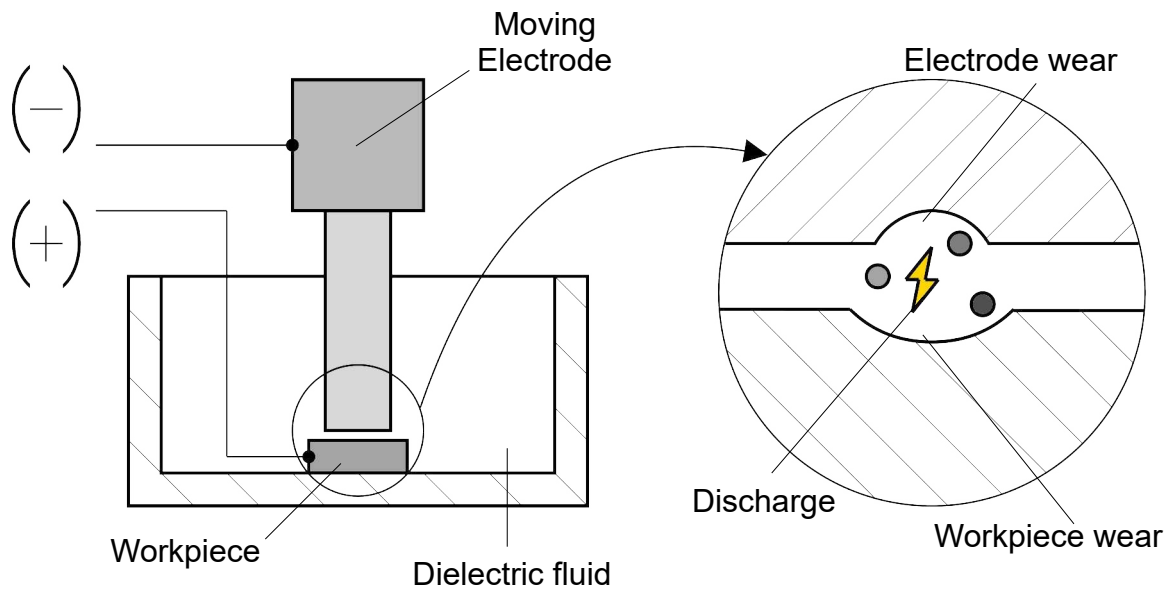


Figure 15: Illustration of Electro-Discharge Machining operation

The machinery is composed by a tub full of dielectric fluid where the workpiece is dipped. On the top is collocated the electrode, which moves and place the spark in the desired location.

The electrode consists is made out of graphite and its wear rate is critical and must be controlled since the distance between it and the surface influences tolerances and roughness. In addition the dielectric fluid influences the distance to keep and operate as refrigerant and electrically insulating material until the potential is high enough, furthermore it also wash away scraps.

On the advantages side of this manufacturing process can be found the ability to manufacture material of every hardness level, since the material is eroded by temperature and not friction, furthermore the tolerances and surface roughness achievable are high (if the machinery can keep constant the workpiece electrode distance), moreover no tensions are generated on the workpiece and thanks to its handling system even 3D shape and single-pass holes can be created.

On the other hand this manufacturing process can only be used on conductor materials and the process is slow. In addition, the tool wears at a fast pace and needs to be replaced due to the high temperatures of the spark which also cause the creation of heat affected zone (HAZ) near the cutting edge.

2.4.5 Process simulation

The process will be simulate thanks to “Simufact Forming” in order to have gather the main data points and subsequently they will be interpolate with “Minitab” to create a model of the manufacturing process.

2.4.5.1 Simufact Forming

Simufact Forming (SF) is a simulation tool to simulate the forming process. It's developed from "Hexagon" and uses a combination of two calculation methods that complement each other: A finite-volume solver, based on MSC's explicit Dytran solver, is used for the especially efficient simulation of warm and hot forging processes with significant burr formation, and A finite-elements solver, based on MSC's implicit Marc solver for non-linear applications, is used to simulate all process types. [17]

2.4.5.2 Full-factorial DOE

It's a study consisted by 2 or more factors correlated each other with "statistical units" or rather real-life experiments [18]. Such experiments allows the investigator to bare the linkage between each parameters, as well as the response of each factor when each variable changes.

This approach allow the investigator to create a map and analysing every possible combination of each factor without the necessity to carry out a large number of trials, leading to a fast, cheap and reliable way of finding the optimal factors knowing the desired output.

Once data are carried out they are represented by a hyper cube in n-dimensional design space where the experimental design points are the vertices and the length of the edges are defined by the minimum and the maximum values of each of the factors, all the remaining points are usually only derived from interpolation, keeping in mind that the response of every parameters is assumed as linear, condition not always verified.

2.4.5.3 Minitab

Minitab it's a statistical software useful to create, visualize and evaluate Full-factorial DOE [19]. It's developed at the Pennsylvania State University in conjunction with Triola Statistics Company in 1972. It began as a light version of OMNITAB 80, a statistical analysis program by National Institute of Standards and Technology.

2.5 Tribological aspects

Considered all manufacturing aspect of the production of microtextures, the tribological performance and its variation in relation to the shape must be presented.

Considering the cam-tappet system a decrease of relative friction can be observed. The reduction of friction is proportional to the camshaft speed up to 12.3 per cent in case of pure mineral oil FVA 3 compared to polished shims [5].

2.5.1 Influence of microtexturization

The reduction in friction can be attributed to the enlargement of the lubricant gap and additional hydrodynamic pressure with simultaneously increased viscosity [5]. This

behaviour is produced by the velocity gap between the counter parts and lubricant being squeezed out of the microtextures.

Thus, the design of the microtexture, and in particular the depth, can lead to an improved supply of lubricant to the contact area. In general, this condition allows a transition in the lubricant regime, shifting the Stribeck curve. In addition, microtextures may also absorb wear particles and therefore reducing wear due to abrasion. In fact, microtexture serve also as particle reservoir avoiding.

However this is only the general behaviour and is mainly dependent on the lubricant used, proper design, contact pressure and boundary conditions. Thus the design of microtextures is tailored to the application.

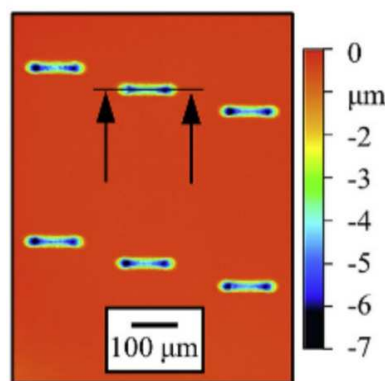


Figure 16: Microtexture depth measurement

In summary, textures oriented transversally to the direction of the motion with small depths below $5\ \mu\text{m}$, lateral dimensions smaller than the elastically deformed contact area and area coverage between 5 and 20% were found advantageous. [20]

2.5.1.1 FEM simulation

In order to predict the friction behaviour of every specific design of microtexture without the need to manufacture and experimental measurement is convenient to simulate the elastohydrodynamical behaviour via software.

In the main studies like [4], the friction behaviour is simulated through a transient simulation of microtextured EHL contacts implemented in the software COMSOL MULTIPHYSICS to compute indicators for the friction and wear behaviour.

In addition a possibility for optimizing the microtexture with a simplified model is implemented in the commercial software OPTISLANG though the MOP method. The MOP method is a meta-model of optimal prognosis that uses approximation functions that must be selected appropriately based on the boundary conditions.

In order to implement these model beforehand all the starting parameters must be defined (theoretical fluid model, microtexture geometry and variation parameters). Then all the parameter combinations must be defined, based on the respective range

of variation. After computation of the simulations with the parameter combinations of all individual trial-points and evaluation of target values, the meta-model can be calculated. [5]

3 Objective and methodology

3.1 Goals

The purpose of this research is to investigate the two most promising forming processes currently available for the manufacture of microtextured parts under various circumstances: Sheet-Bulk metal forming and Bulk metal forming. The final scope of this comparison will be to find the best fitting forming process for microtexture micro-coining.

In addition, an investigation on the effectiveness of multiple parameters on the outcome will be carried out. The investigation is used to identify the main effects on the material flow, the geometry of the part but also on the wear of the tools (not quantifying it but identify critical stresses and measures to reduce them) since some simulations are intended to evaluate the stress on them.

3.2 Process

The goals are reached through a series of simulations in Simufact Forming with various geometry in order to have different outcomes. The number and order of the simulations is chosen by Minitab once a Full-Factorial DOE study is set up.

Afterwards the simulations are analysed in all their parameter (including final geometry of the workpiece) and added to the Minitab study, in order to have response curves that approximate the effect of every parameter on the final result.

In addition, final considerations are made on the geometry, material flow and equivalent stress of the workpiece after the forming process.

3.3 Methodology

3.3.1 Final part geometry

Before the comparison starts, the final geometry must be fixed: the workpiece for both SMF and BMF needs the same material volume, in order to be comparable between the results, and the main dimensions are common for the two processes, as die internal diameter and punch diameter.

3.3.2 Numerical process design

The process starts with the definition of the model in Simufact Forming. Since the 3D simulation is computationally too heavy to process for the number of the simulations required by Minitab on the DOE study, the modelling process starts with the definition of a simplified model.

The 3D model is reduced to 2D with the same geometry and boundary conditions, thus the simulations' outputs are compared to verify the fitness of the results and the according of the final shapes. The main parameters to be compared are: part geometry (shape of the final workpiece), forming force (force-stroke curve of the

press) and plastic strain (the images of the “effective plastic strain” for both the profile and 60 degrees expansions). All these comparison are conducted for both Sheet-bulk metal forming and Bulk metal forming.

Once the reliability of the simplified model is verified, it is possible to conduct the main analysis faster and with less computational overhead.

Subsequently the full-factorial DOE in Minitab is set up, and therefore the parameters to be varied chosen, together with their variation ranges. It's critical to choose plausible ranges of variation along with main geometrical features, in order to have useful results that can be applied in concrete cases. In addition, simulations with unexpected values usually make the simulation crash due to inconsistent geometry.

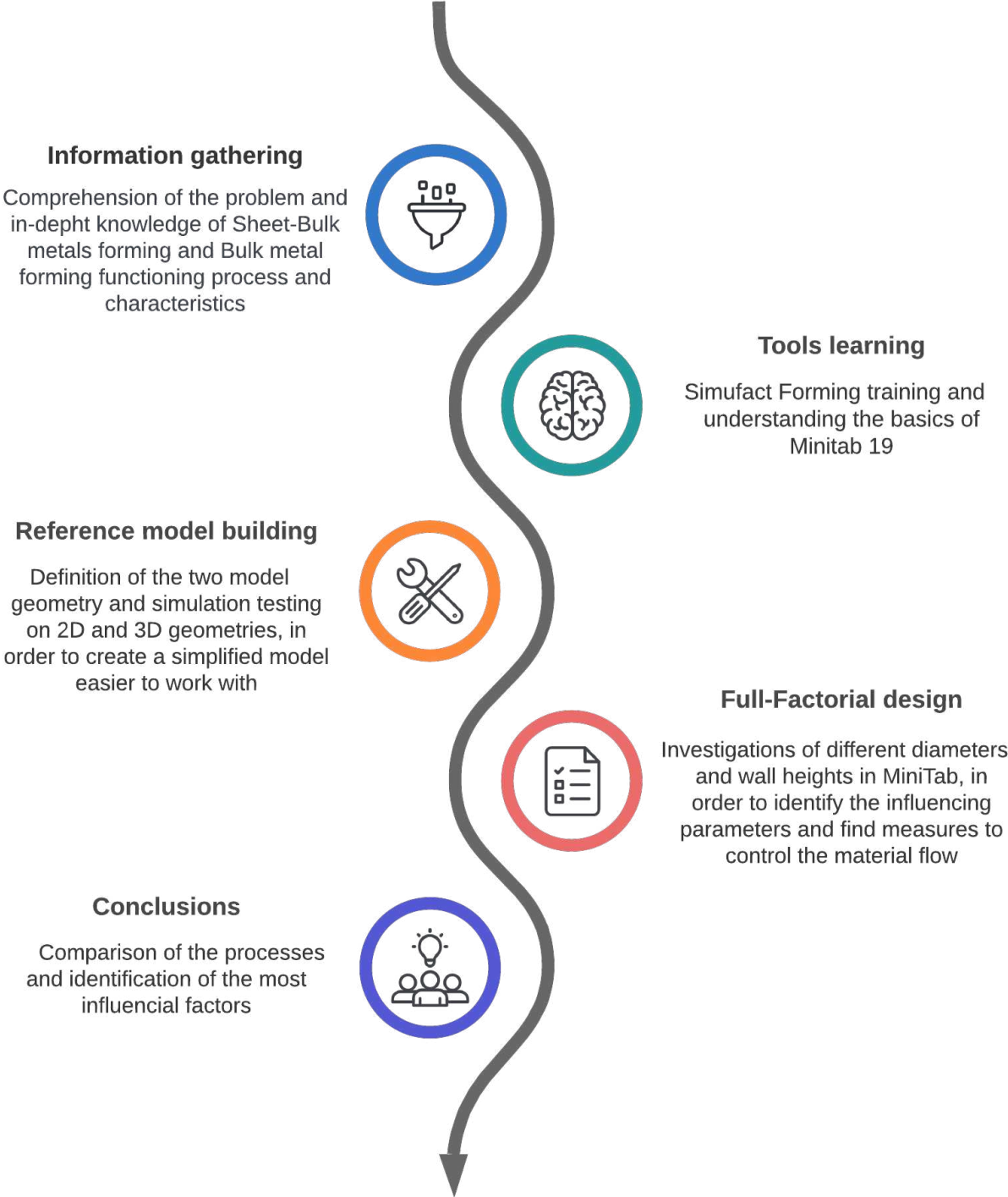
Minitab then returns the combinations of parameters to set in every simulation that can be applied to the CAD files or as parameters in the simulations.

Once all the simulations are done, all the results are gathered and organized in charts in order to have a clear view, in addition the values of the maximum of the equivalent stress (Von Mises equivalent stress), maximum of the maximum principal stress and minimum of the minimum principal stress are exported from the simulations for every part of the tool: forming die, microtextured counterholder and forming punch in order to evaluate the stress on it and determine also the wear of the tools.

3.3.3 Comparison 2D vs 3D

All these data are submitted in the factorial design inside Minitab, in order to be processed and get the resulting graphs with the correlations between input parameters and stresses on the tools.

In addition, investigations on different diameters and wall heights are conducted. These are 2D simulations with either, in the diameters case, shape of the die modified, or, in the wall height once, the height of the workpiece and therefore its volume. As before, the most important parameters to be recorded are: forming force, part geometry, plastic strain and material flow. Material flow, on the other hand, can only be investigated in a more approximate way through images gathered from the simulations showing the radial displacement, to have a more detailed view of the evolution of the process, the images are taken in the 25%, 50%, 75% and 100% progress.



Information gathering

Comprehension of the problem and in-depht knowledge of Sheet-Bulk metals forming and Bulk metal forming functioning process and characteristics

Tools learning

Simufact Forming training and understanding the basics of Minitab 19

Reference model building

Definition of the two model geometry and simulation testing on 2D and 3D geometries, in order to create a simplified model easier to work with

Full-Factorial design

Investigations of different diameters and wall heights in MiniTab, in order to identify the influencing parameters and find measures to control the material flow

Conclusions

Comparison of the processes and identification of the most influential factors

4 Boundary conditions

4.1 Processes

4.1.1 Bulk metal forming

The process is implemented in Simufact Forming through a hydraulic press with constant speed, initially locked to 5 mm/s (thereafter varied in order to highlight the differences for the Full-factorial DOE), that pushes on the pressure plate and consequently to the workpiece. In fact, the pressure plate is a non deformable die that spreads evenly the force which otherwise would be punctual, avoiding calculation errors. Finally, the forming punch pushes the workpiece onto the dies, giving the final shape to the part.

Due to simulation error, the upper part and the base are required, in order to hold in place the dies that otherwise would have shifted up due to the little force pointing upwards developed from the forming punch pressure.

Also to correct computational errors, two “virtual” overlaps, of 0.2 mm, between the counterholder and the forming die and between the forming die and the intermediate reinforcement ring are added, in order to avoid upwards shifting and infiltrations of the workpiece’s material between the counterholder and the forming die, generating mesh errors.

The process is all conducted in a cold forming environment with an ambient temperature of 20°C and all the dies (excluding the non deformable ones) are conductive with temperature set at 20°C.

When the simulation is three-dimensional, only a 60° chunk is simulated in order to diminish the calculation time without losing much details. In addition, symmetry planes are positioned on the sides in order to reconstruct the 3D model.

When the simulation is bi-dimensional, the cutting plane (or rather the plane where the simulation is solved) is placed more or less in the middle of the model, in order to have a representative geometry.

Finally, constrain planes are added on the top of the Upper constraint plane and in the bottom of the Base constraint plane, since there’s no deformation in that region and therefore is useless to compute the positions of those nodes.

4.1.2 Sheet-bulk metal forming

The implementation is similar to Bulk metal forming: a hydraulic press pushes on the pressure plate (present due to simulation error reasons), which itself compresses the forming punch and therefore the workpiece, deforming it. The press is initially locked to 5 mm/s and during the testing phase it is changed to the values suggested by Minitab. As explained above, the pressure plate is a non deformable die for the same motivations.

To avoid the downwards shifting caused by calculation errors, the Base constraint plane is introduced as a non deformable die, the overlaps in this simulation are not necessary.

The process is conducted in a cold forming environment with an ambient temperature of 20°C and all the dies (excluded the not deformable ones) conductive with starting temperature set at 20°C.

If the simulation is three-dimensional, symmetrical planes are added as well, located in the same positions in order to rebuilt the whole 3D model.

Instead, if the simulation is only bi-dimensional, the cutting plane is placed as before in the middle of the model region.

Eventually constrain planes are added on top of the dies (forming die, Intermediate reinforcement ring and Reinforcement ring) and on top of the Base constraint plane die, since outside there's no deformation.

4.2 Materials

4.2.1 Tools materials

In both Sheet-bulk metal forming and Bulk metal forming all the tools are made out of HSS Steel with the exception of the Reinforcement ring in the Bulk forming that uses X37CrMoV5-1 Steel.

4.2.1.1 High Speed Steel

High speed steel (HSS) is a tool steel with a carbon proportion of up to 2,06 % usually also alloyed with wolfram, molybdenum, vanadium, cobalt, nickel or titanium. The main features are: special hardness, temper resistance, high wear resistance, heat resistance up to 600°C and resistance to corrosion.

The material is used used in machining as a cutting material for tools like drills, saw blades, thread cutters, milling cutters, turning tools or many others. [21]

Mechanical properties:

- Young's modulus: 210000 MPa (constant)
- Poisson's ratio: 0.3 (constant)
- Density: 7890 kg/m³

4.2.1.2 X37CrMoV5-1 Steel

It's a hot work tool steel with high temperature strength and wear resistance with high thermal shock resistance. Best suited for: plastic molds, die-casting and extrusion tools for light metals. Good toughness and thermal conductivity. [22]

Mechanical properties:

- Young's modulus: 210000 MPa (constant)
- Poisson's ratio: 0.3 (constant)
- Density: 7890 kg/m³

4.2.2 Workpiece materials

In both Sheet-bulk metal forming and Bulk metal forming the workpiece is made out of 16MnCr5 Steel.

4.2.2.1 16MnCr5 Steel

The 16MnCr5 steel is a structural steel for surface hardened parts such as shafts, axles, gears, gear wheels, bolts, levers and other transport and machine-building components. Steel grade 16MnCr5 is used for surface hardening when grouting, nitrocarburising, nitriding and for other types of surface chemical-thermal treatment. The weldability is good however there is a possibility of cracks forming along welds. [23]

Mechanical properties:

- Young's modulus: 200000 MPa (constant)
- Poisson's ratio: 0.3 (constant)
- Density: 7850 kg/m³

4.3 Tools

4.3.1 Bulk metal forming

The Bulk metal forming displacement of the dies is as presented in Figure 17.

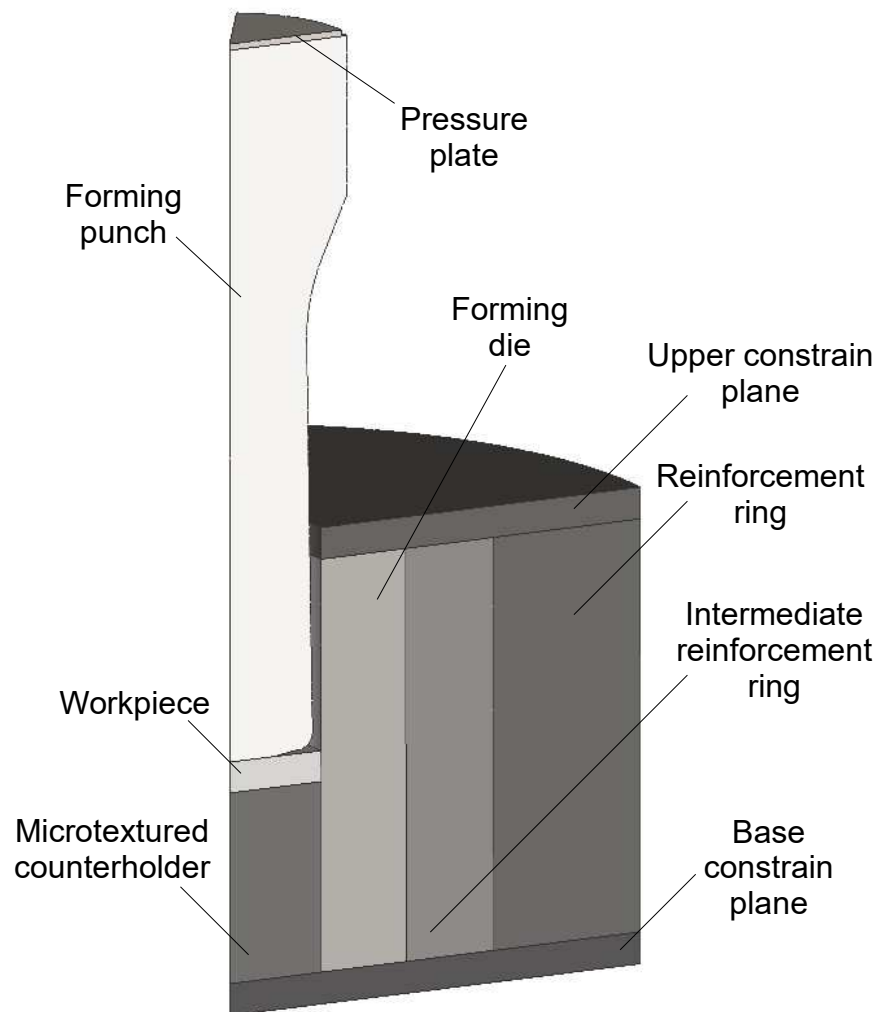


Figure 17: Bulk metal forming model view

4.3.1.1 Workpiece

The final piece is made out of the workpiece's material after deformation. It is modelled in Creo Parametric as a simple cylinder, having the foresight to choose the height so to match the volume of the Sheet-bulk metal forming's workpiece.

It is added in SF as "workpiece", meaning that is subject to deformation and is the less resistant material.

The chosen mesher for the bi-dimensional simulation is "Quadtree" with quad elements of 0.2 mm size in order to have a dense mesh and approximate in an acceptable way the continuous reality, while in the three-dimensional one "Hexmesh" is chosen with hexahedral elements meanwhile SF is left to determine the size.

The workpiece's material is specifically chosen to be the weakest of all and is a 16MnCr5 Steel.

4.3.1.2 Forming punch

The forming punch function is to compress the workpiece until the final piece is made. It is created in Creo Parametric revolving around its axis the sketch of the profile, its most important features are located in the bottom: the tip isn't completely flat but has an is slightly tilted near the edge in order to facilitate the metal flow and after the fillet radius (one of the parameters that are varied in the Minitab design) there is an undercut to improve the metal flow in the upper part of the tappet (even this value is varied in the analysis).

The forming punch is added in SF as a deformable die, since its deformation influence the final shape of the tappet and performs a key role in the contact mesh on mesh with the workpiece.

The critical importance on the shape definition is reflected also in the meshing process: in the bi-dimensional "Advancing front quad" mesher with quad elements is used and in the three-dimensional one the mesher is "Tetmesh" with tetrahedral elements, in both cases the size is automatic. To improve the quality of the results two refinement boxes are added in both cases: one on the tip and another on the side near the bottom, therefore in all the places with high deformation and pressure involved, both refinement levels are set to 5.

The material is HSS steel, a typical tool steel with the "Friction" parameter set to 0.1 so as to mimic the friction developed between the forming punch and the other components.

4.3.1.3 Microtextured counterholder

The microtextured counterholder function is to accommodate the pressures of the workpiece and deform it without suffer much warp. The Creo CAD construction is straightforward, is formed as a simple cylinder.

It is added in SF as a deformable die since has to accommodate the pressure of the workpiece.

The mesher used are: "Advancing front quad" with quad elements for the bi-dimensional and "Tetmesh" with tetrahedral elements for the three-dimensional one, all the sizes are left automatic. In addition, a refinement box is added on the top in order to improve the definition of the deformations in the most relevant part to a factor of 5.

The material is again a HSS, a typical steel tool with friction factor set on 0.1.

4.3.1.4 Forming die, Intermediate reinforcement ring and Reinforcement ring

These 3 components share same function, geometry and settings. Their purpose is to contain the workpiece in its deformation and therefore their retention is critical, even a little warp and it will be reflected on the final part shape. Since are dies at high wear rate they are built using a modular scheme in order to reduce the quantity of

waste during every change. Using Creo they are modelled just revolving around their axis their rectangular profiles.

Since their deformation is critical in the workpiece's shape definition, are added in SF as deformable dies.

The meshing process is simple since they have all "Advancing front quad" with quad elements for bi-dimensional and "Tetmesh" with tetrahedral elements for the 3D one, all elements sizes are standard. No refinement boxes are needed except for the forming die that has a refinement box along the side in contact with the workpiece with 5 as refinement level.

The materials are: HSS steel for the forming die and the Intermediate reinforcement ring and X37CrMoV5-1 Steel for the Reinforcement ring in order to have additional stiffness in the external sides, all the friction parameters are set on 0.1.

4.3.1.5 Pressure plate

The pressure plate is needed only for the purpose of the simulation, since in the real life this component is non existing. It helps to spread the force of the press evenly on the whole forming punch in order to avoid simulation errors. Its creation on Creo consists in a flat cylinder.

It is added in SF as a "non deformable" die, since it has to be as stiff as possible to even the pressure and therefore has no mesh, material nor friction.

4.3.1.6 Upper constraint plane and Base constraint plane

As before, their function is needed only for the purpose of the simulation, they help to hold in place the set of external dies. They are modelled in Creo as simple cylinders.

They're added in SF as a "non deformable" die, since they have to be as stiff as possible and they don't have to move from their placement.

Therefore they have no mesh, material nor friction.

4.3.2 Sheet-bulk metal forming

The Sheet-bulk metal forming displacement of the dies is as presented in Figure 18.

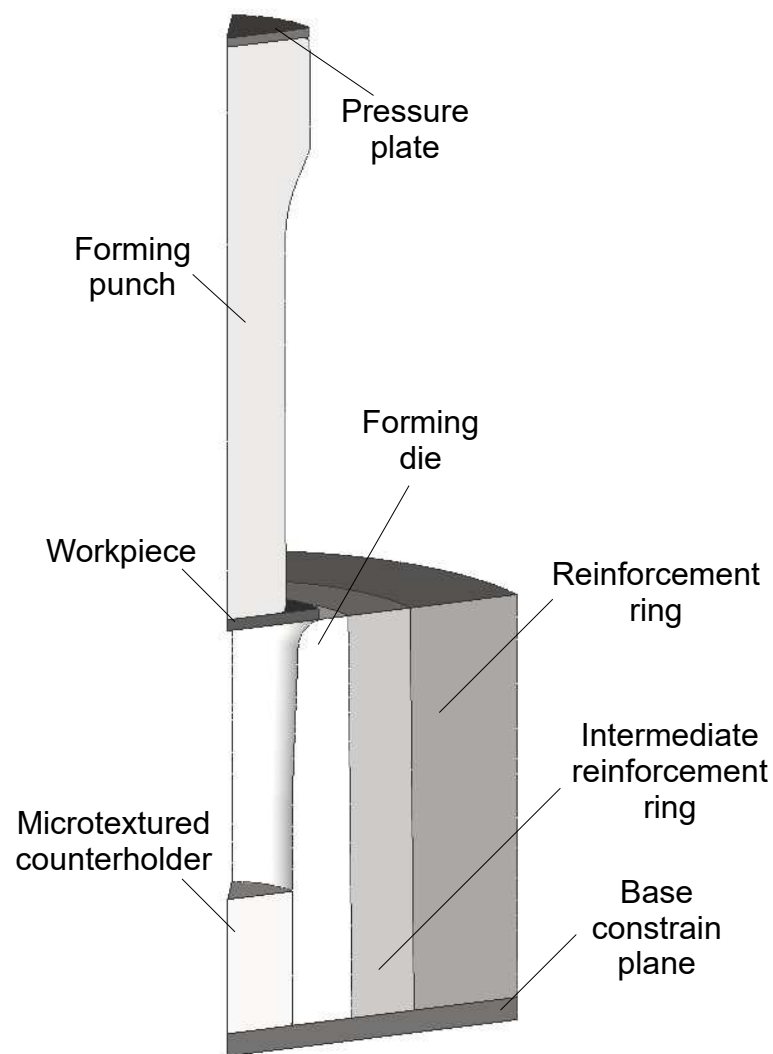


Figure 18: Sheet-Bulk metal forming model view

4.3.2.1 Workpiece

The workpiece is the starting material that after deformation became the final part. The modelling process is made in Creo Parametric and is a simple cylinder taking care that the initial volume is the same as in Bulk metal forming so that the two processes can be comparable in the final shape.

The part is added in SF as “workpiece” so as a deformable part.

The bi-dimensional mesher is “Quadtree” with quad elements of 0.2 mm size and the three-dimensional one is “Sheetmesh” with hexahedral elements still of 0.2 mm size.

The material is as with Bulk metal forming a 16MnCr5 steel with weaker Young’s modulus than dies’ ones, since it’s the workpiece there’s no need to specify a friction parameter.

4.3.2.2 Forming punch

The main function of this component is to compress the workpiece against the microtextured counterholder and the forming die in order to create the final part. The geometry created in Creo is simpler than the Bulk metal forming one because the undercut and the angle in the tip are not necessary, since the metal flow is much lower. The tip is flat instead. It's created as outlined above from the revolving of its profile, the only main feature that differentiates from a cylinder is the fillet radius (feature that is altered in the Minitab study) on the tip.

The CAD is eventually added in SF as deformable die connected to the pressure plate.

Since it is a key part in the definition of the final shape, the mesh has particular importance, it's created with "Advancing front quad" mesher using quad elements with automatic elements size as far as bi-dimensional simulation is concerned, for the three-dimensional one, instead, "Tetmesh" is used with tetrahedral elements with automatic size. To increase the accuracy of the mesh, two refinement boxes are placed in the regions of maximum stress: one is in the tip in the contact surface with the workpiece and the second is on the side, because as soon as the metal is deformed it starts to get in contact in that area with the forming punch.

As almost all the other tools even the forming punch is made out of HSS steel with friction factor set on 0.1.

4.3.2.3 Microtextured counterholder

As in the Bulk metal forming, the microtextured counterholder is key in contain the deformation pressure on the workpiece. The geometry is equal to the BMF one, it's modelled in Creo as a cylinder.

Once it's added in SF it's recognized as deformable die in order to account for the unavoidable warping due to the extreme forces involved.

The meshing process is comparable to as seen before: "Advancing front quad" with quad shape and automatic elements size for the bi-dimensional and "Tetmesh" with tetrahedral type and automatic size for the three-dimensional one. Fundamental is the refinement box positioned on the top of the tool, with a refinement factor of 5, in order to account for the little deviations during the forming process.

The material is still HSS steel with friction factor of 0.1.

4.3.2.4 Forming die, Intermediate reinforcement ring and Reinforcement ring

As in the Bulk metal forming these three components share the same function, which is to contain the expansion of the workpiece during the forming process. The modelling process in Creo of Intermediate reinforcement ring and Reinforcement ring are simply two cylinders meanwhile the forming die is made through the revolution of its profile. Its two features are the fillet radius on the top, to facilitate the bending of the metal sheet, and the lean angle on the internal side of the forming die, useful to

make the bulking phase of the process less sudden, both these parameters are varied in the Minitab study.

All three dies are added in SF as deformable die, in order to account for their deformation, that influences the final part's shape, and their wear.

The meshing process is straightforward for Intermediate reinforcement ring and Reinforcement ring: "Advancing front quad" with quad shape and automatic elements size for the bi-dimensional and "Tetmesh" with tetrahedral type and automatic size for the three-dimensional one. For the forming die, instead, the mesher, shape and element size are the same but with two refinement boxes positioned in the most stressed regions: on the top of the forming die to account for the pressure in the bending phase and another on the internal profile, in order to improve the quality of the final result of the bulking process, both boxes have refinement factor of 5.

Unlike Bulk metal forming, the chosen material is always the same: HSS steel with a friction factor of 0.1.

4.3.2.5 Pressure plate

This component is needed only for the purpose of the simulation, since it's only needed to spread the force of the press evenly on the whole forming punch in order to avoid simulation errors. Its creation on Creo consists in a flat cylinder.

It's added in SF as a "non deformable" die, since it has to be as stiff as possible to even the pressure and therefore has no mesh, material nor friction.

4.3.2.6 Base constraint plane

As mentioned beforehand, it's function is needed only for the purpose of the simulation, it helps to hold in place the set of external dies. it's modelled in Creo as a simple cylinder.

It's added in SF as a "non deformable" die, since they have to be as stiff as possible and it doesn't have to move.

Therefore it has no mesh, material nor friction.

5 Results

5.1 2D vs 3D comparison

In the following chapter all the results, of the comparison between the 60 degrees cut three-dimensional model and the bi-dimensional one, are presented in order to verify if the assumptions made in the simplification are acceptable.

5.1.1 Shape comparison

The first comparison is the shape of the profile of the final part (after tools release). The profiles are exported from SF in .igs format where all the nodes are expressed as coordinates sets and afterwards copied in a .csv file, through the use of a script, to be represented and compared in Excel.

For the bi-dimensional simulation the profile is acquired with the use of a cutting plane: the bi-dimensional results is expanded to a 60 degrees chunk and then cut with a plane in the middle. Since the expansion is simply the repetition of the initial results, the cutting plane is positioned randomly inside the expansion.

For the three-dimensional one, the profile is acquired positioning the cutting place in the central region taking care that the chosen profile is representative of the results.

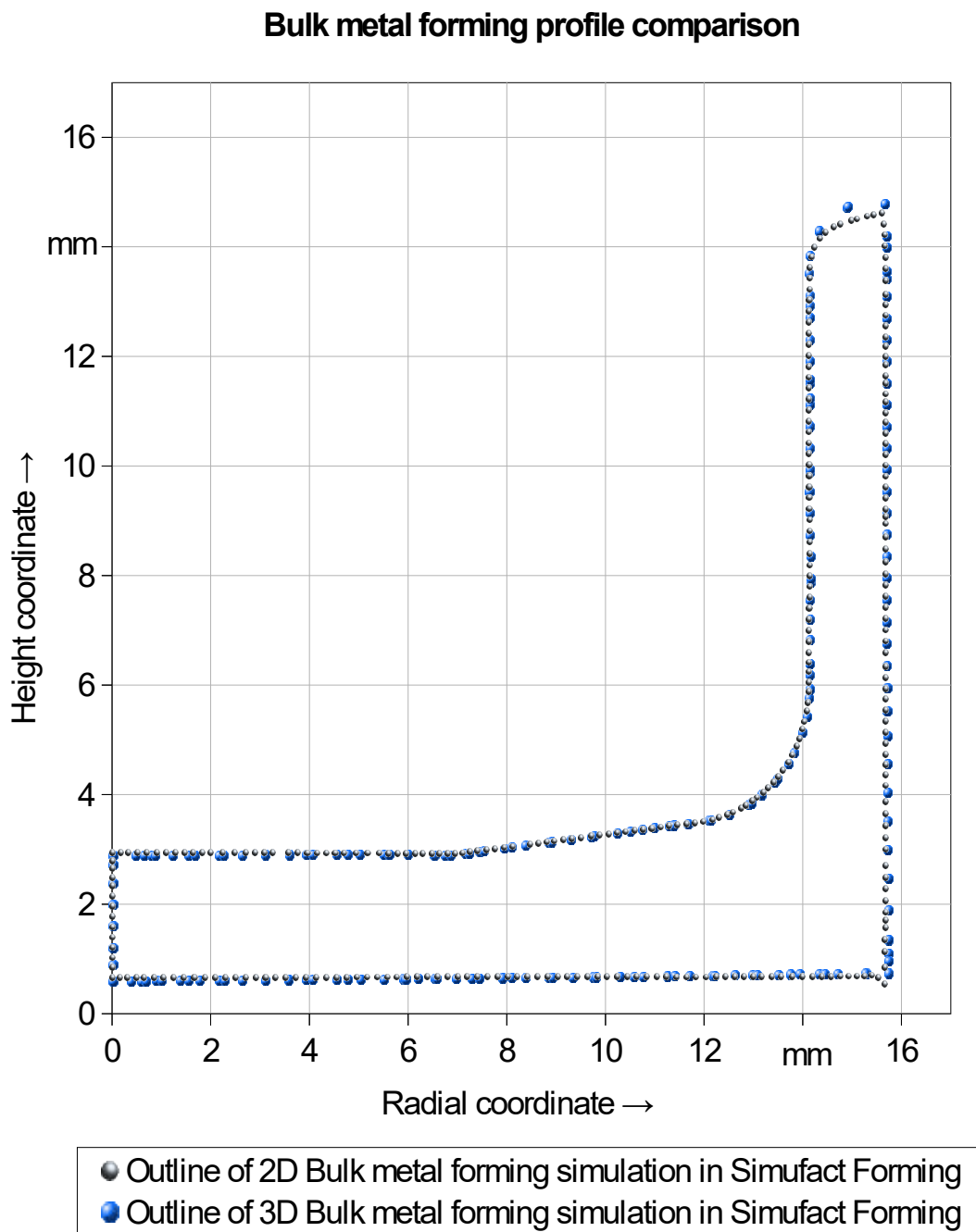


Figure 19: Bulk metal forming profile comparison 2D vs 3D

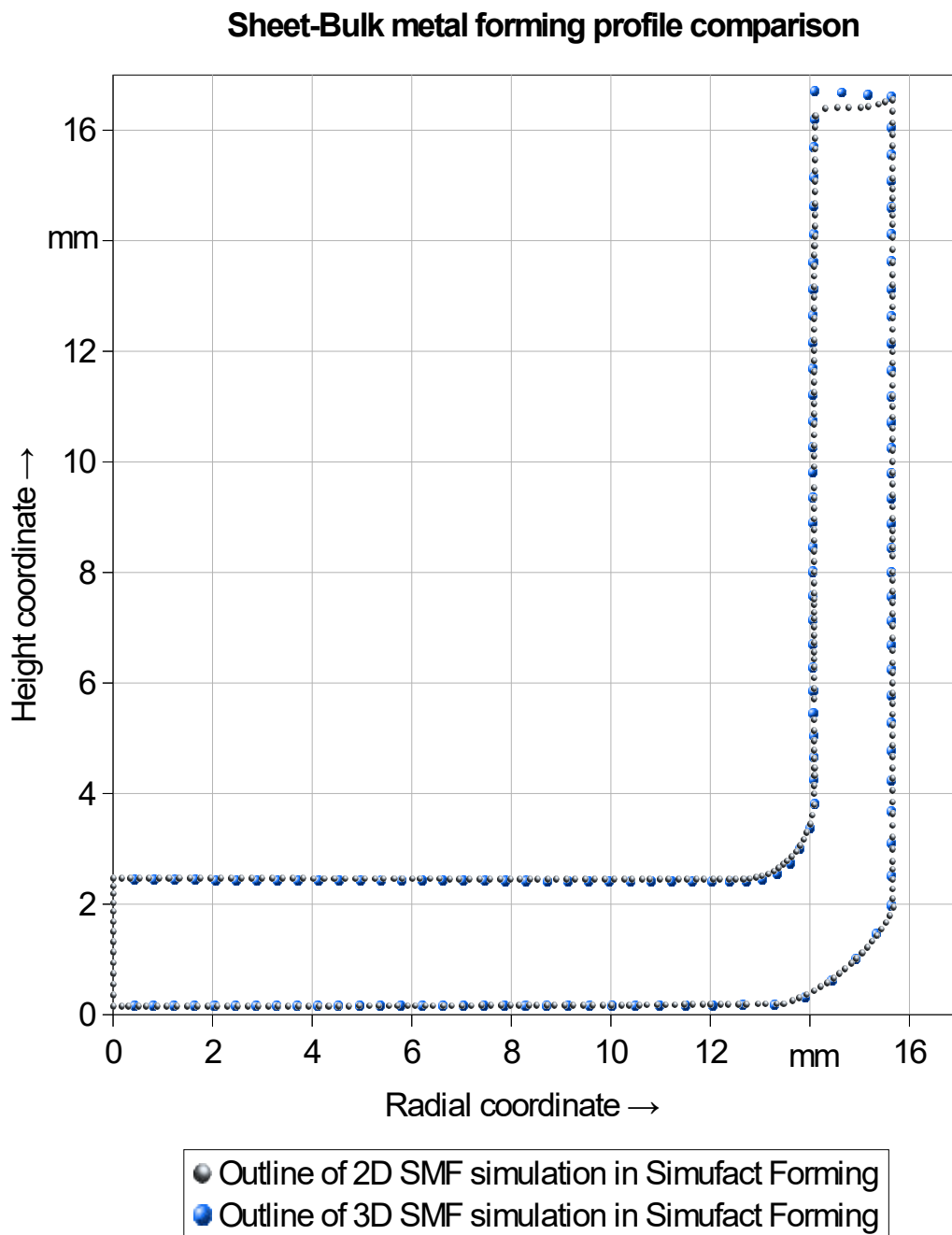


Figure 20: Sheet-Bulk metal forming profile comparison 2D vs 3D

5.1.2 Force-stroke curve comparison

Once the final result is compared, to have a shallow view of the internal stresses is useful to compare the force-stroke curve of the two simulations.

The data is simply exported from SF in .csv format, taking care to select “stroke” as the second variable, and then visualized in Excel for a better comparison weight.

Bulk metal forming Force-Stroke curve comparison

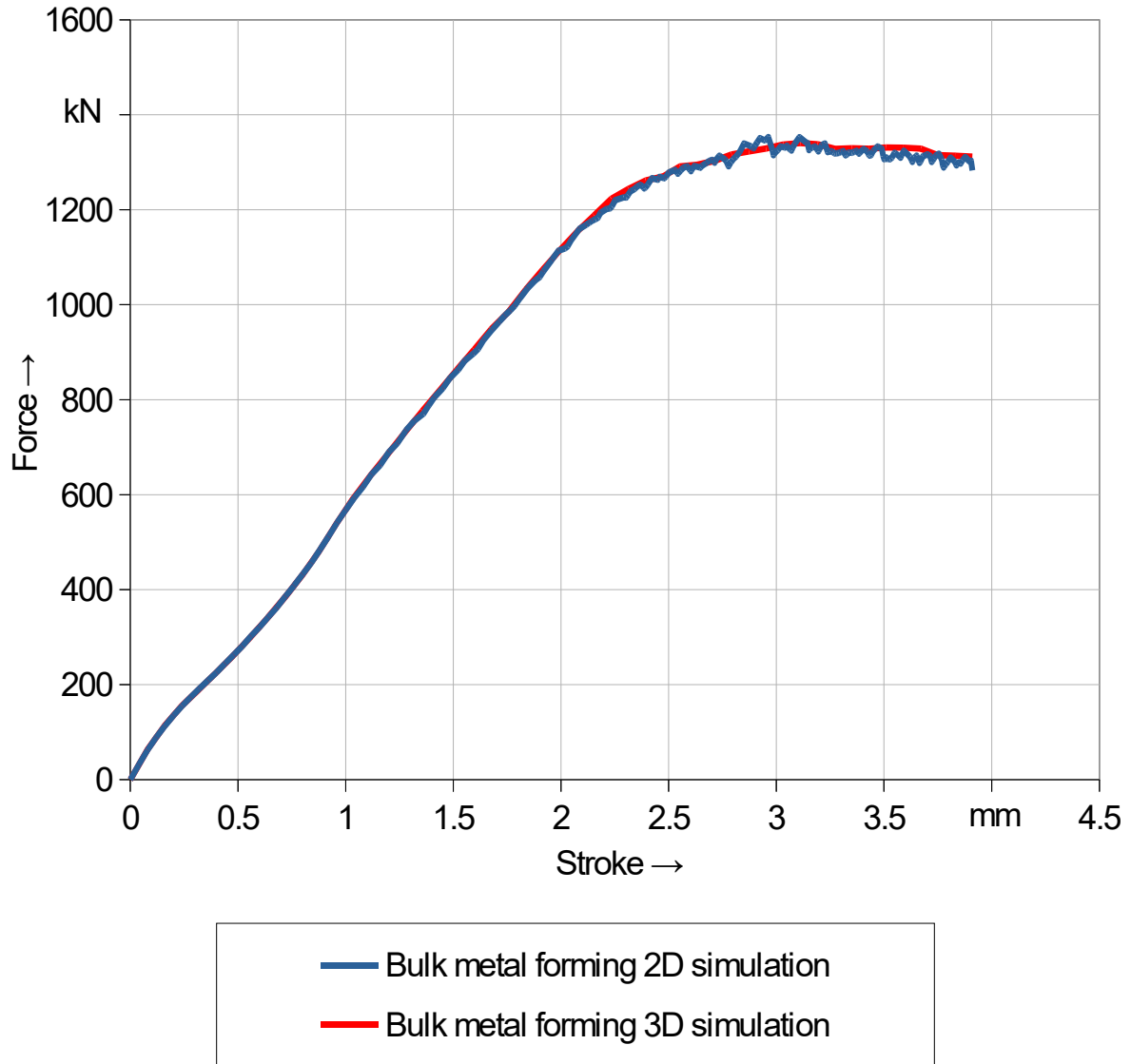


Figure 21: Bulk metal forming force-stroke curve comparison 2D vs 3D

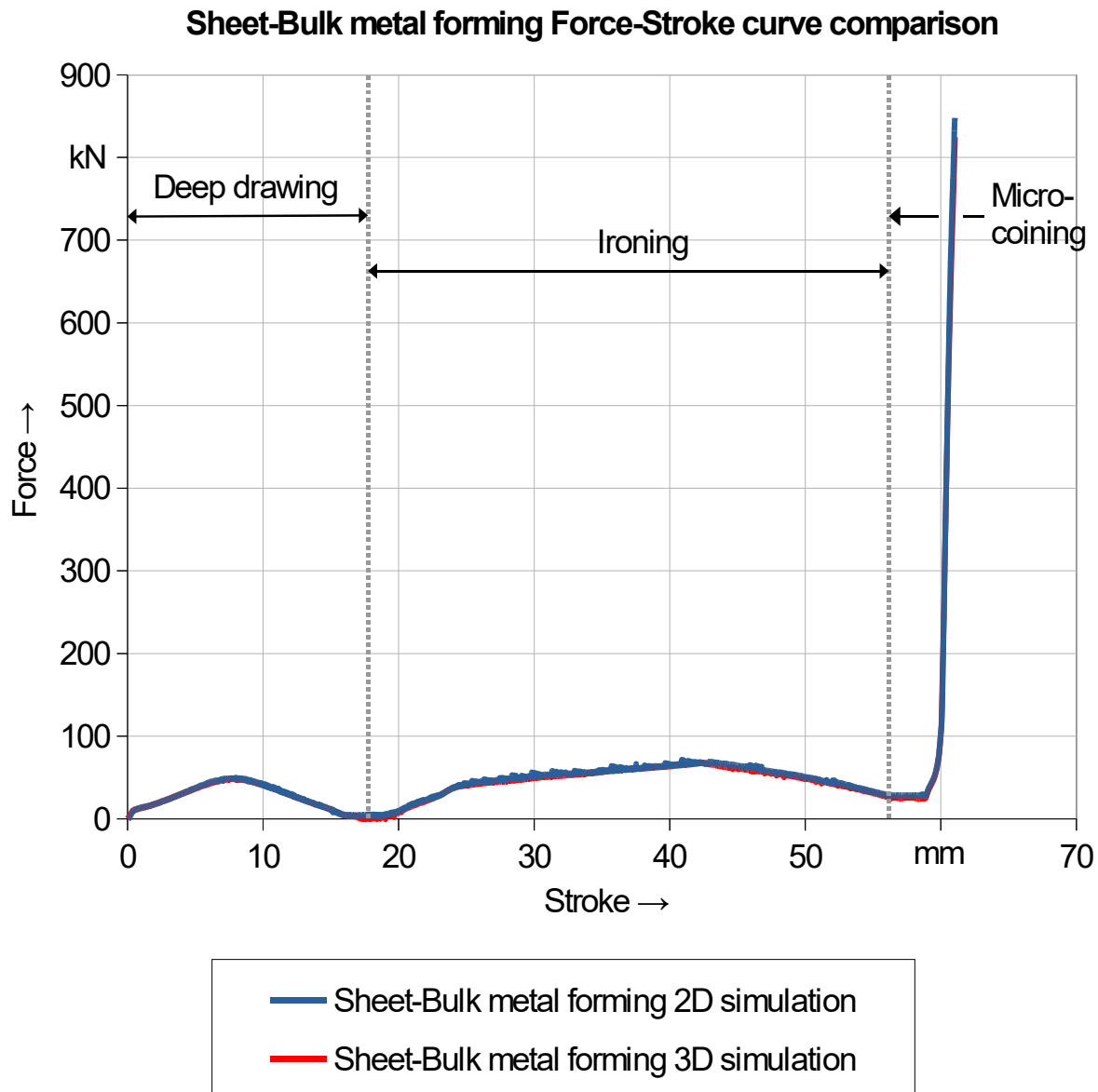


Figure 22: Sheet-Bulk metal forming force-stroke curve comparison 2D vs 3D

5.1.3 Effective plastic strain comparison

In addition to the previous quantitative analysis, it's important to evaluate the stress distribution inside the final part. Unfortunately it's really difficult to examine the distribution without extensive evaluation, therefore to have a qualitative view of the situation is interesting to compare the "effective plastic strain" distribution graphs of the final part. The graphs have all the same scale and the expansion of the bi-dimensional it's only the repetition multiple times of the 2D graph.

5.1.3.1 Bulk metal forming

In the following images are displayed the differences of the effective plastic strain distribution in the expansion and in the profile.

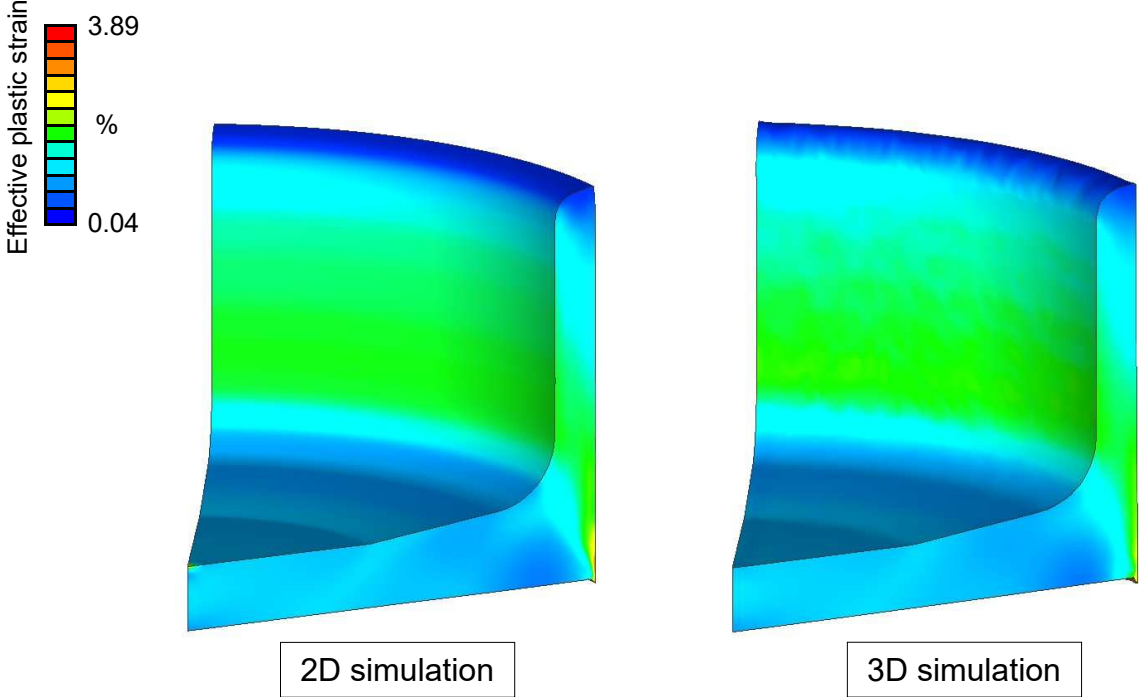


Figure 23: Bulk metal forming expansion 60 degree effective plastic strain comparison 2D vs 3D

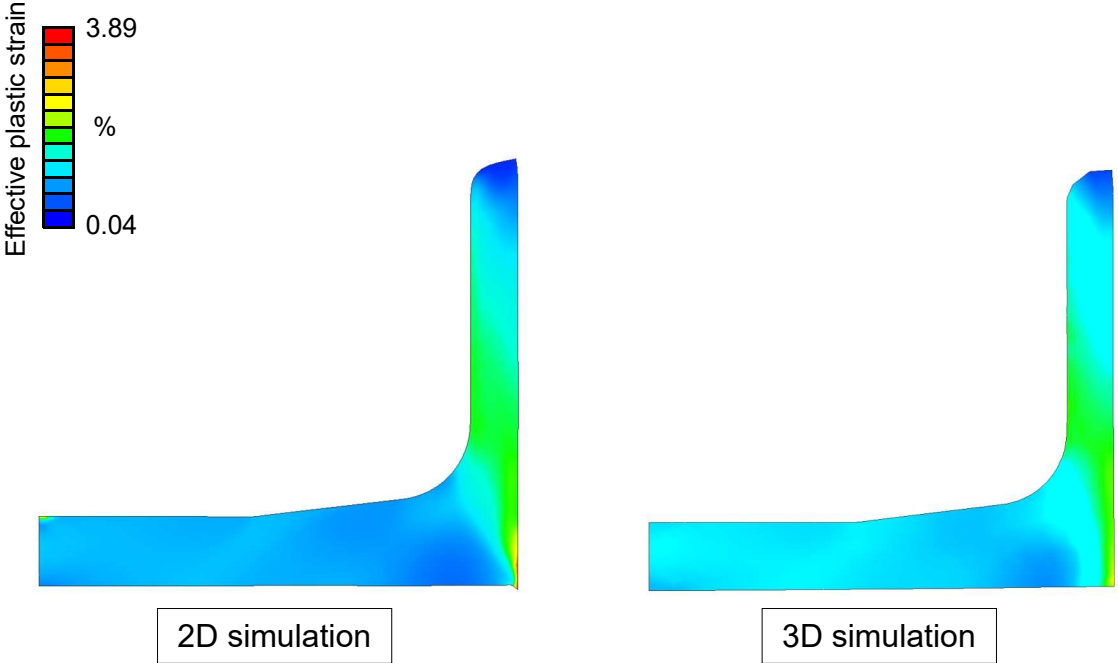


Figure 24: Bulk metal forming profile effective plastic strain comparison 2D vs 3D

5.1.3.2 Sheet-bulk metal forming

In the following images are displayed the differences of the effective plastic strain distribution in the expansion and in the profile.

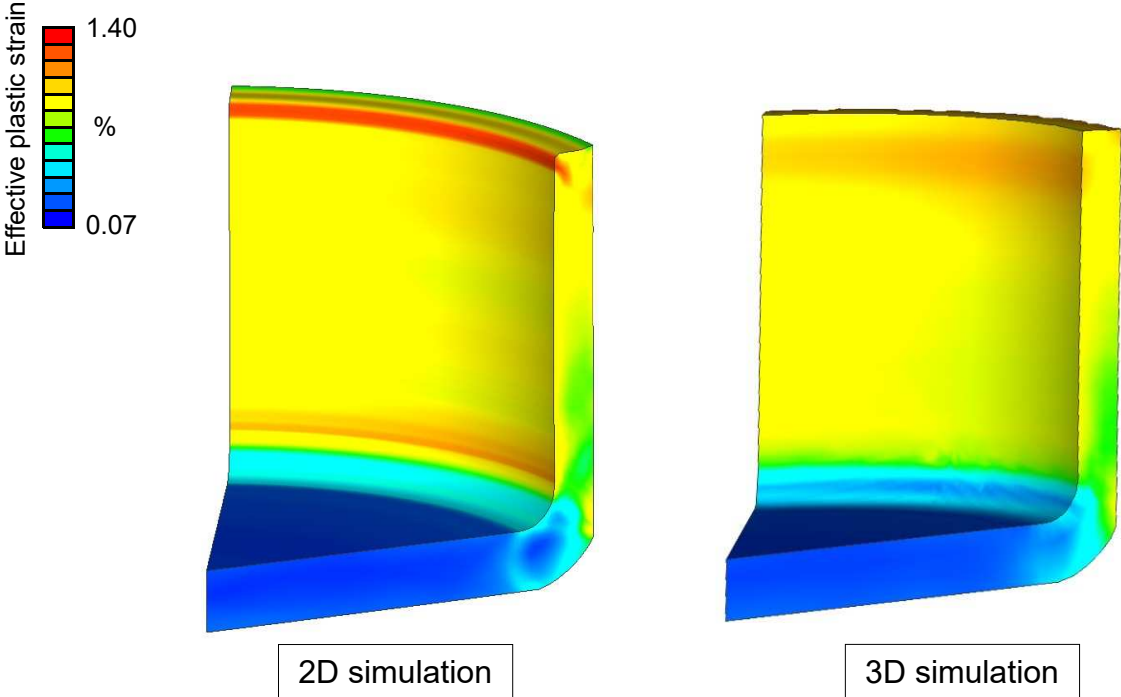


Figure 25: Sheet-Bulk metal forming expansion 60 degree effective plastic strain comparison 2D vs 3D

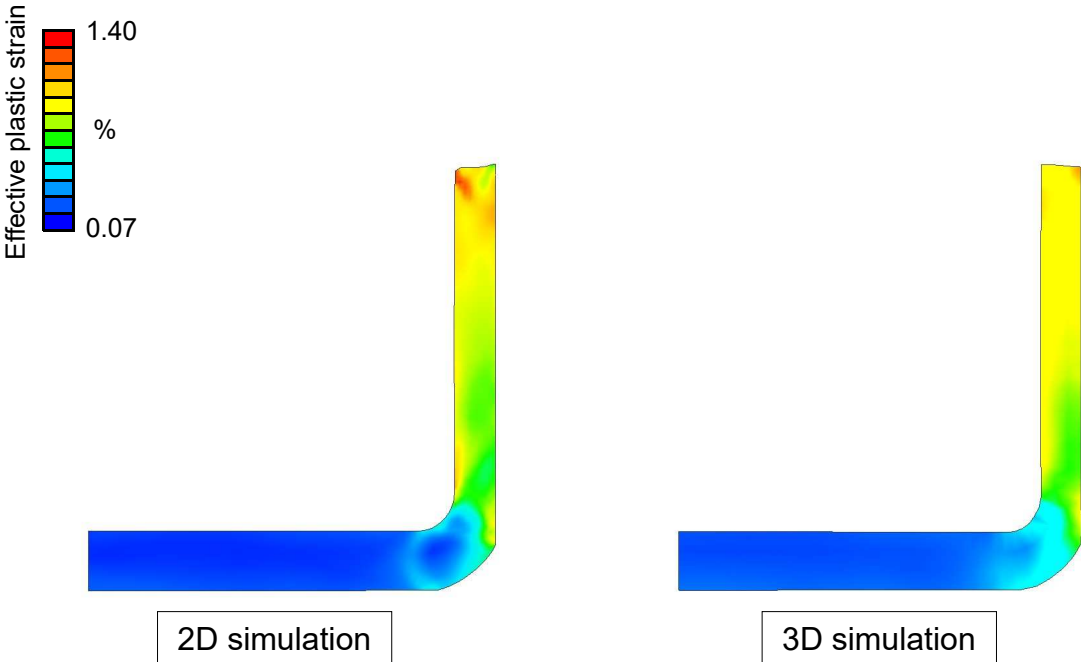


Figure 26: Sheet-Bulk metal forming profile effective plastic strain comparison 2D vs 3D

5.2 Tools stress investigation

After assuring that the bi-dimensional simulation is an acceptable approximation, the real analysis starts. It consists in the choice and variation of some parameters in the CAD to then generate multiple versions of the model and afterwards recording the changes in the results. All these results are then imported in Minitab in a full-factorial DOE to be processed and find any correlations between inputs and outputs.

5.2.1 Parameters choice

The parameters to vary are chosen based on their influence on the final stress configuration. Therefore are usually fillet radius, angles that influences the deformation speed and press speed.

5.2.1.1 Sheet-bulk metal forming

In the Sheet-bulk metal forming process four parameters are chosen: 3 features and the press speed.

The first parameter is the forming punch fillet radius, it is chosen because it may influence the speed and the pace at which the workpiece is formed in the first section. It's located on the forming punch's tip as shown in figure.

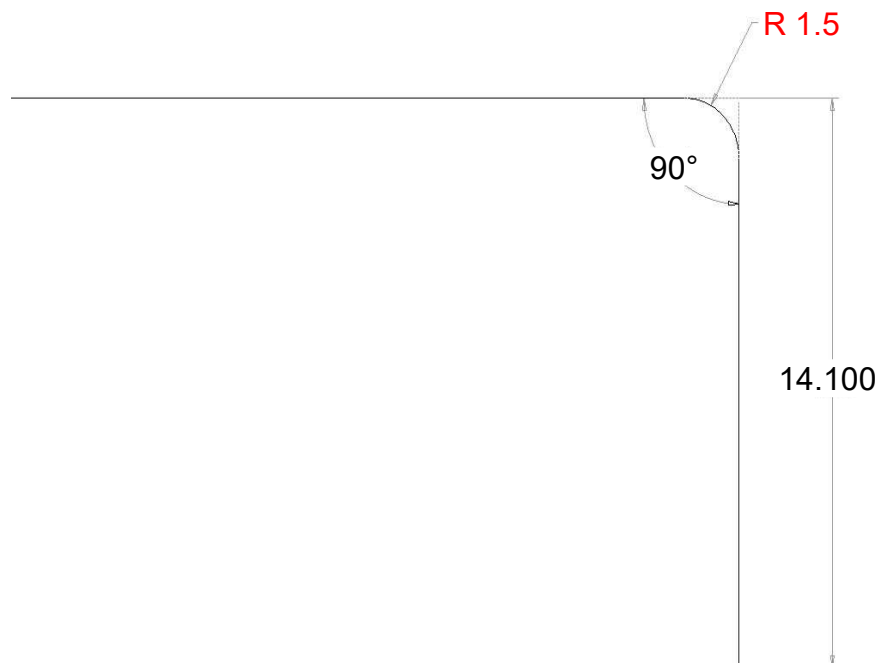


Figure 27: Creo Parametric sketch of the forming punch fillet radius in Sheet-bulk metal forming

In addition, the parameter's range of variation is chosen based on its initial value and identifying a plausible range based on geometry and previous knowledge.

The second parameter is the forming die fillet radius because as before it influences the deformation speed, the smaller the radius, the faster it is. It's located in the forming die top as visible in the following figure. The parameter range is chosen as before.

Finally the last parameter is the forming die lean angle, it influences the speed of the bulking part of the deformation, since it reduces the thickness of the tappet's walls. The steep is the forming die's wall, and therefore the smaller is the angle, the gentler is the deformation and the other way around, influencing the hardening process naturally occurring. The parameter range is chosen as before.

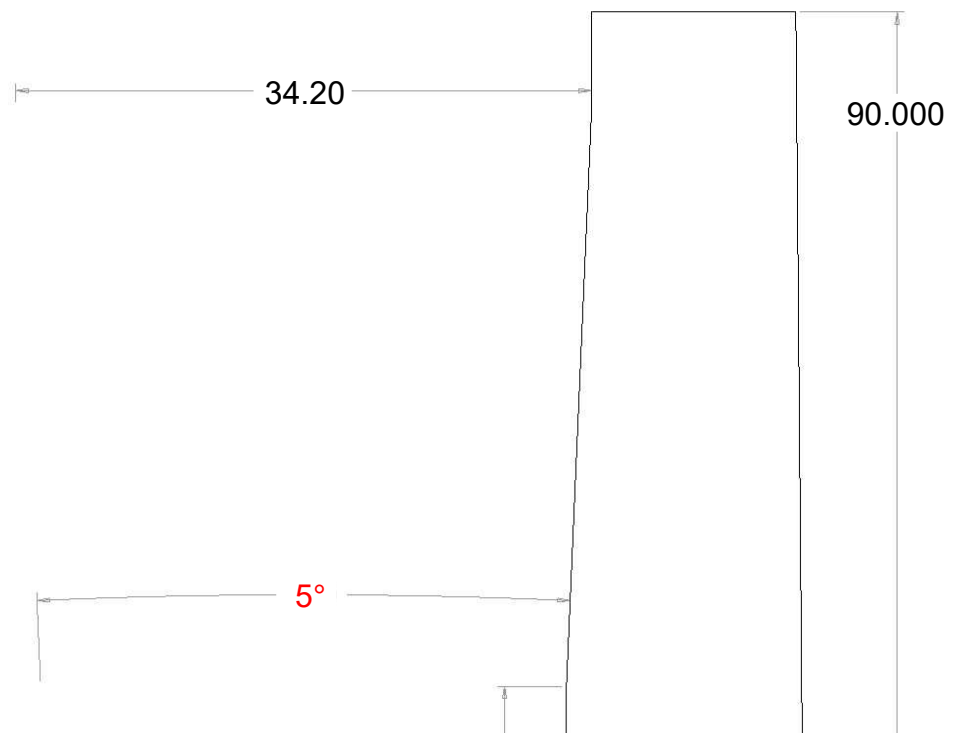


Figure 28: Creo Parametric sketch of the forming die lean angle in Sheet-bulk metal forming

5.2.1.2 Bulk metal forming

In the Bulk metal forming process three parameters are chosen: 2 features and the press speed.

The first parameter is the forming punch fillet radius. The reasons and the location are the same as the SMF as visible in the figure.

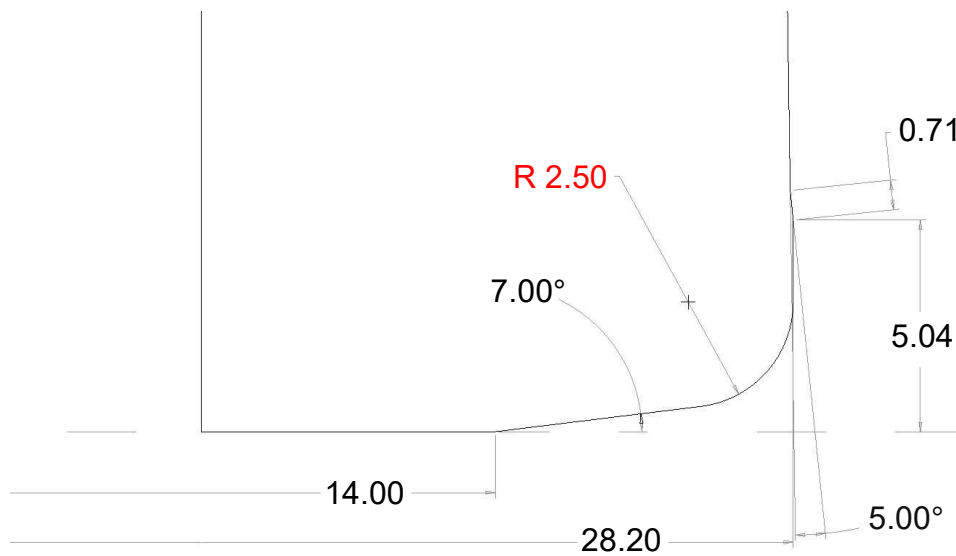


Figure 29: Creo Parametric sketch of the forming punch fillet radius in Bulk metal forming

The second parameter is the undercut angle. It influences the ease with which the material flows on the walls region and therefore determining their tensional state. It's located in the tip of the forming punch as visible in the figure.

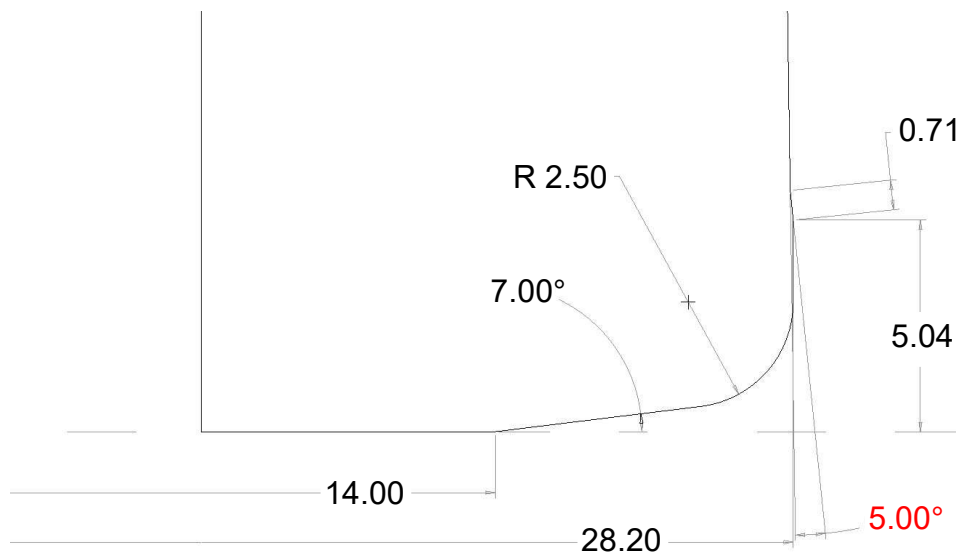


Figure 30: Creo Parametric sketch of the undercut angle in Bulk metal forming

5.2.2 Full-factorial DOE design setup

After the choice of the parameters and their range of variation, a full-factorial DOE can be set up.

5.2.2.1 Sheet-bulk metal forming

For simulation time reasons, since 4 variables are present, a three levels study results impossible to conduct for the extensive number of simulations required, therefore only 2 values for each parameters are used: the upper and lower limit.

Subsequently the 2 levels design is initiated and the variables with their ranges entered, Minitab output the whole list of simulations to conduct in order to complete the study as presented in the following table.

Simulation number	Punch fillet radius	Die fillet radius	Die lean angle	Press speed
1	1	1	5	5
2	4	1	5	5
3	1	6	5	5
4	4	6	5	5
5	1	1	20	5
6	4	1	20	5
7	1	6	20	5
8	4	6	20	5
9	1	1	5	20
10	4	1	5	20
11	1	6	5	20
12	4	6	5	20
13	1	1	20	20
14	4	1	20	20
15	1	6	20	20
16	4	6	20	20

5.2.2.2 Bulk metal forming

For the BMF, since the variables are only three, a three levels study is feasible: lower limit, upper limit and mean value.

Therefore design is initiated and the variables with their ranges entered, Minitab output the whole list of simulations to conduct in order to complete the study as presented in the following table.

Simulation number	Fillet forming punch radius [mm]	Undercut angle [deg]	Press speed [mm/s]
1	1	2	5
2	1	2	12.5
3	1	2	20
4	1	5	5
5	1	5	12.5
6	1	5	20
7	1	8	5
8	1	8	12.5
9	1	8	20
10	2.5	2	5
11	2.5	2	12.5
12	2.5	2	20
13	2.5	5	5
14	2.5	5	12.5
15	2.5	5	20
16	2.5	8	5
17	2.5	8	12.5
18	2.5	8	20
19	4	2	5
20	4	2	12.5
21	4	2	20
22	4	5	5
23	4	5	12.5
24	4	5	20
25	4	8	5
26	4	8	12.5
27	4	8	20

5.2.3 Minitab results

Once all the simulations are conducted and the value all the data of the maximum of “Equivalent stress”, “Maximum principal stress” and “Minimum principal stress” are collected from the results, usually all the values are in the final forming phases but it’s important to analyse the whole process. Those values are collected for forming punch, forming die and microtextured counterholder, in order to have a clear view of the tools stresses.

After Minitab has processed all those data, it outputs a set of graphs that describes the correlation between the stresses and the variation of the chosen parameters.

Below are shown the plots of the main effect of all the three parameters collected from the results by the three tools related to the features variations.

5.2.3.1 Sheet-bulk metal forming

In the following pages are presented main effect plots of the maximum equivalent stress, maximum principal stress and minimum principal stress as the punch fillet radius, die fillet radius, die lean angle and press speed change. The readings of the values are conducted for the three main Sheet-bulk metal forming tools: forming punch, forming die and microtextured counterholder.

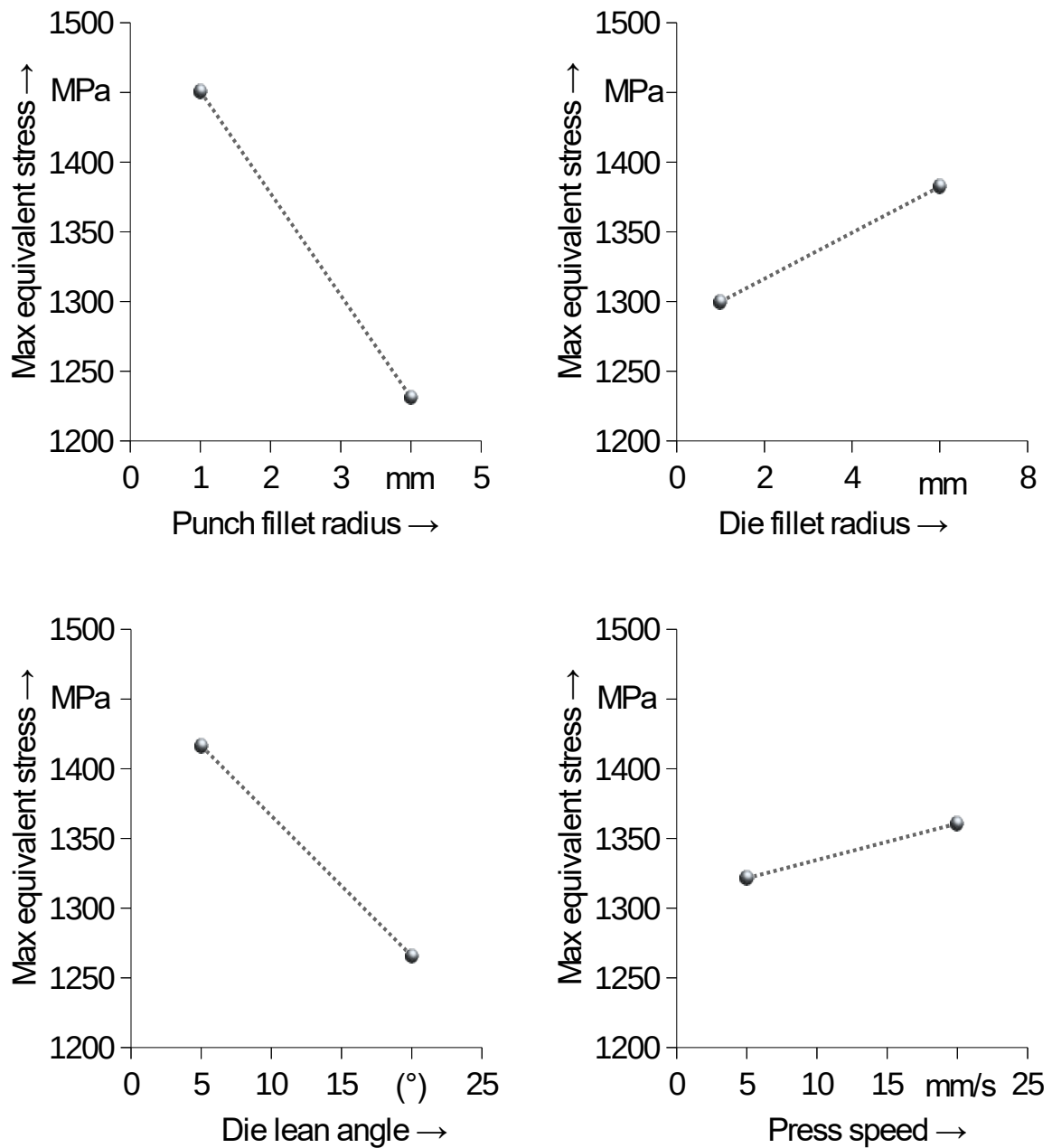
Forming punch

Figure 31: Main effect plot for the maximum equivalent stress on the Forming Punch

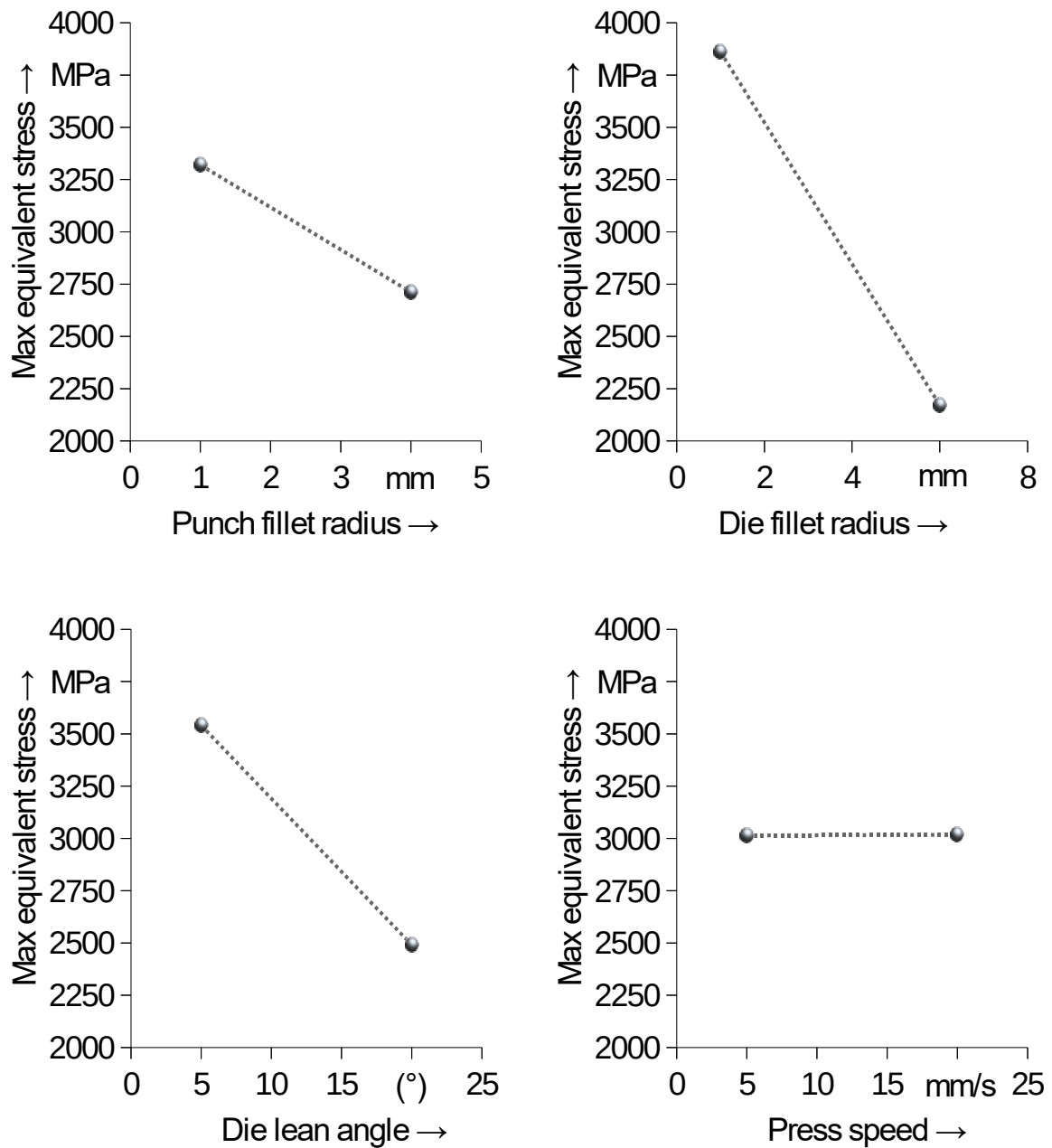
Forming die

Figure 32: Main effect plot for the maximum equivalent stress on the Forming Die

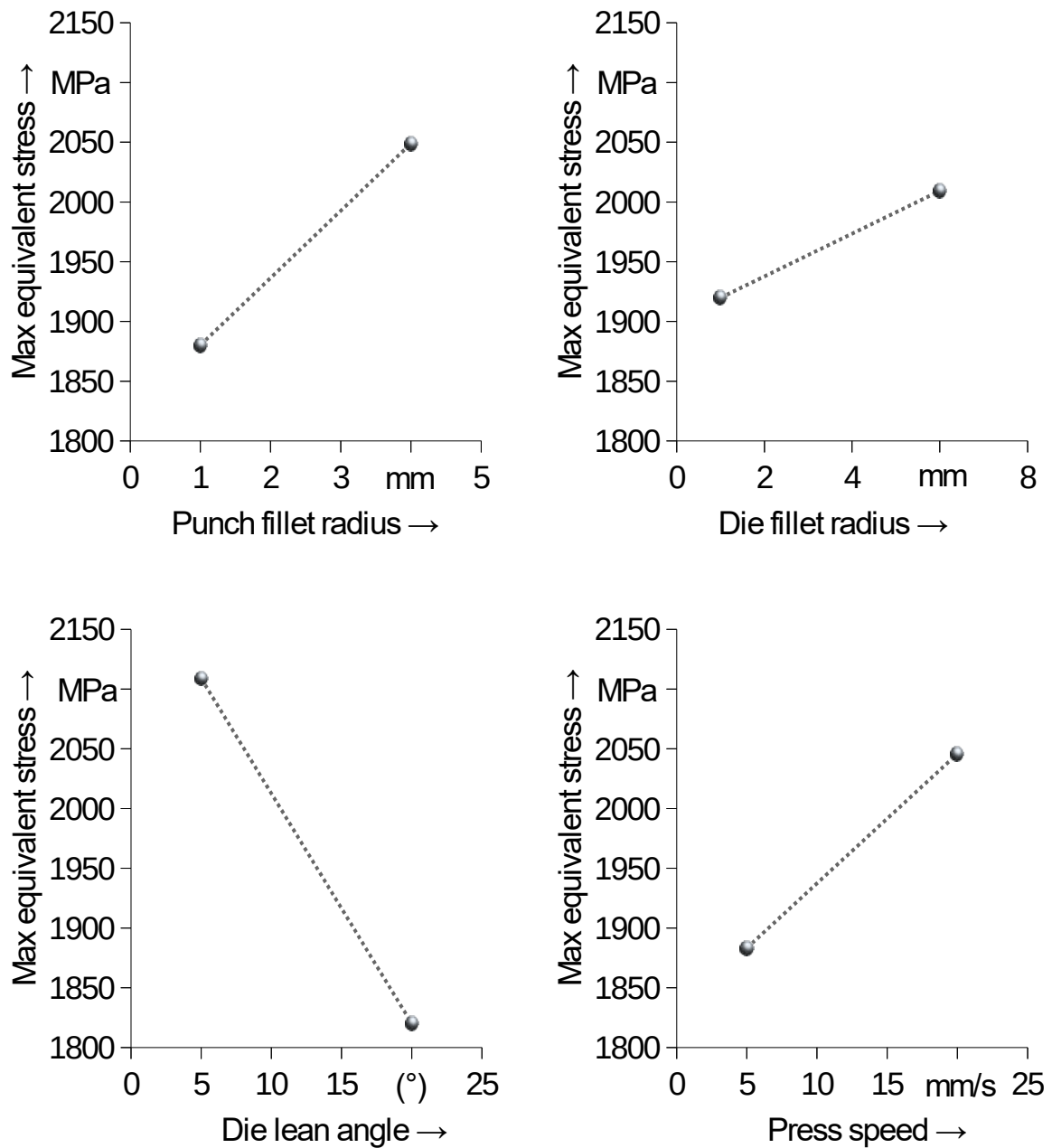
Microtextured counterholder

Figure 33: Main effect plot for the maximum equivalent stress on the Microtextured Counterholder

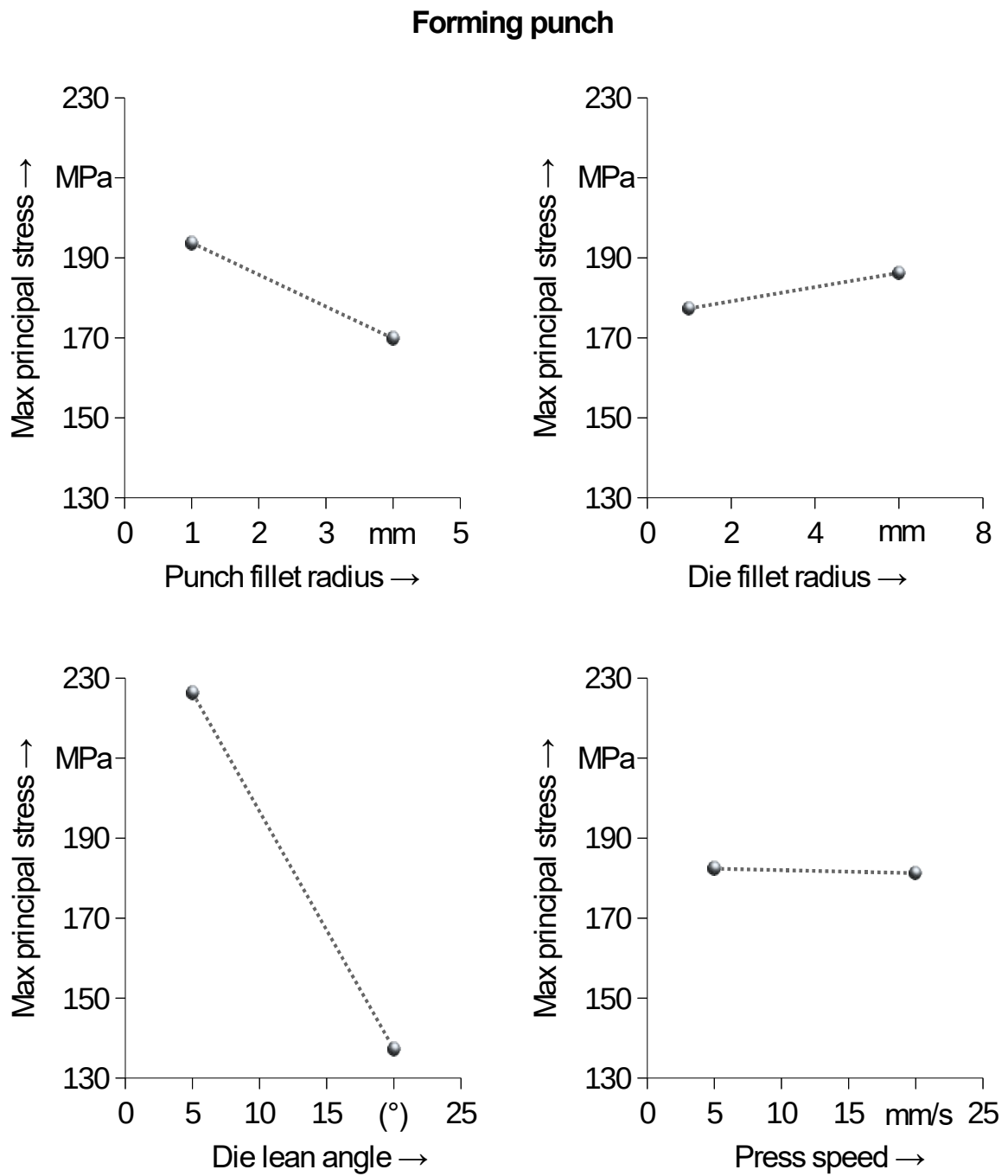


Figure 34: Main effect plot for the maximum principal stress on the Forming Punch

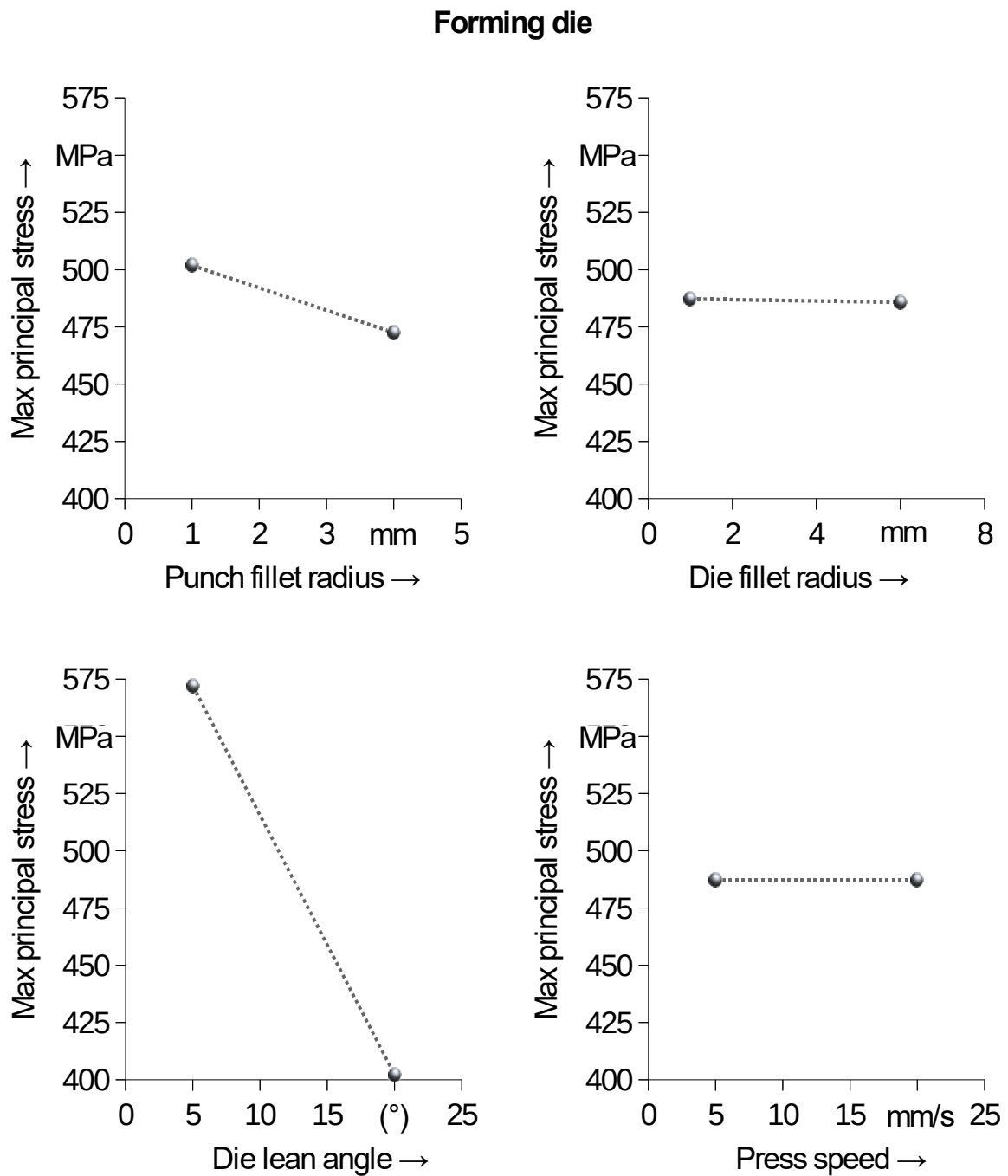


Figure 35: Main effect plot for the maximum principal stress on the Forming Die

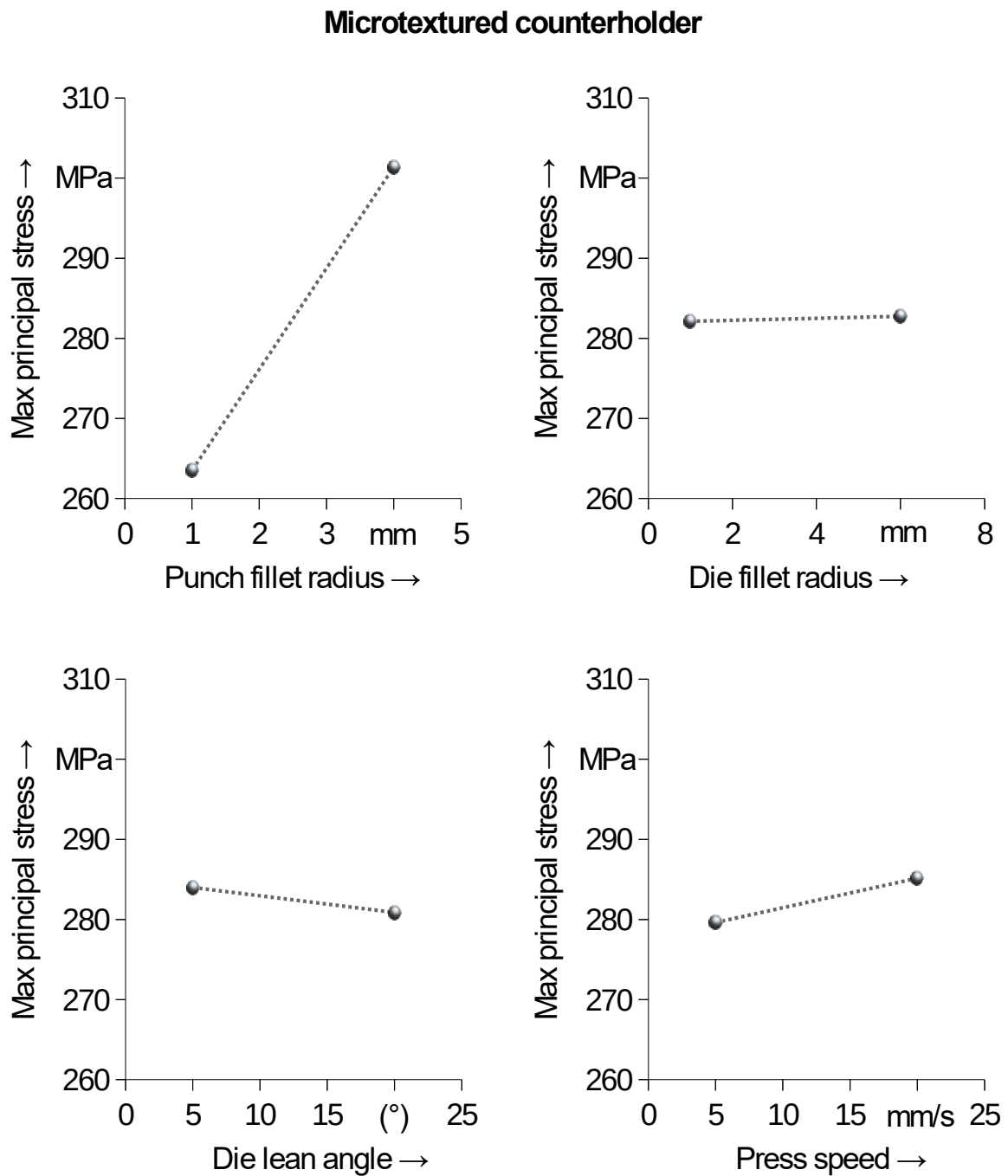


Figure 36: Main effect plot for the maximum principal stress on the Microtextured Counterholder

Forming punch

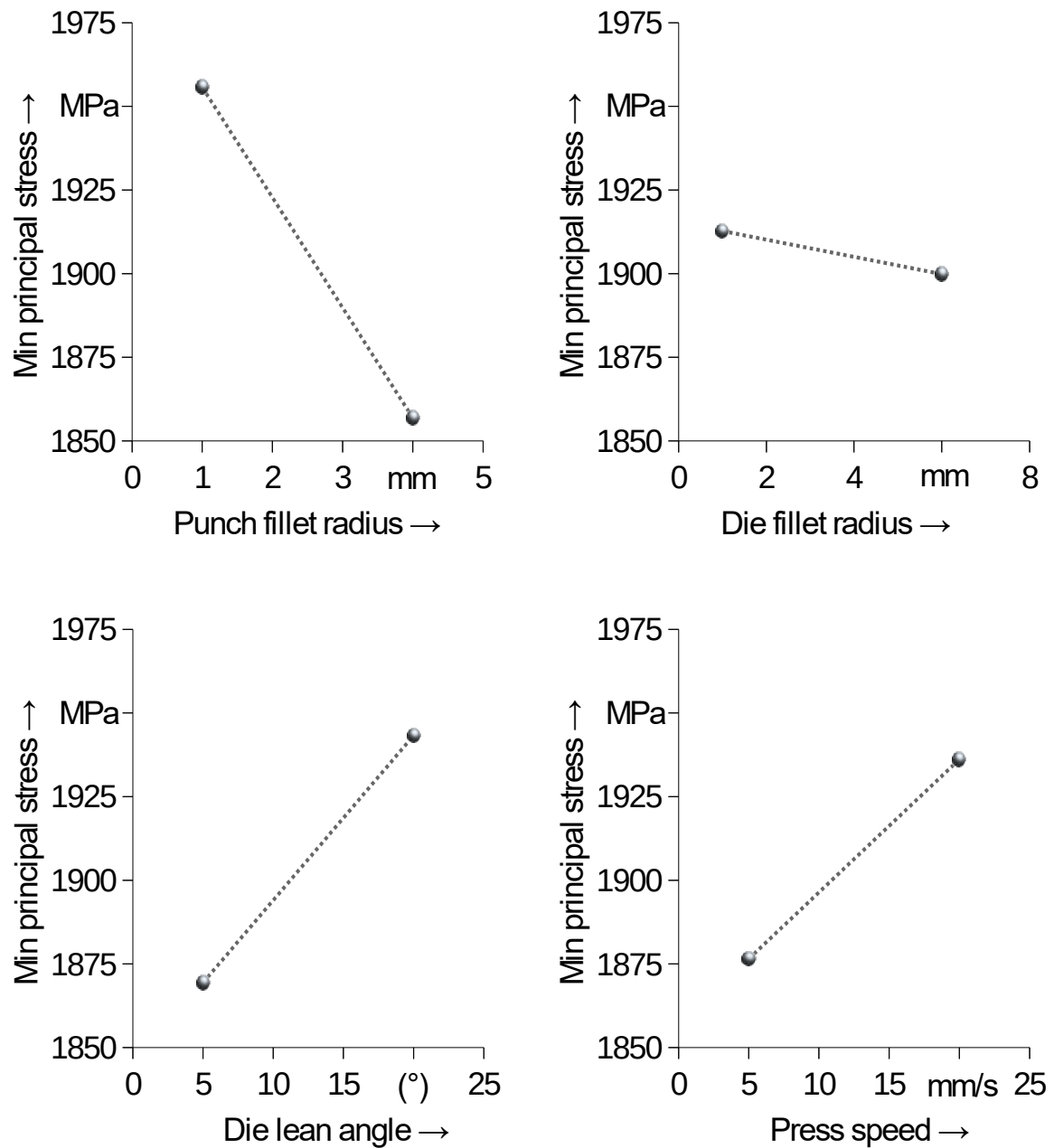


Figure 37: Main effect plot for the minimum principal stress on the Forming Punch

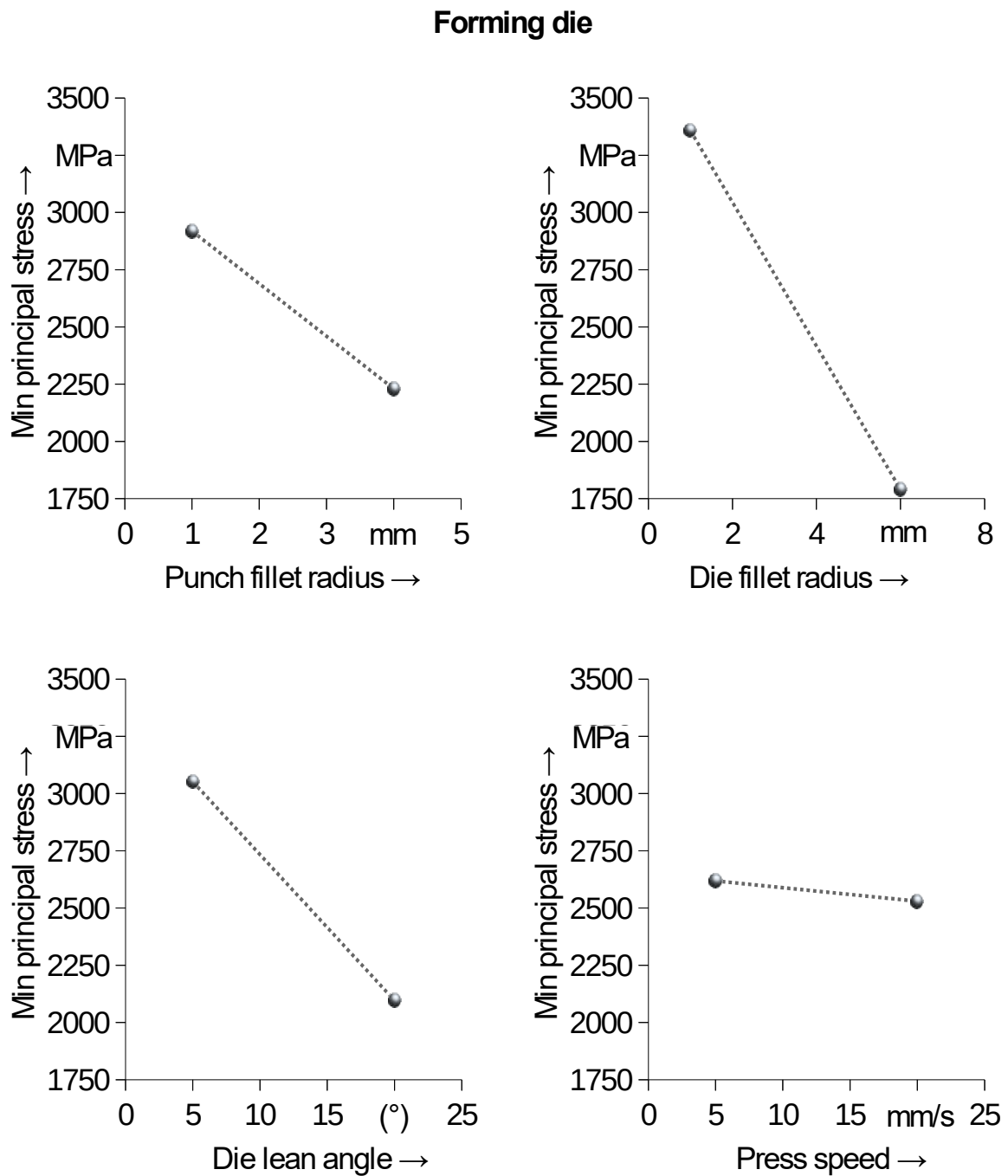


Figure 38: Main effect plot for the minimum principal stress on the Forming Die

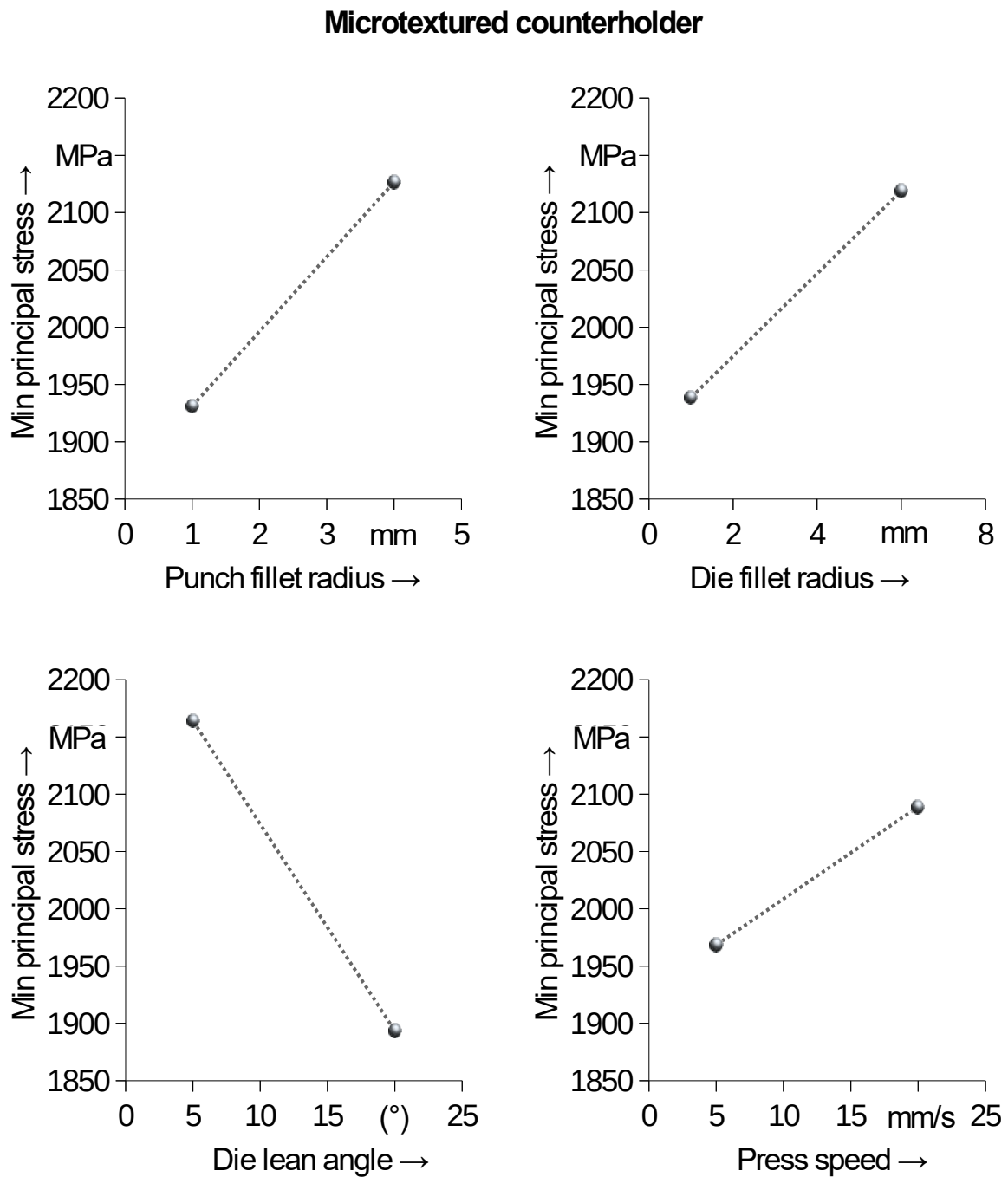


Figure 39: Main effect plot for the minimum principal stress on the Microtextured Counterholder

5.2.3.2 Bulk metal forming

In the following pages are presented main effect plots of the maximum equivalent stress, maximum principal stress and minimum principal stress as the punch fillet

radius, undercut angle and press speed change. The readings of the values are conducted for the three main BMF tools: forming punch, forming die and microtextured counterholder.

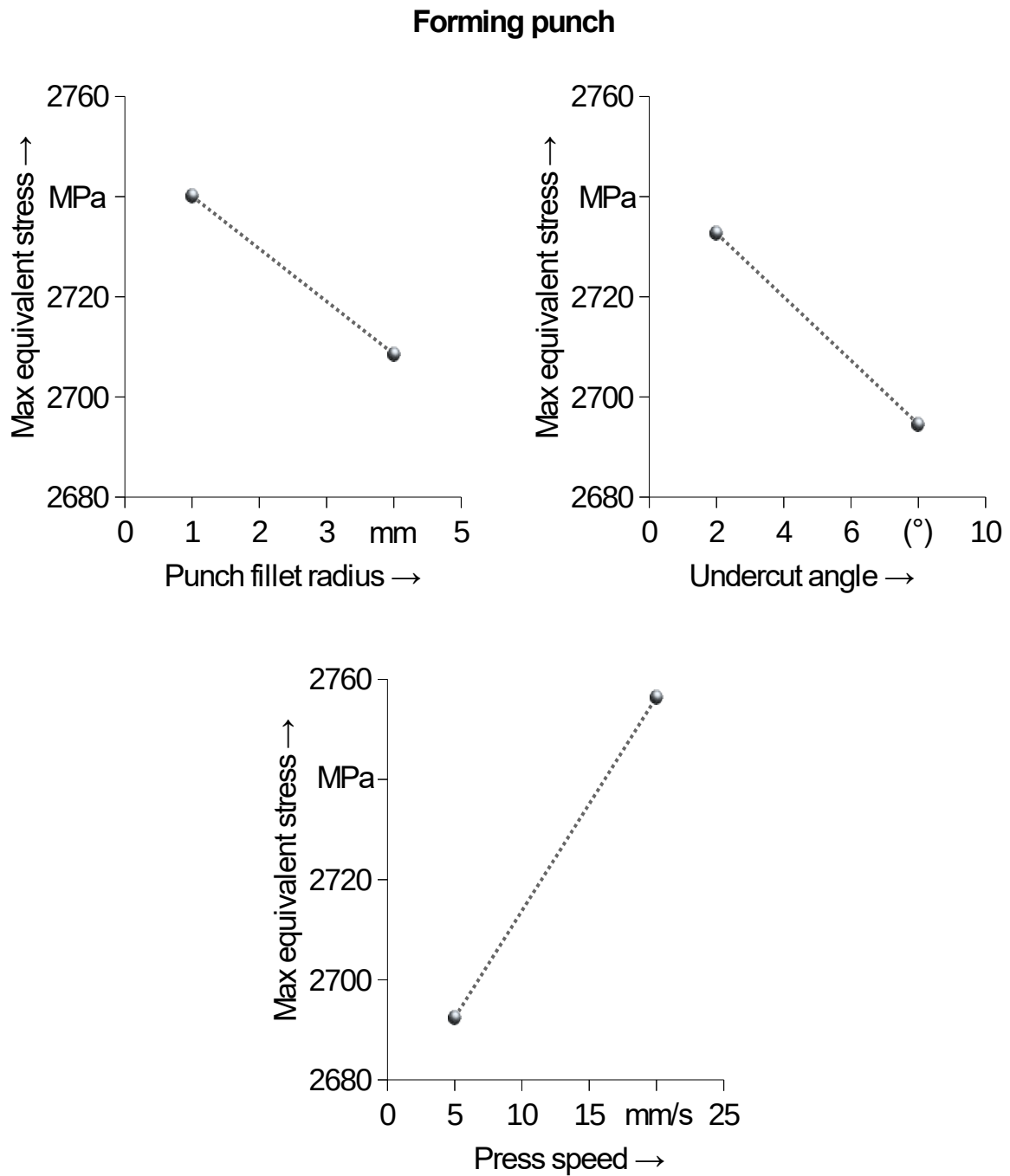


Figure 40: Main effect plot for the maximum equivalent stress on the Forming Punch

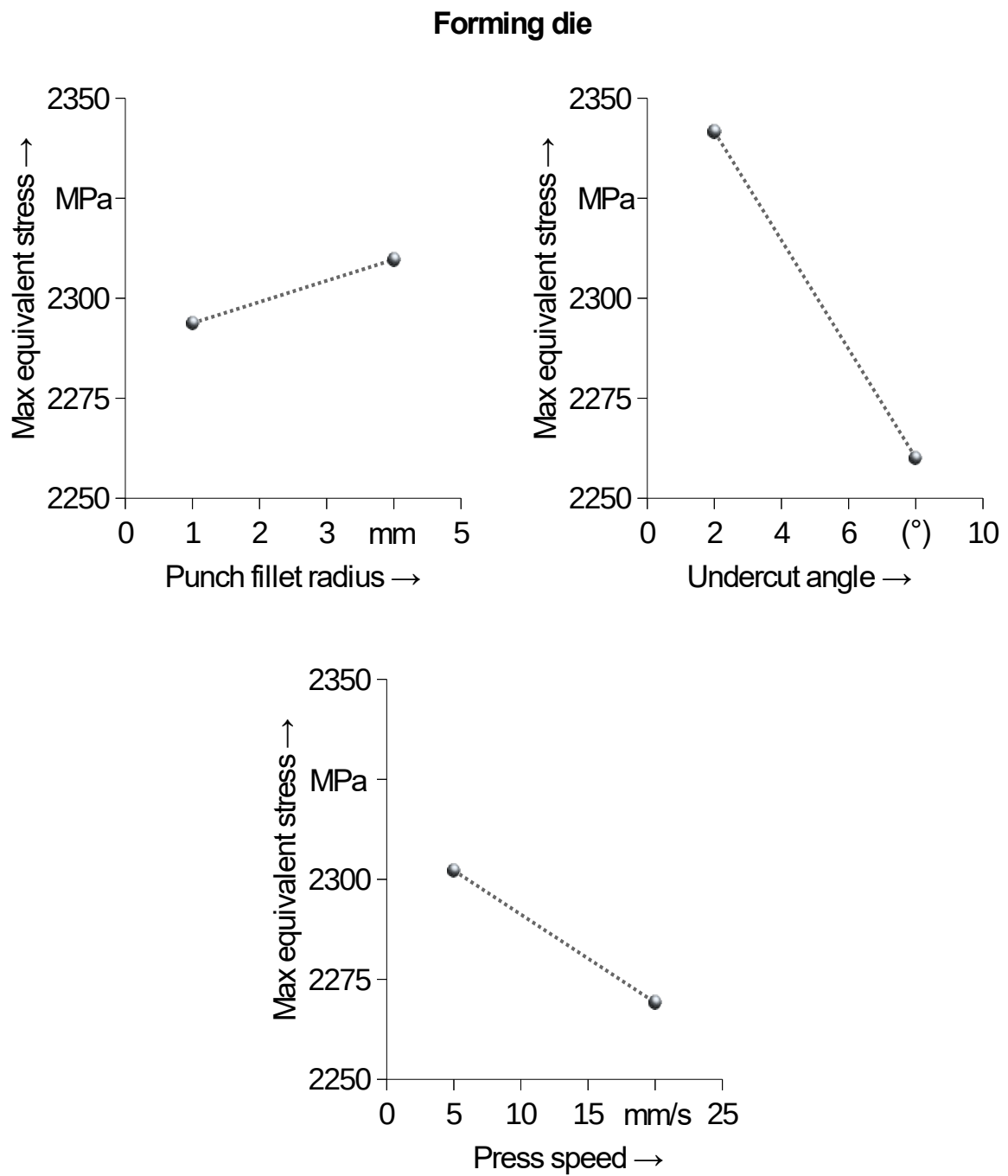


Figure 41: Main effect plot for the maximum equivalent stress on the Forming Die

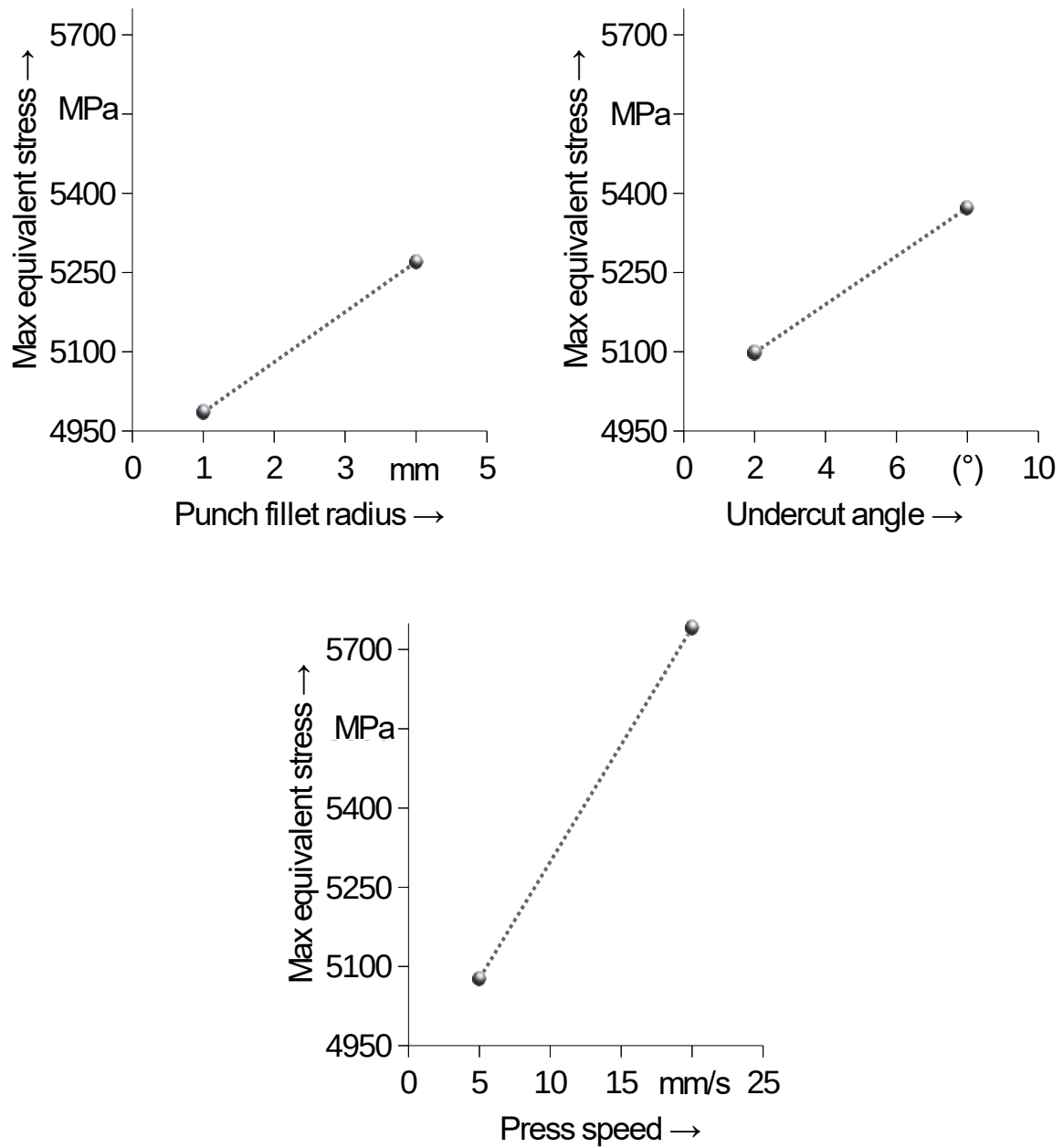
Microtextured counterholder

Figure 42: Main effect plot for the maximum equivalent stress on the Microtextured Counterholder

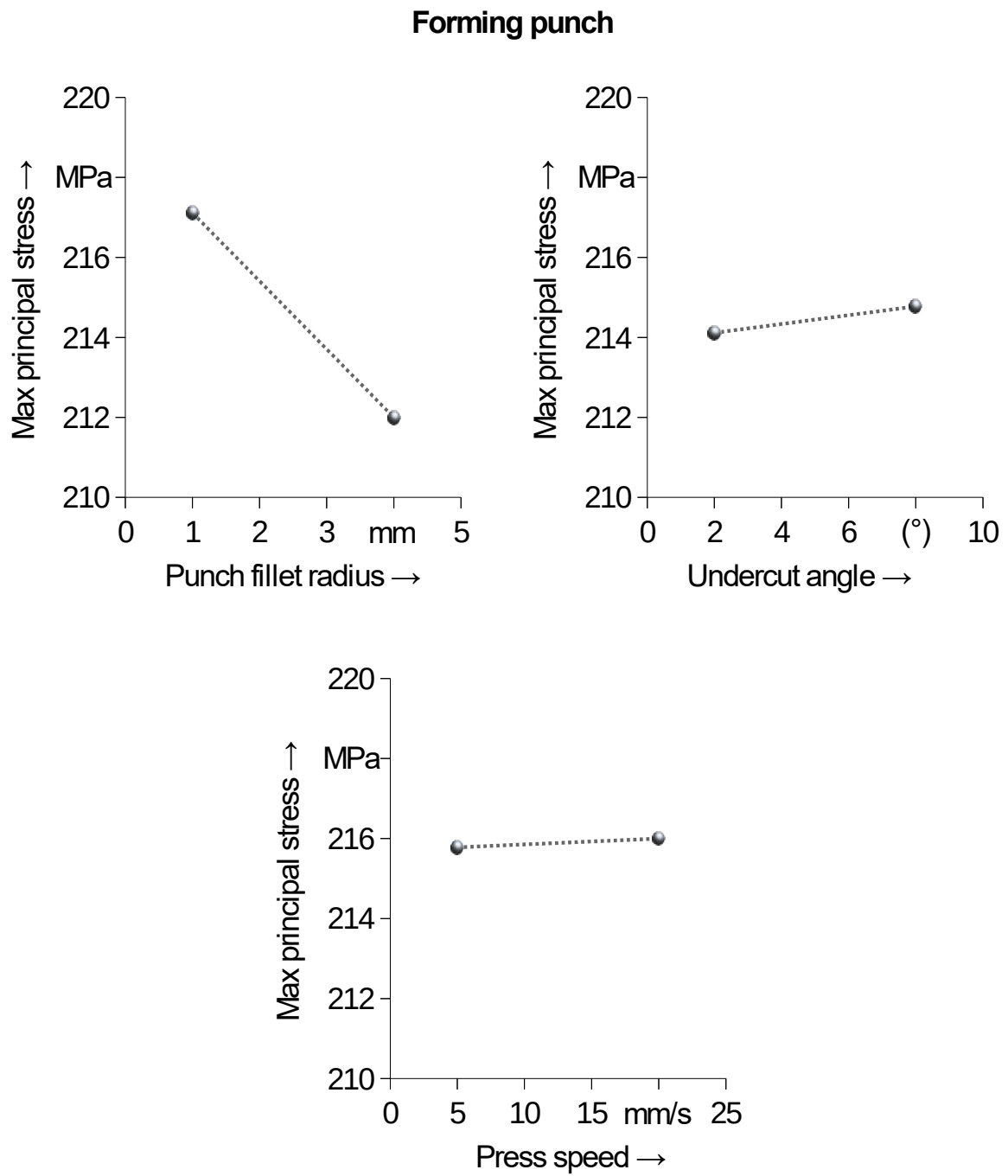


Figure 43: Main effect plot for the maximum principal stress on the Forming Punch

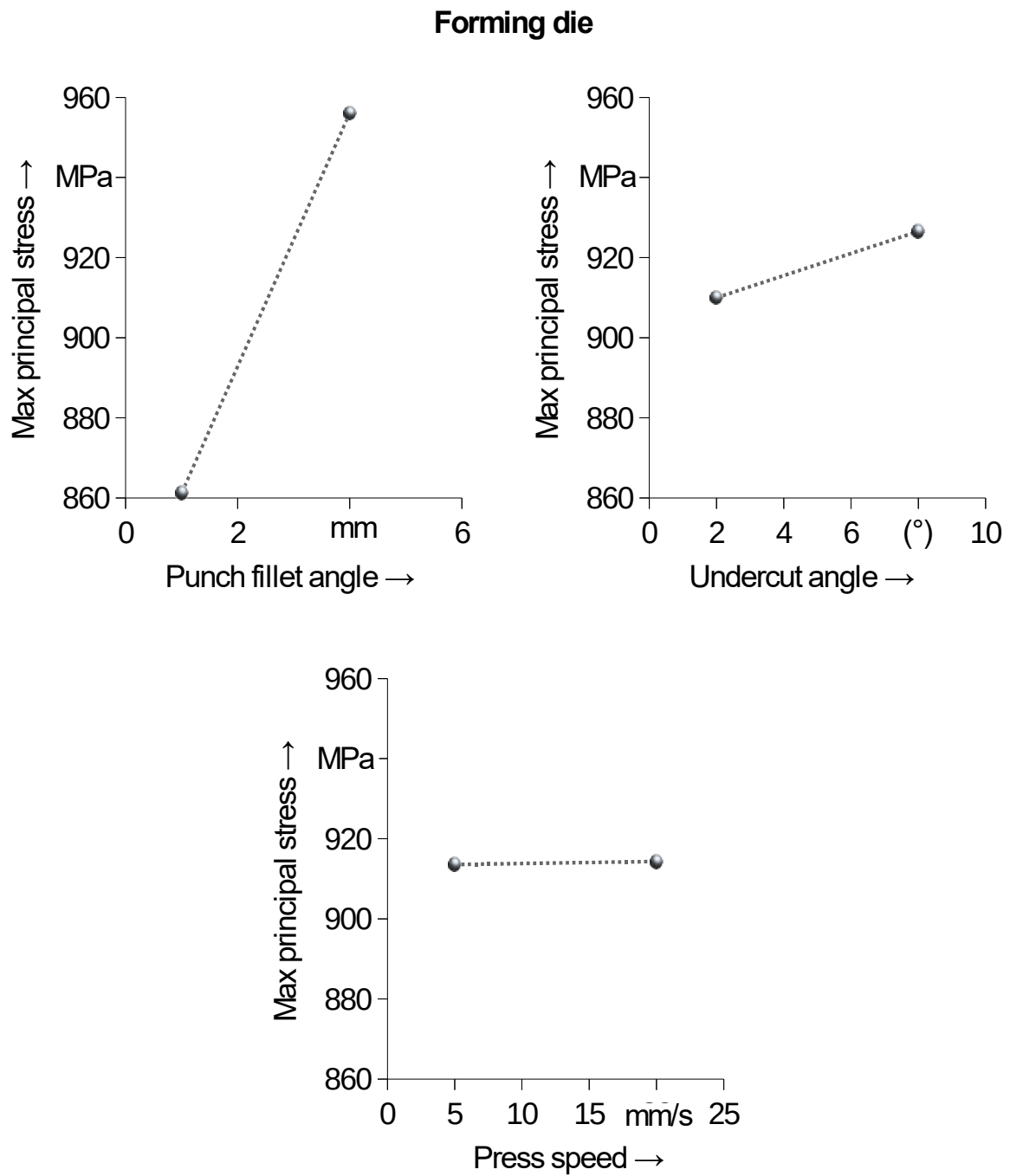


Figure 44: Main effect plot for the maximum principal stress on the Forming Die

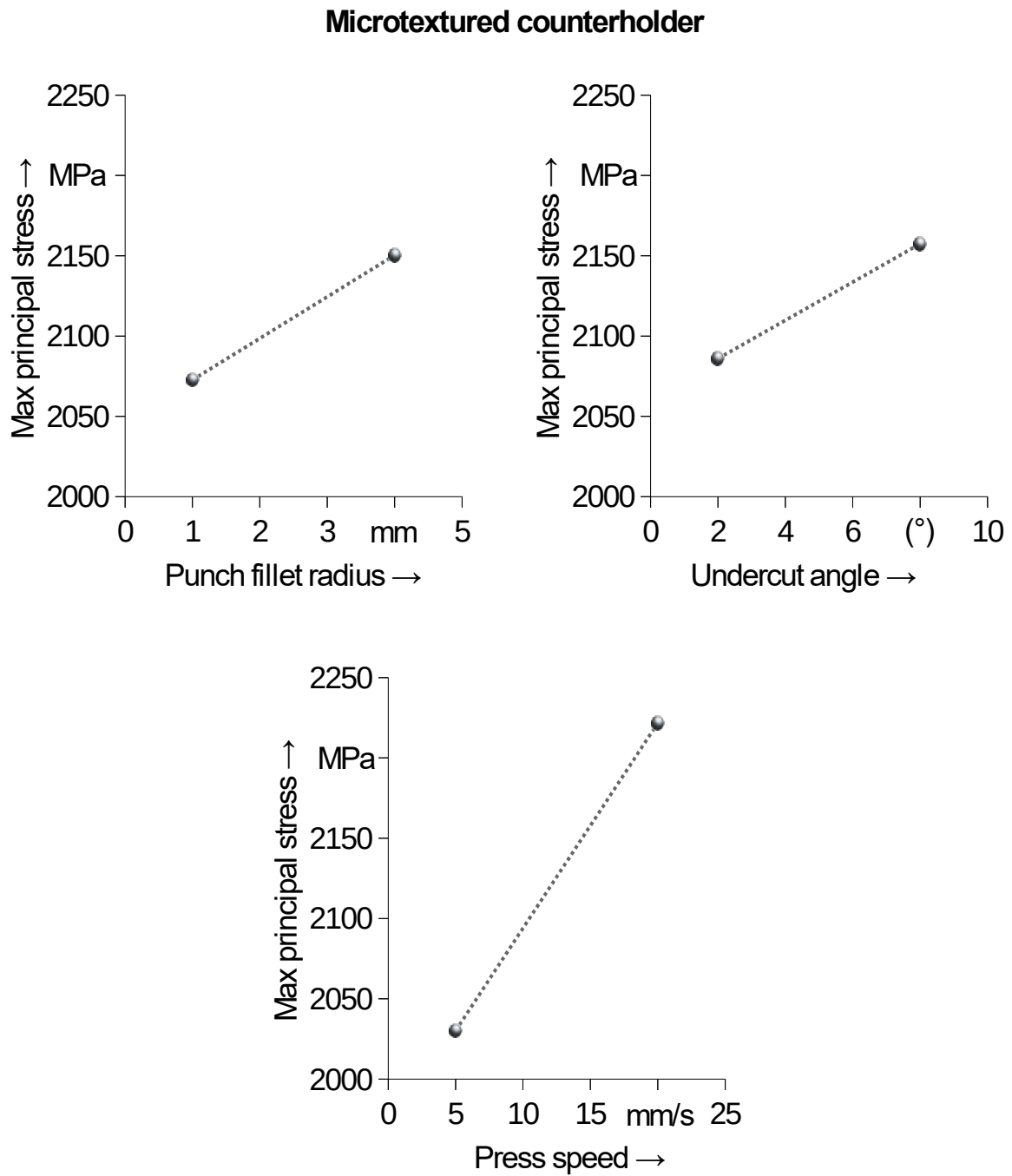


Figure 45: Main effect plot for the maximum principal stress on the Microtextured Counterholder

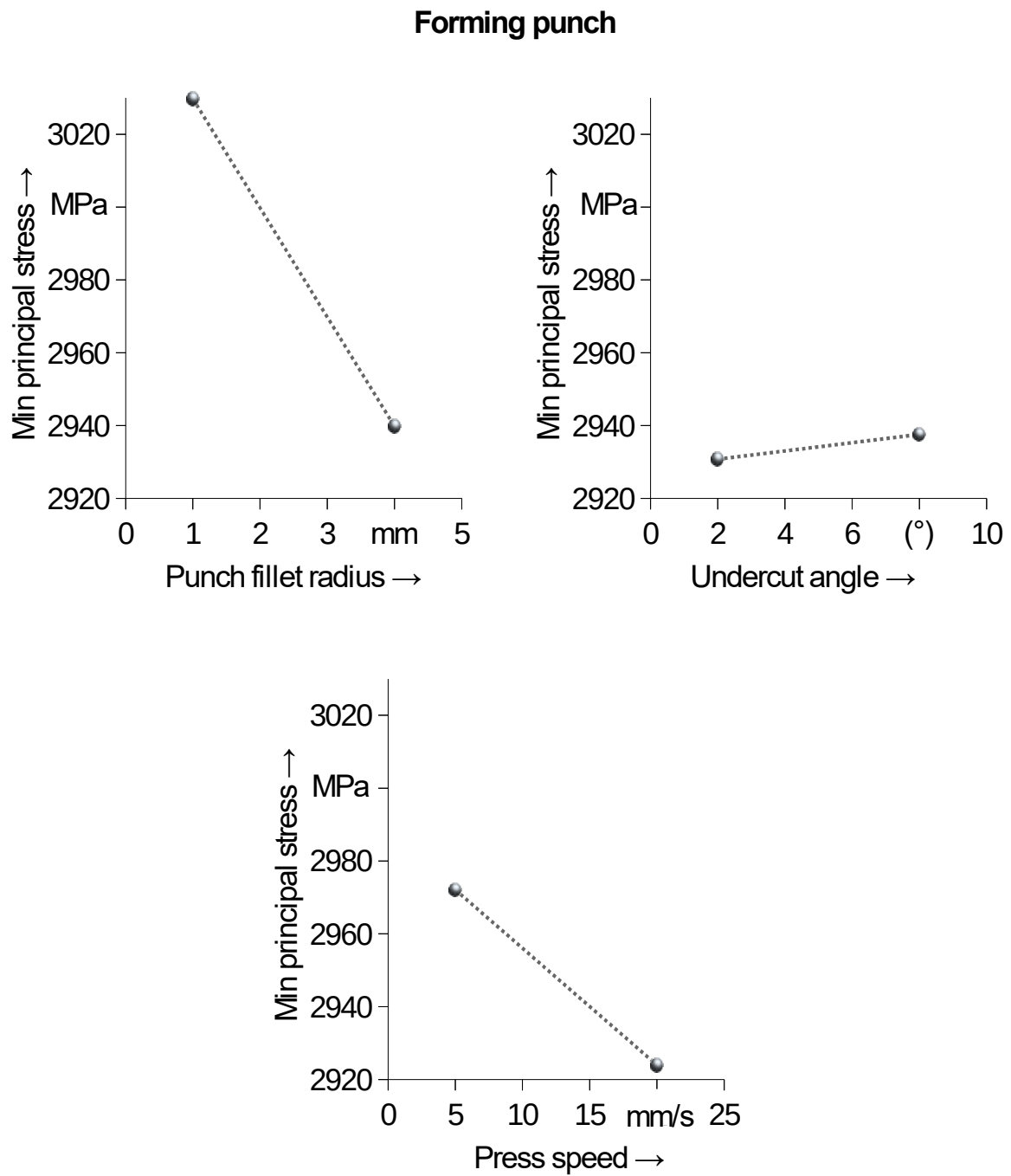


Figure 46: Main effect plot for the minimum principal stress on the Forming Punch

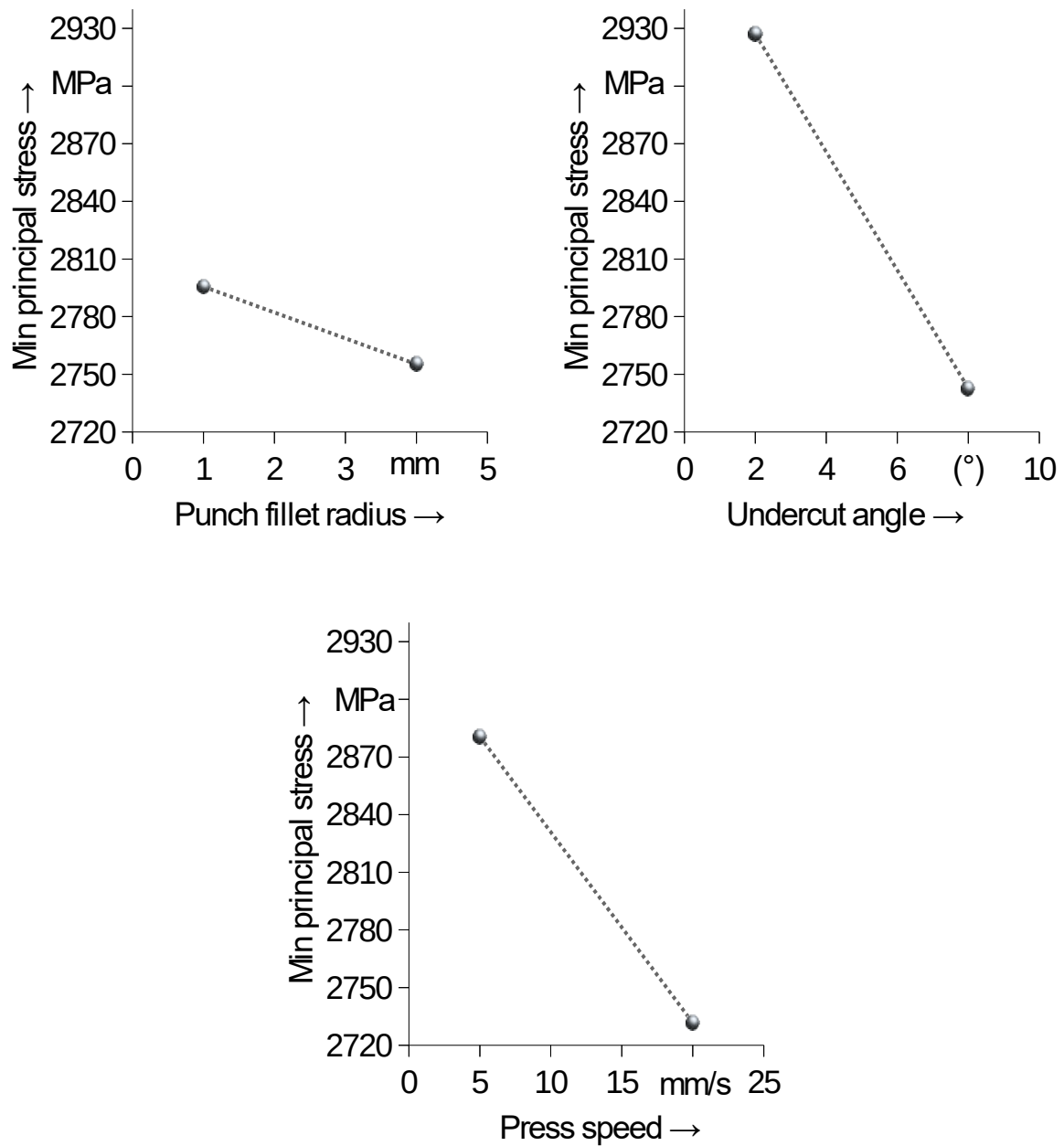
Forming die

Figure 47: Main effect plot for the minimum principal stress on the Forming Die

Microtextured counterholder

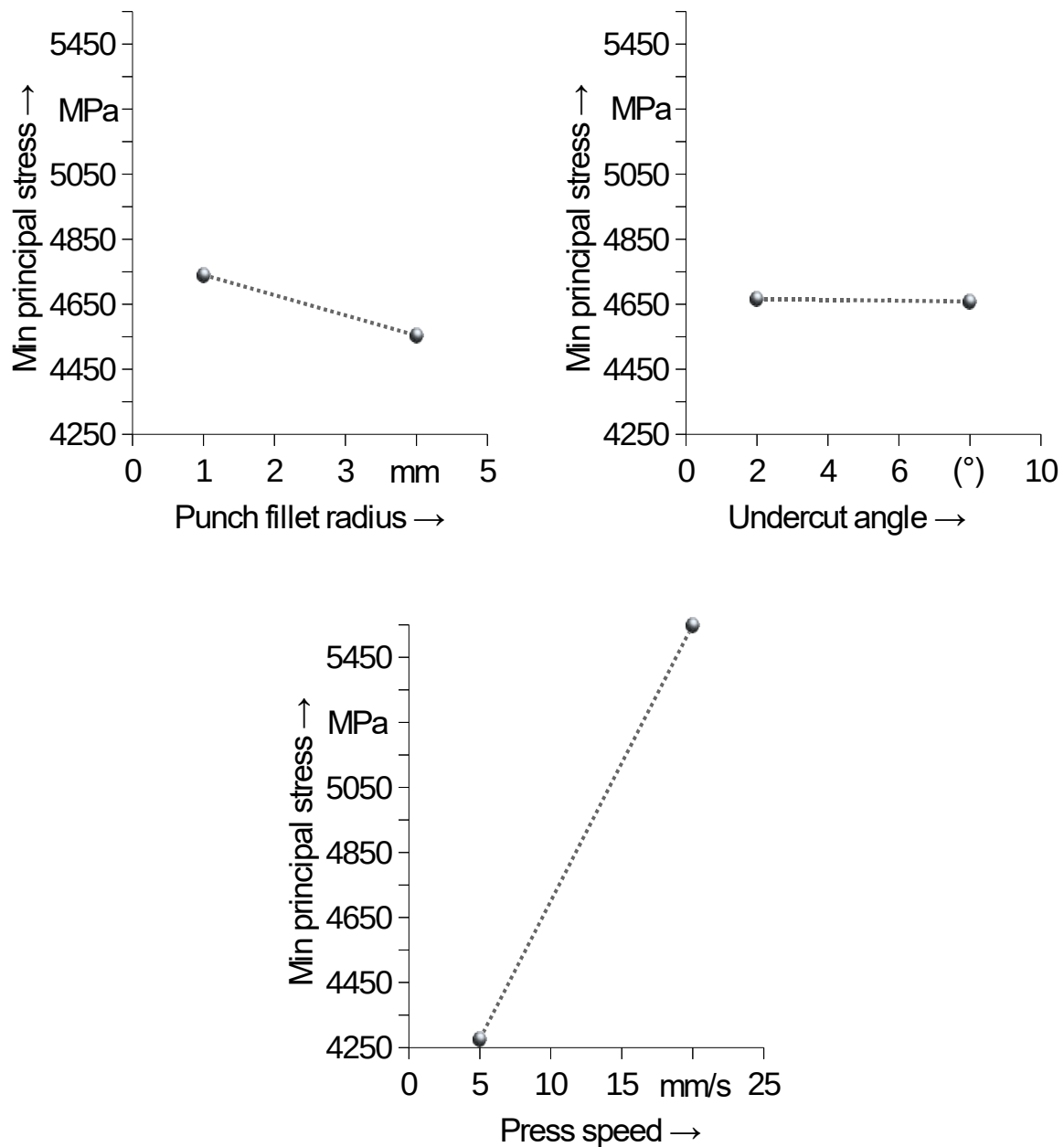


Figure 48: Main effect plot for the minimum principal stress on the Microtextured Counterholder

5.3 Diameter investigation

Furthermore, to verify the differences when the geometry of the final part is changed, the diameters of the forming die, and therefore of the product, are changed. The diameters are changed between 31 and 34 mm to give an expected range of values.

The CAD are modified from the previous taking care that the SMF and BMF have always the same amount of material, to achieve this, the external diameter of the blank sheet of metal in SMF is augmented (or diminish in the 31 mm case) to match the volume of the BMF raw blank with bigger (or smaller in the 31 mm case).

5.3.1 Shape comparison

The first comparison is the final part's profile (after tools release). The profiles are exported from SF in .igs format where all the nodes are expressed as coordinates sets and afterwards copied in a .csv file, through the use of a script, to be represented and compared in Excel.

Sheet-Bulk metal forming profile comparison

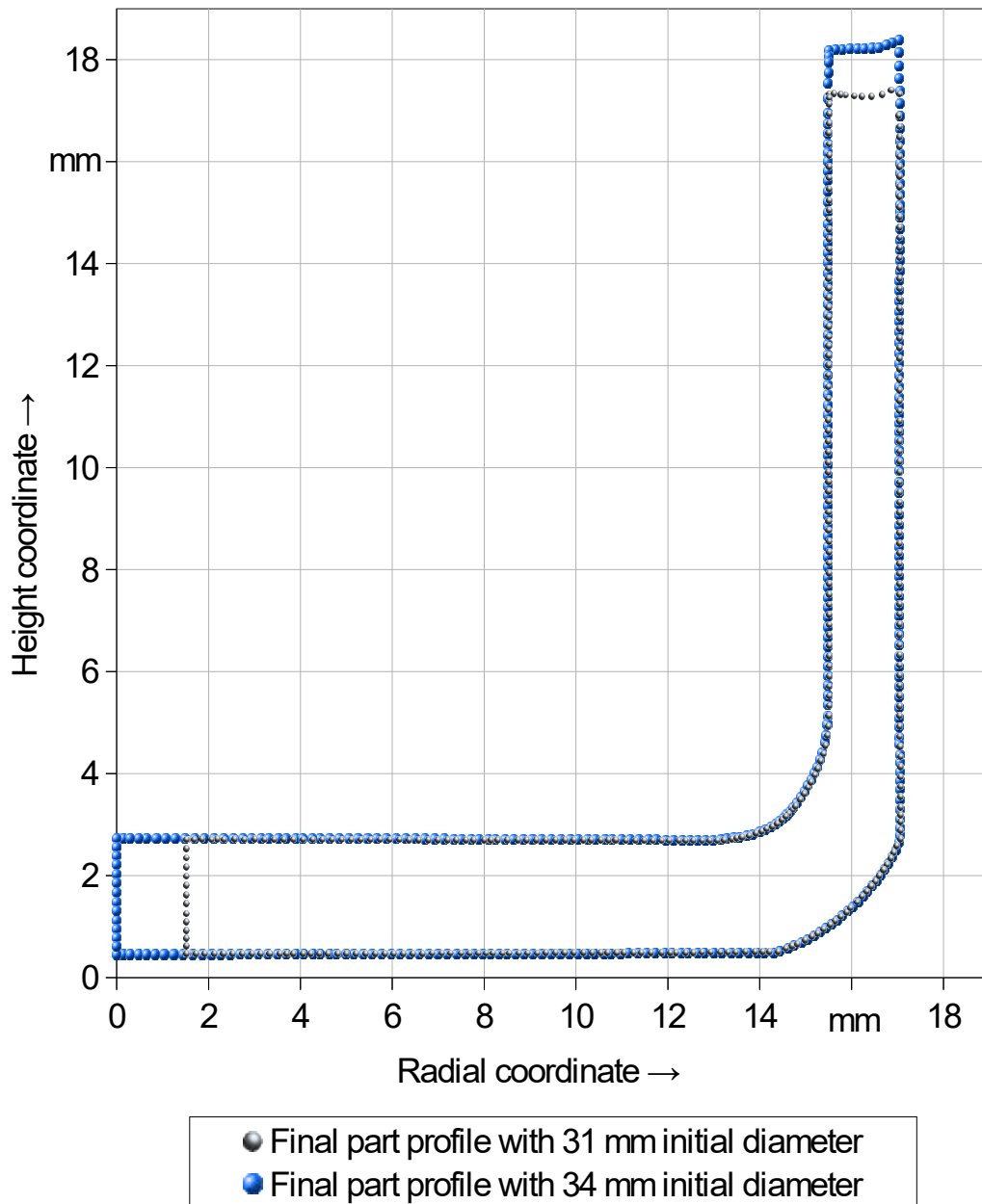


Figure 49: Sheet-bulk metal forming shape comparison between 31 and 34 mm forming die diameter

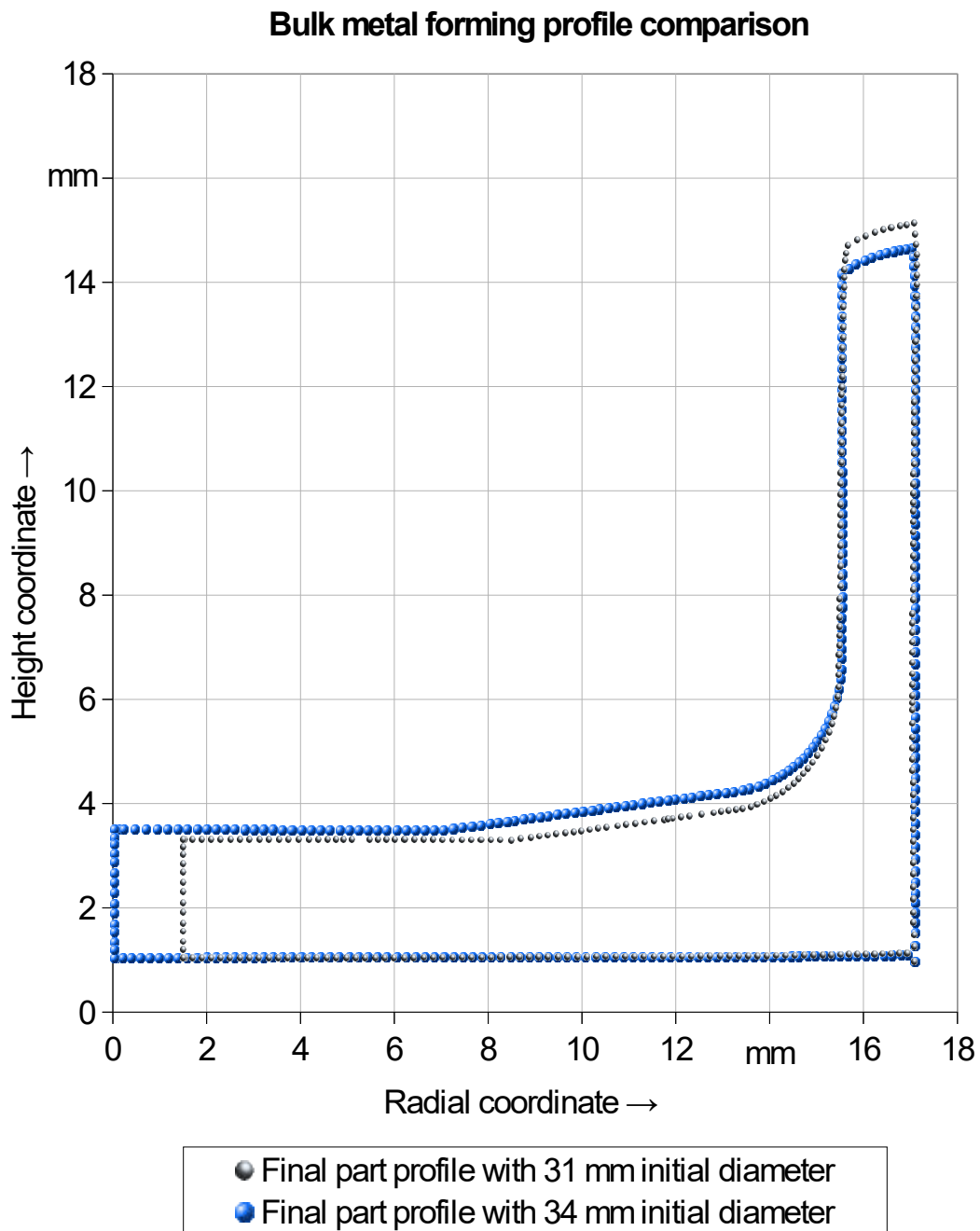


Figure 50: Bulk metal forming shape comparison between 31 and 34 mm forming die diameter

5.3.2 Force-stroke curve comparison

Once the final result is compared, to have a shallow view of the process as a whole and of the internal stresses is useful to compare the force-stroke curve of the two simulations.

The data is simply exported from SF in “.csv” format, taking care to select “stroke” as the second variable, and then visualized in Excel for a better comparison weight.

Sheet-Bulk metal forming Force-Stroke curve comparison

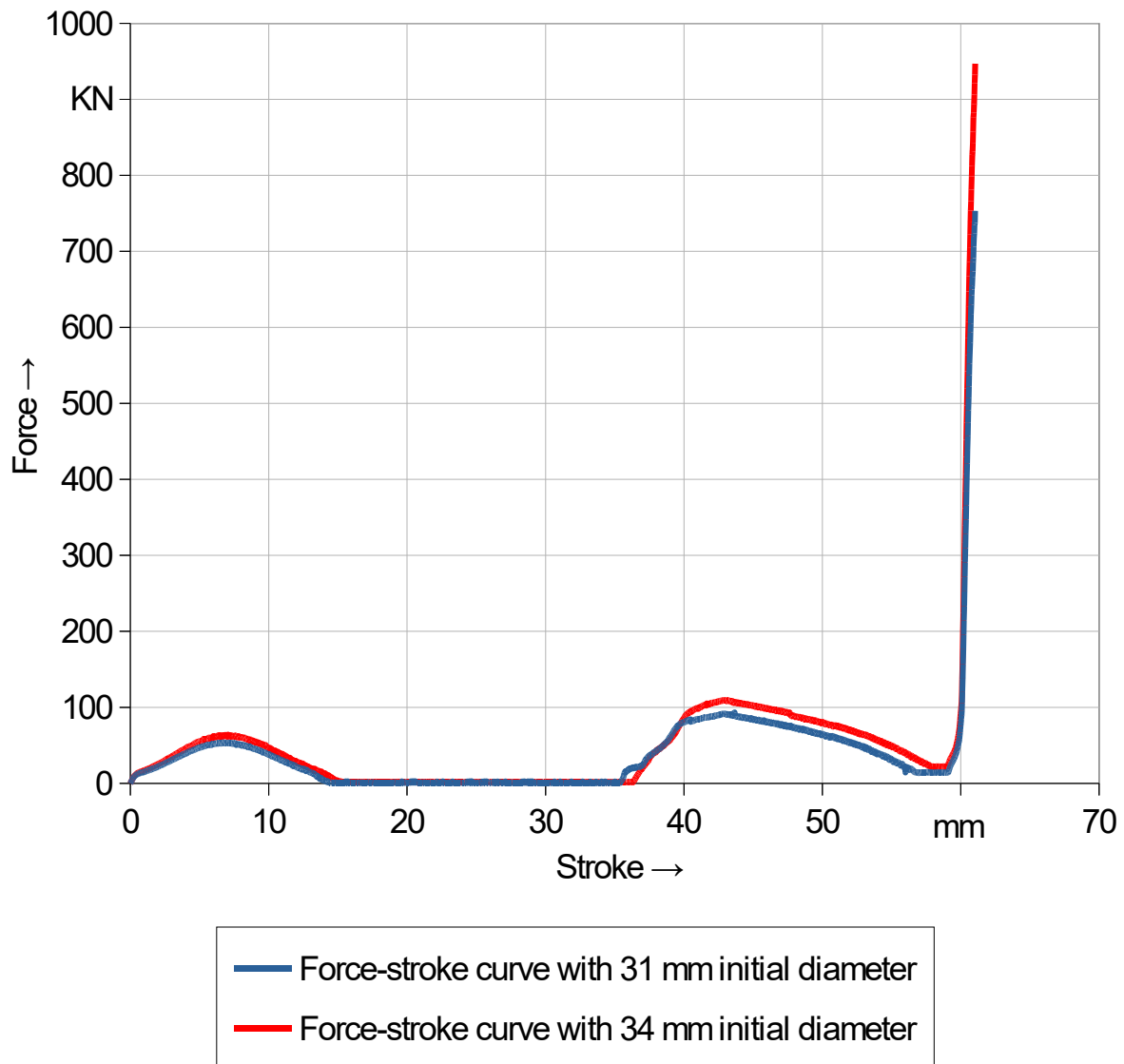


Figure 51: Sheet-Bulk metal forming force-stroke curve between 31 and 34 mm forming die diameter

Bulk metal forming Force-Stroke curve comparison

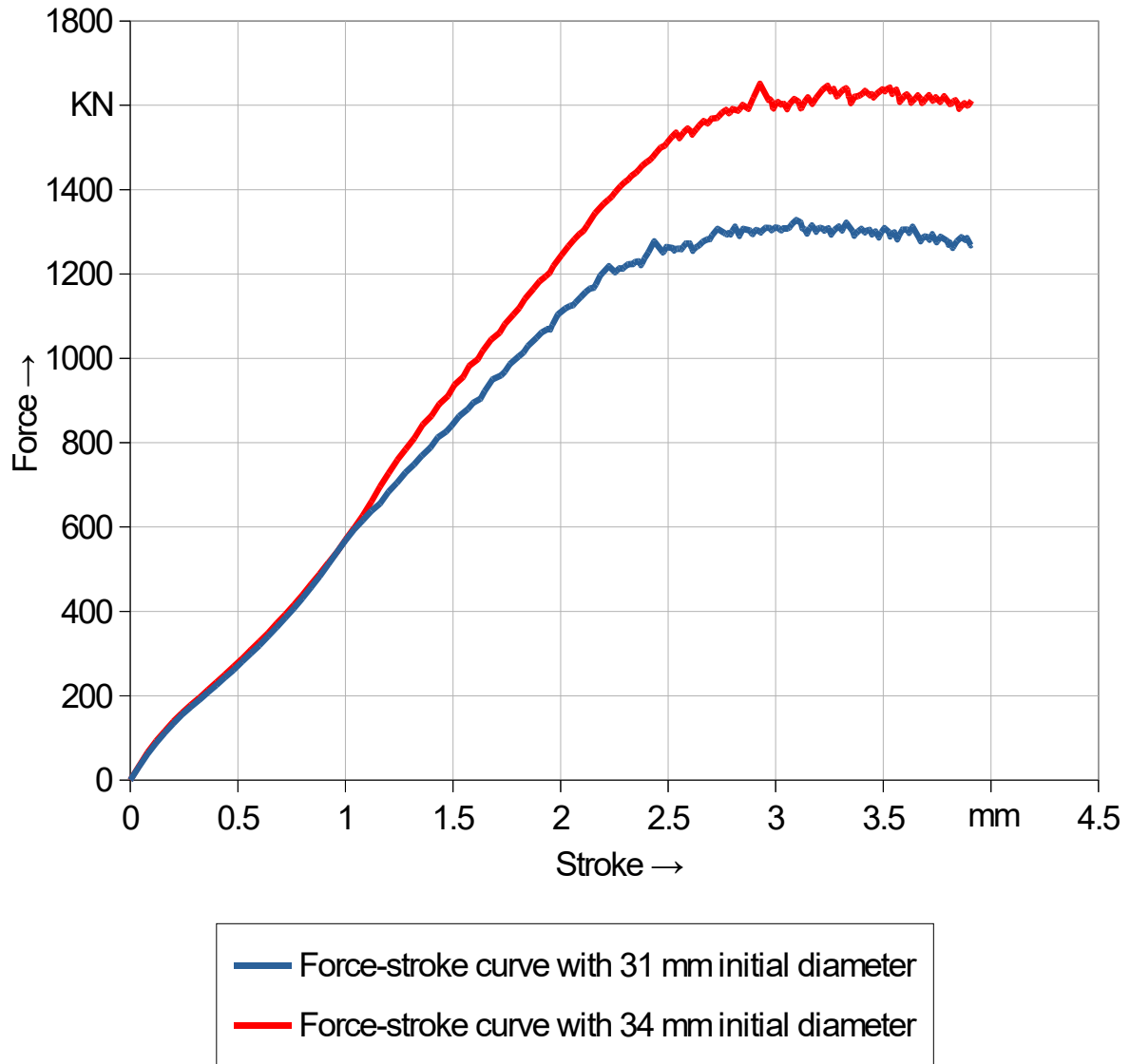


Figure 52: Bulk metal forming force-stroke curve between 31 and 34 mm forming die diameter

5.3.3 Effective plastic strain comparison

Finally, in addition to the previous quantitative analysis, it's important to evaluate the stress distribution inside the final part. Unfortunately it is really difficult to examine the distribution without extensive evaluation, therefore to, at least, have a qualitative view of the situation, is interesting to compare the "effective plastic strain" distribution graphs of the final part.

5.3.3.1 Sheet-bulk metal forming

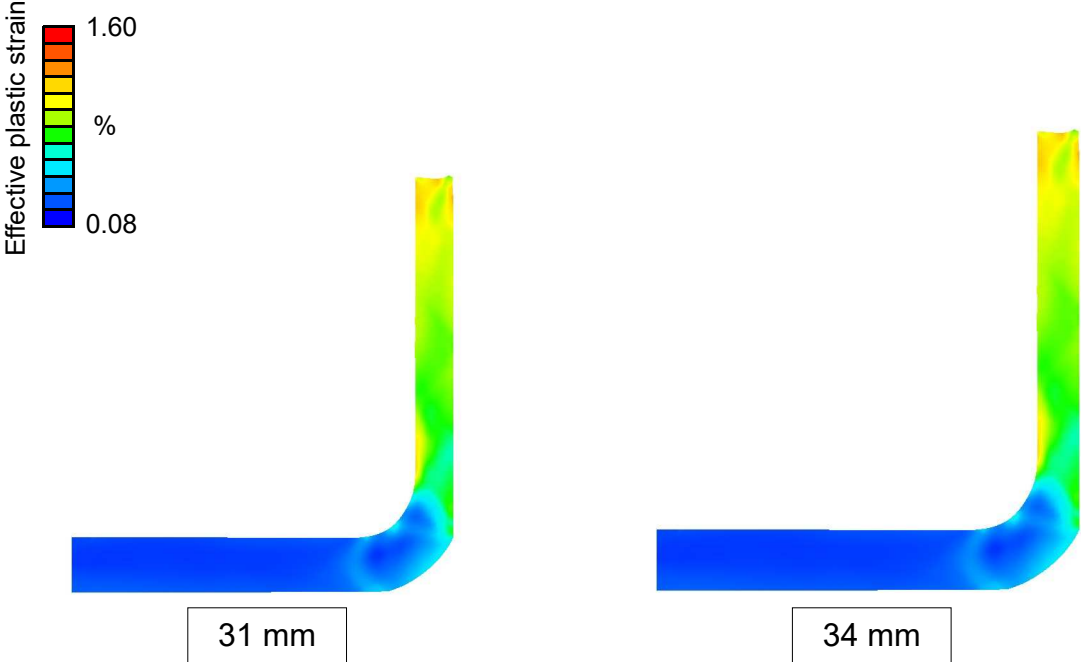


Figure 53: Sheet-Bulk metal forming effective plastic strain comparison between 31 and 34 mm forming die diameter

5.3.3.2 Bulk metal forming

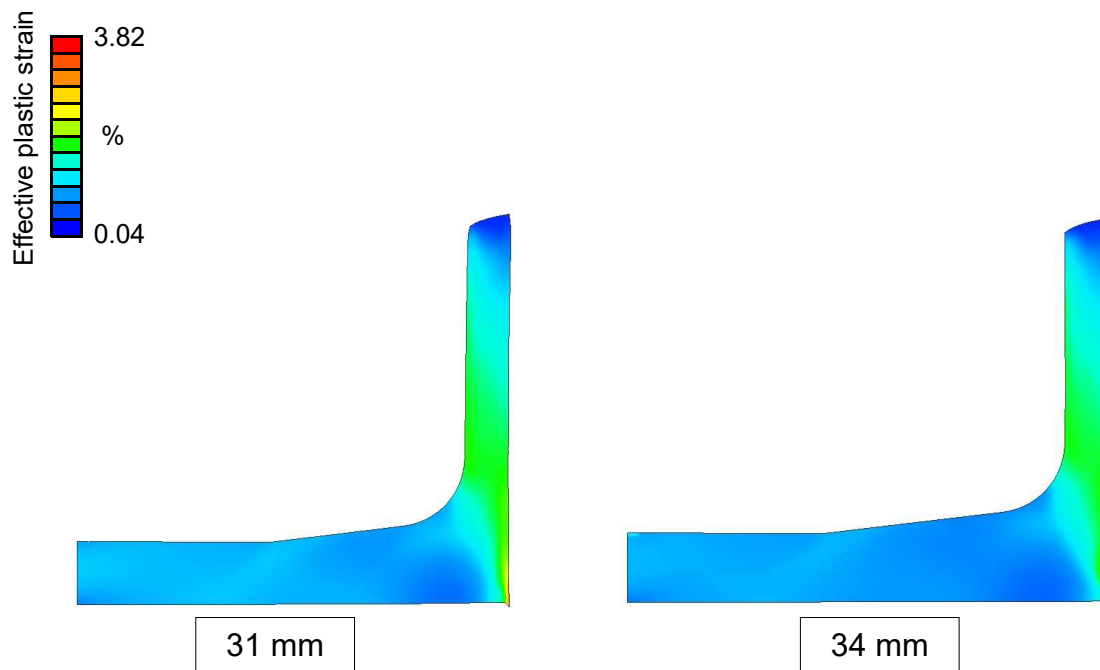


Figure 54: Bulk metal forming effective plastic strain comparison between 31 and 34 mm forming die diameter

5.3.4 Material flow comparison

In order to evaluate in a more in detail the material displacement and therefore flow, in SF are created some “tracking particles” as shown in Figure 55.

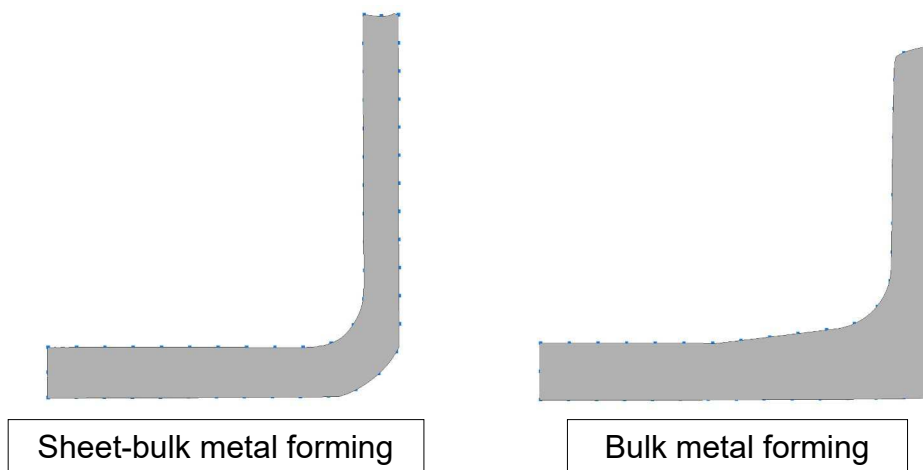


Figure 55: Particle tracking set up in Simufact Forming for SMF and BMF

Since the region on interest is the cap of the tappet (so the bottom side of the final part) the only interest is to keep the same number of particles in both simulations to

be comparable. Therefore those particles are so arranged on the bottom line: 11 on SMF and 15 on BMF both in the 31 and 34 mm simulation.

To better display the results, those are divided in three groups: apex (the first points near the centre of the tappet), middle (points in the middle of the tappet) and end (points near the external edge).

Once tracked the particles the results are displayed in the following graphs.

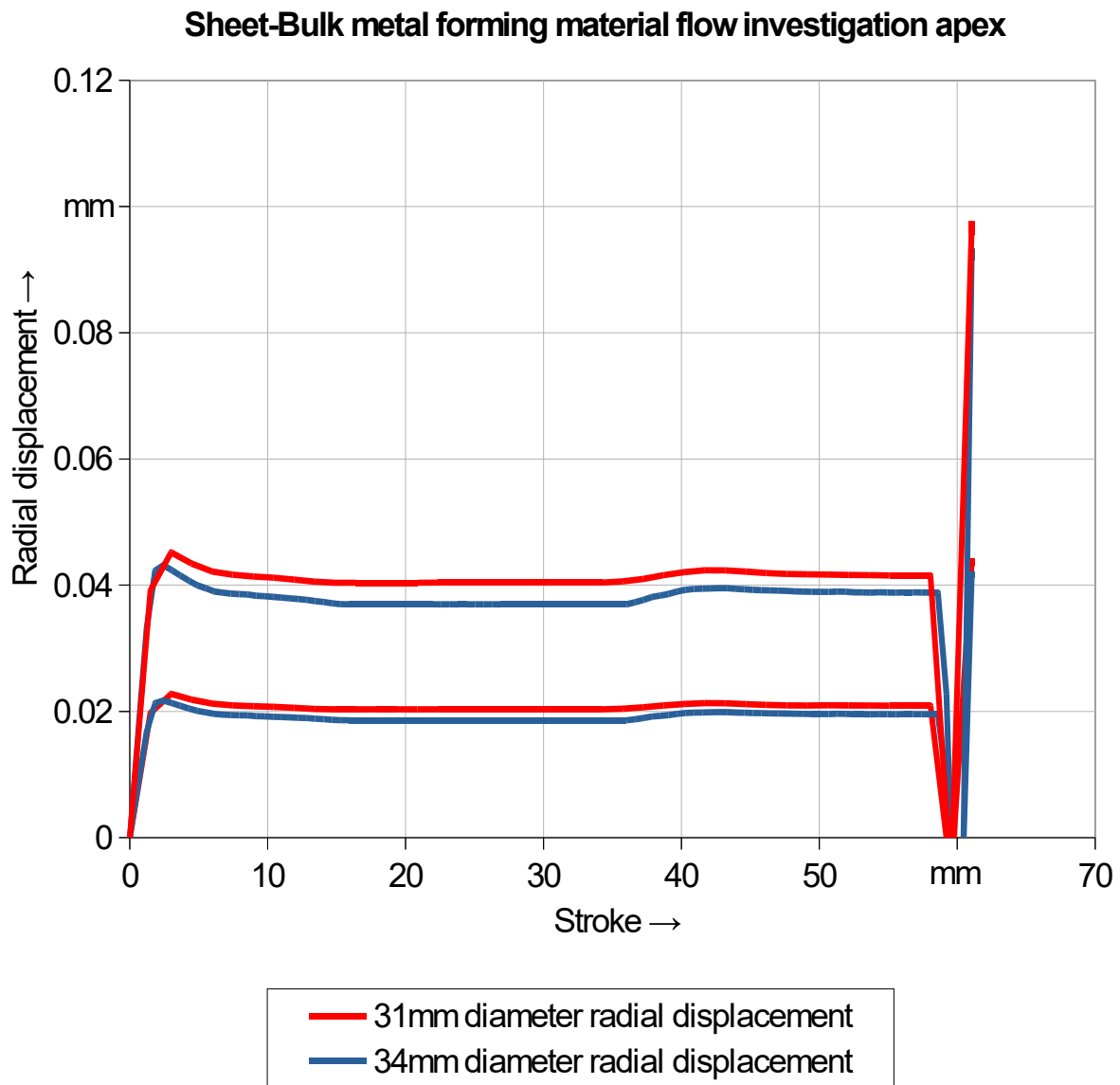


Figure 56: Apex radial flow comparison between 31 mm and 34 mm tappet diameter

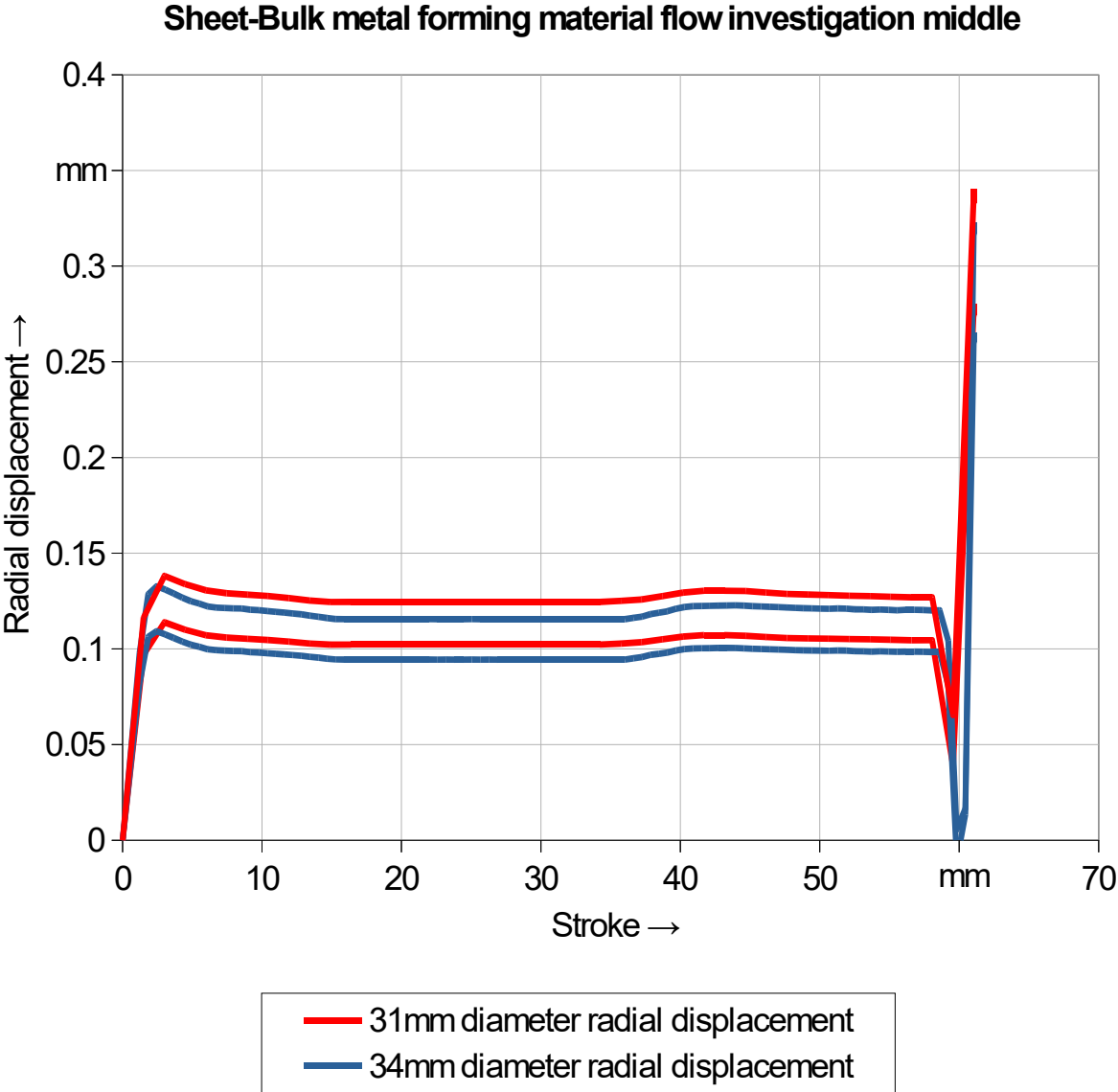


Figure 57: Middle radial flow comparison between 31 mm and 34 mm tappet diameter

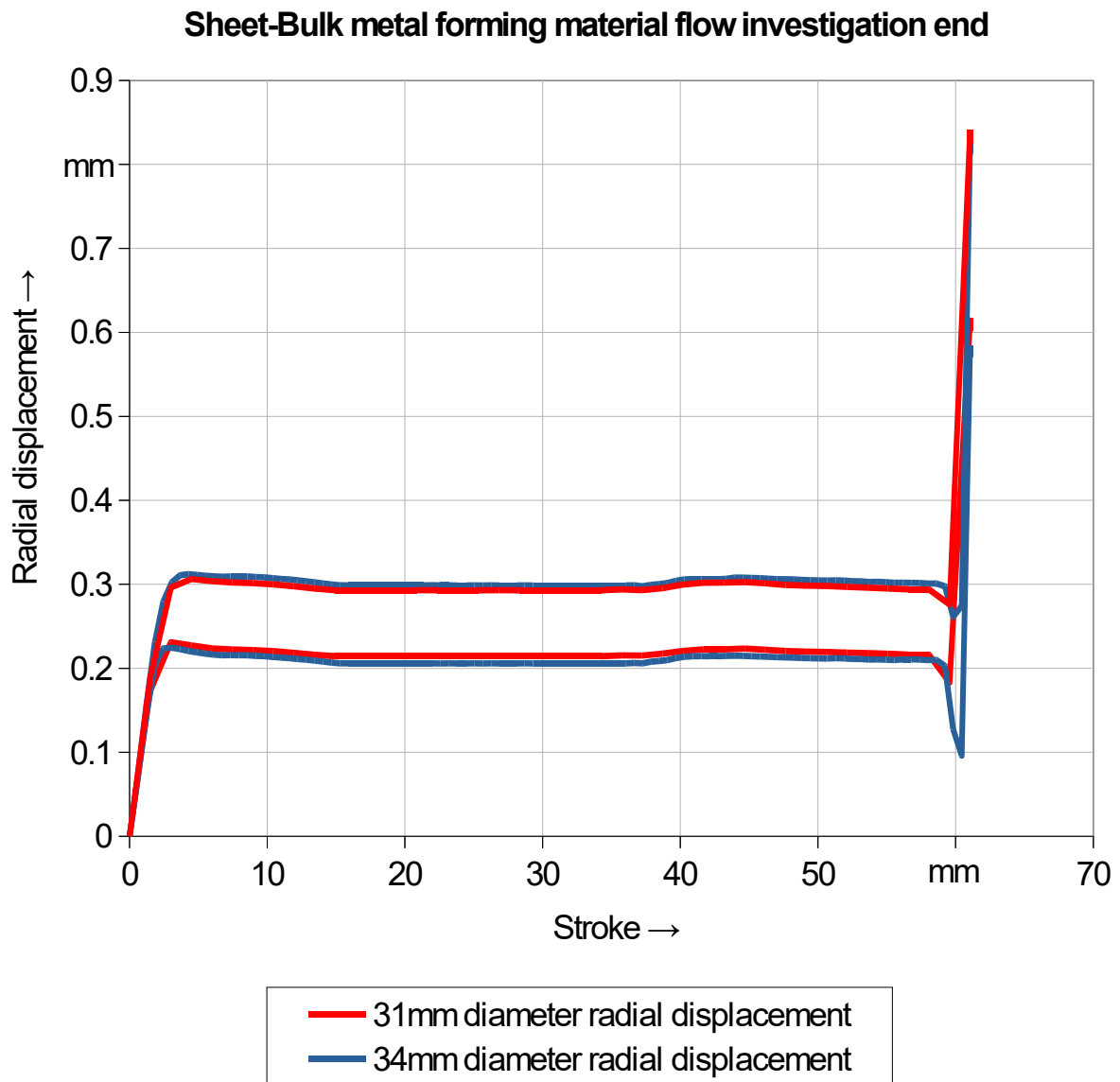


Figure 58: End radial flow comparison between 31 mm and 34 mm tappet diameter

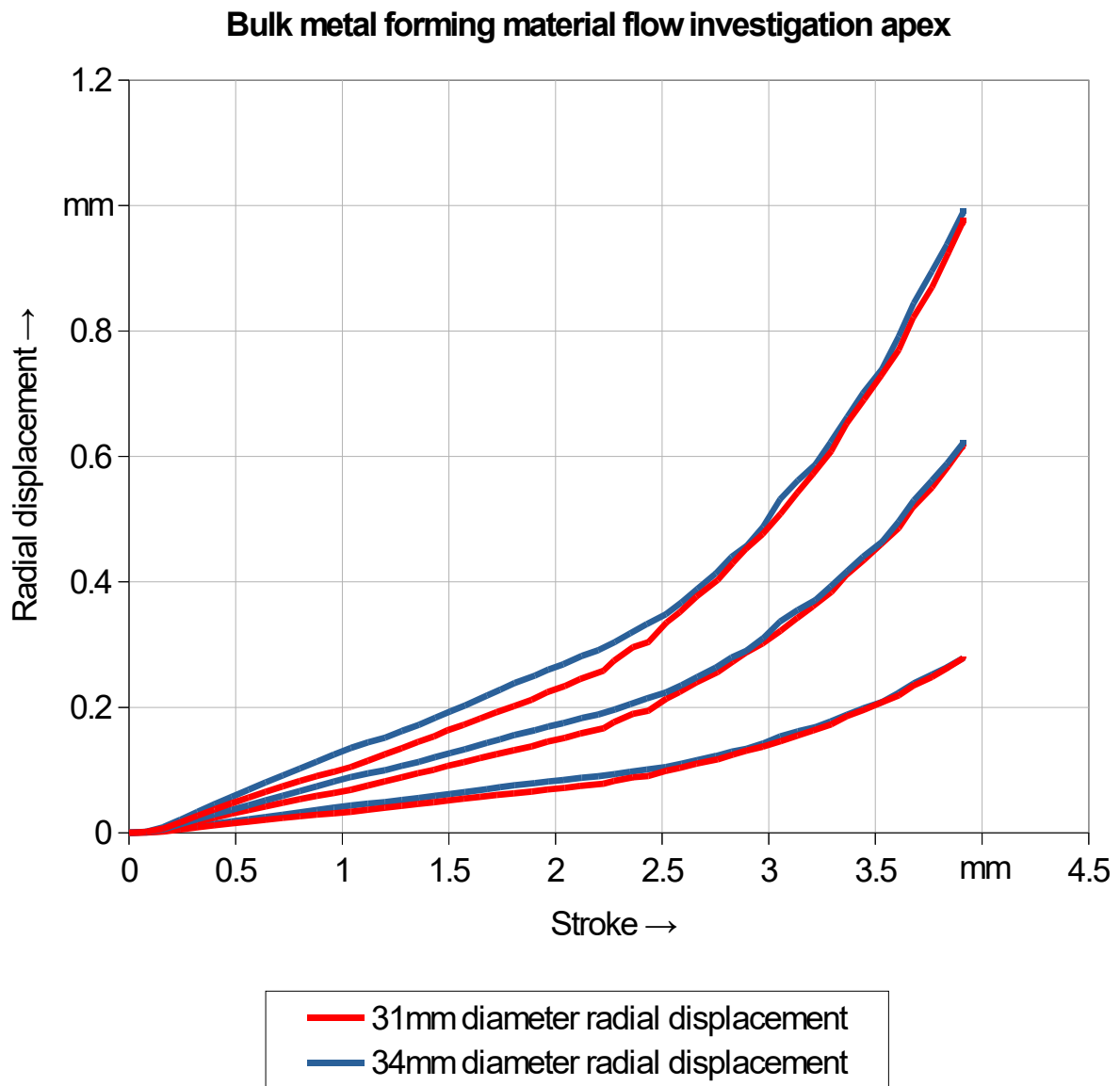


Figure 59: Apex radial flow comparison between 31 mm and 34 mm tappet diameter

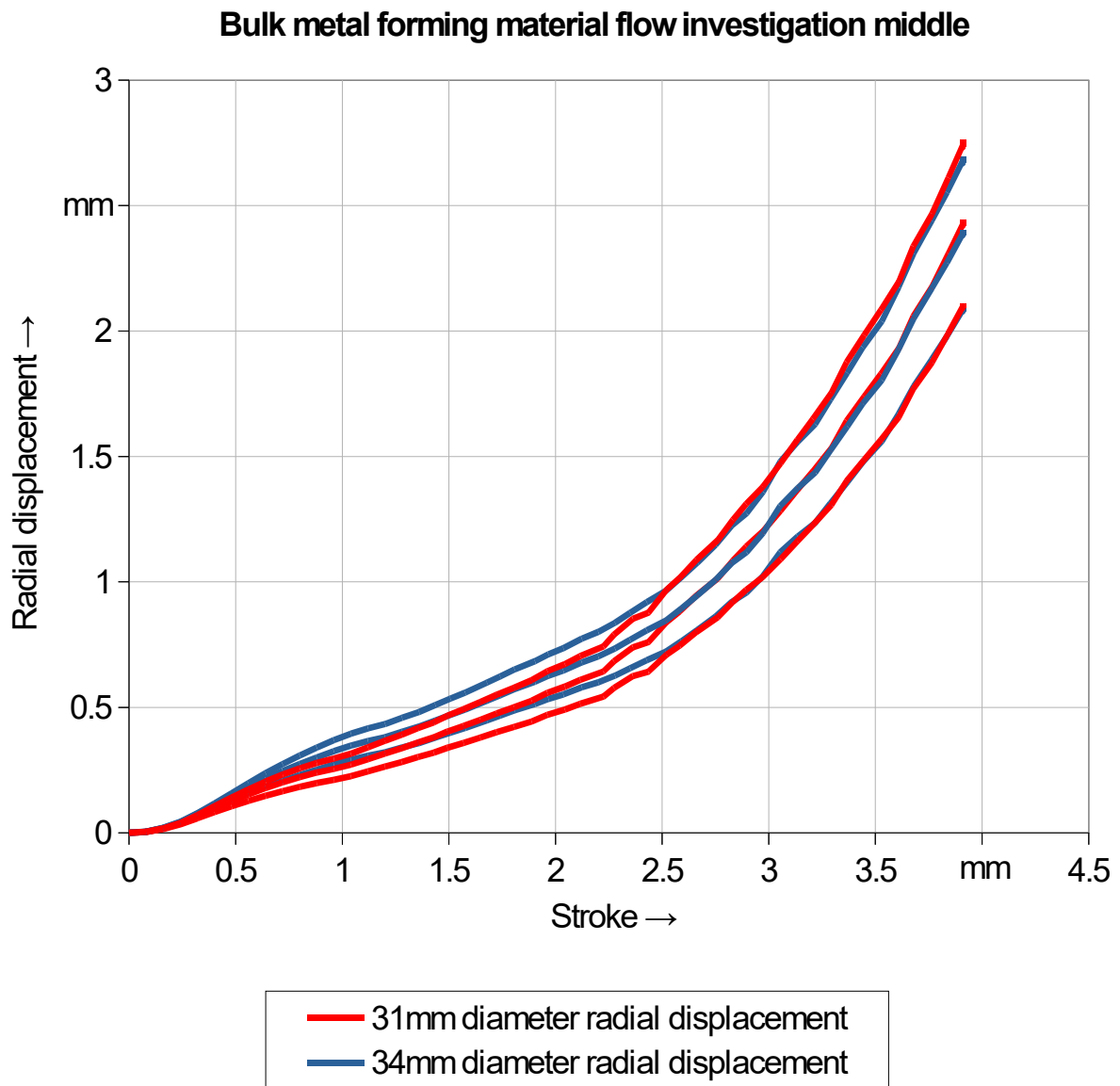


Figure 60: Middle radial flow comparison between 31 mm and 34 mm tappet diameter

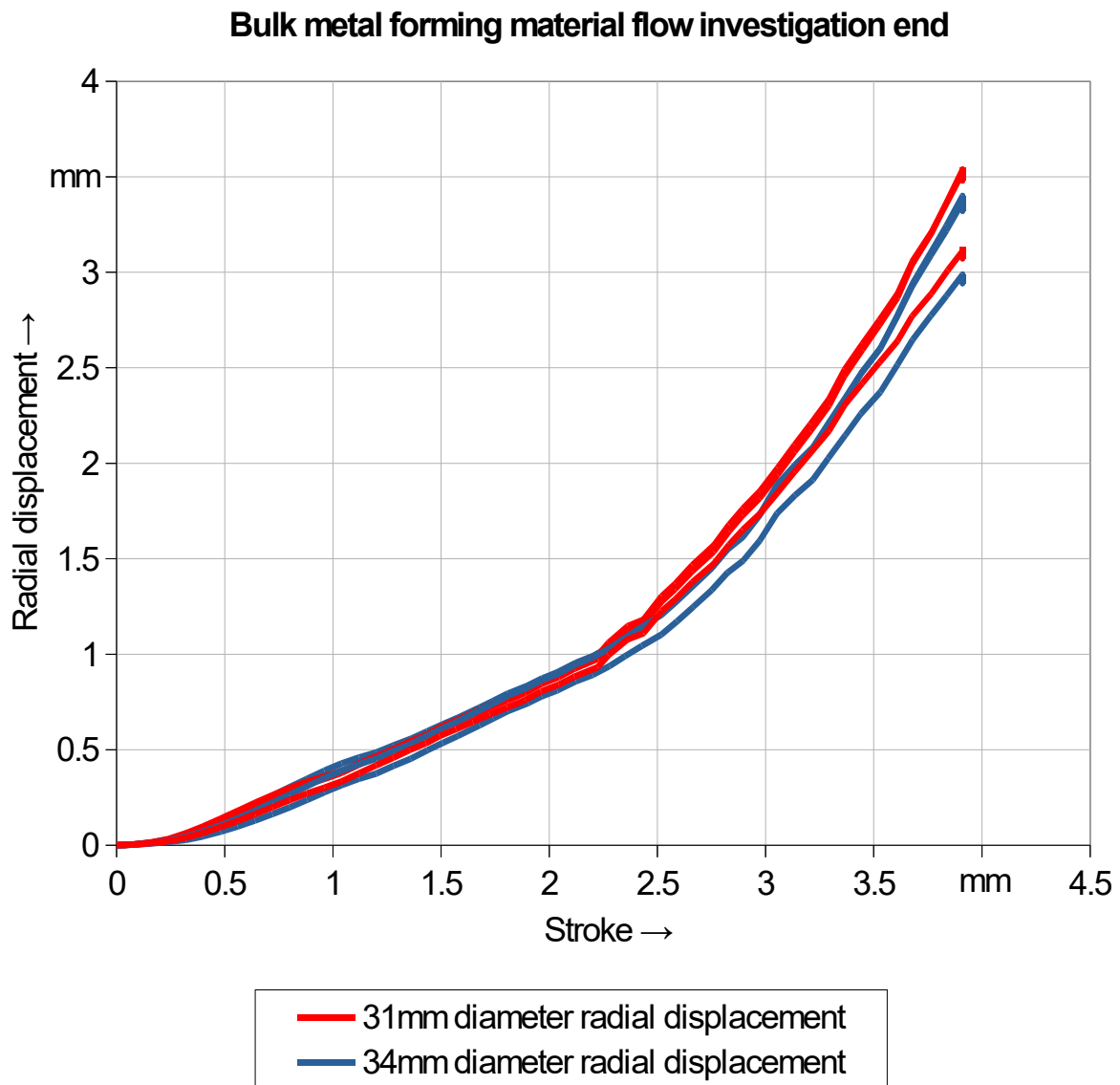


Figure 61: End radial flow comparison between 31 mm and 34 mm tappet diameter

6 Summary and outlook

6.1 2D vs 3D comparison

6.1.1 Shape comparison

As visible in Figure 19 the shape of both Bulk-metal forming and Sheet-bulk metal forming are completely overlapping in every place except for little deviations.

In the BMF simulation a little divergence is present in the external edge of the tappet's edge, in the 2D simulation the material entered slightly the cleft between the forming die and the counterholder, this defect is caused by calculation errors since

it's not present in the real manufacturing process. Furthermore, the material slotted in the cleft makes less overall material available, causing the wall of the tappet to be marginally shorter. Despite the minimal differences, it is still possible to affirm that the simplified model approximates with excellent reliability the 3D once, since the slotting defect is present in numerous sections even in the 3D simulation as visible in the expansion in Figure 23. The defect, then, is only caused by the choice of the analysed section.

In the SMF simulation, instead, the profiles are exactly overlapping in every point with the exception of the wall's height. Despite the small variation it is still possible to affirm the complete agreement on the results of the two simulations, since the shift is located in a non-functional region and therefore it's not in our interest. In addition, it's still profile related and, as is possible to see in Figure 25, there are lower profile along the expansion that matches better the 2D once.

6.1.2 Force-stroke curve comparison

The curves for both BMF and SMF are fully overlapping in every part, with the benefit of added definition in the 2D ones, since it's possible to diminish the calculation step, due to the less computational resources required. The benefits are visible especially in the last part of the BMF curve in Figure 21 where the mean values are the same but there's more variation around it.

6.1.3 Effective plastic strain comparison

Even on internal tensions side, the differences are minimal and mainly referable to the choice of the region of the 3D simulation to place the section in the profile comparison.

The BMF images, qualitatively speaking, are fully in accordance both in the expansion (Figure 23) and in the profile (Figure 24), the variations, if present, are minimal.

The SMF images present some differences on the inside edge of the tappet as visible in Figure 25 and in the inner part of the fold as visible in Figure 26. The edge part is useless, since it is not a functional part and doesn't interfere in any way with neither external shape nor functionality. On the other hand the difference in the bend curve is pretty important, since it determines the mechanical properties of the material in a crucial region of the part, however the gap in actual values are pretty limited.

6.1.4 Conclusions and processing time considerations

In conclusion 2D approximation is more than acceptable for both accordance in shape and internal stresses distribution.

In addition it is important to make some observations about the gap in processing time between the two simulation types.

Accordingly to SF, the bi-dimensional SMF simulation lasted for 28243.98 s whereas the three-dimensional one lasted for 369984.98 s instead, yielding the 3D simulation 13 times more computational expansive than the 2D.

For what BMF is concerned, the bi-dimensional simulation lasted for 1485.57 s whereas the three-dimensional one lasted for 61450.80 s instead, yielding the 3D simulation about 41 times more computational expansive than the 2D.

6.2 Tools stress investigation

The maximum equivalent stress (EqS in short or rather Von Mises stress) is the maximum stress recorded and is a combination of the three principal stresses in the three different directions.

6.2.1 Maximum equivalent stress SMF

The EqS is decreasing in both forming punch and forming die as the punch fillet radius grows, since the bigger the radius, the smaller are the forces involved in its bending. On the other hand, since the contact patch on the counterholder is smaller, due to the bigger radius, and the pressure must be the same, the force pressing on the counterholder are bigger as its maximum equivalent stress.

In regard the die fillet radius: as it grows it slightly augments the EqS on punch and counterholder since a bigger angle bend less in the initial part of the forming process, as visible in Figure 62 the external part of the sheet with bigger radius is not as deformed as the smaller radius one, therefore moving this deformation on the final part of the simulation when it is also probed for counterholder and punch.

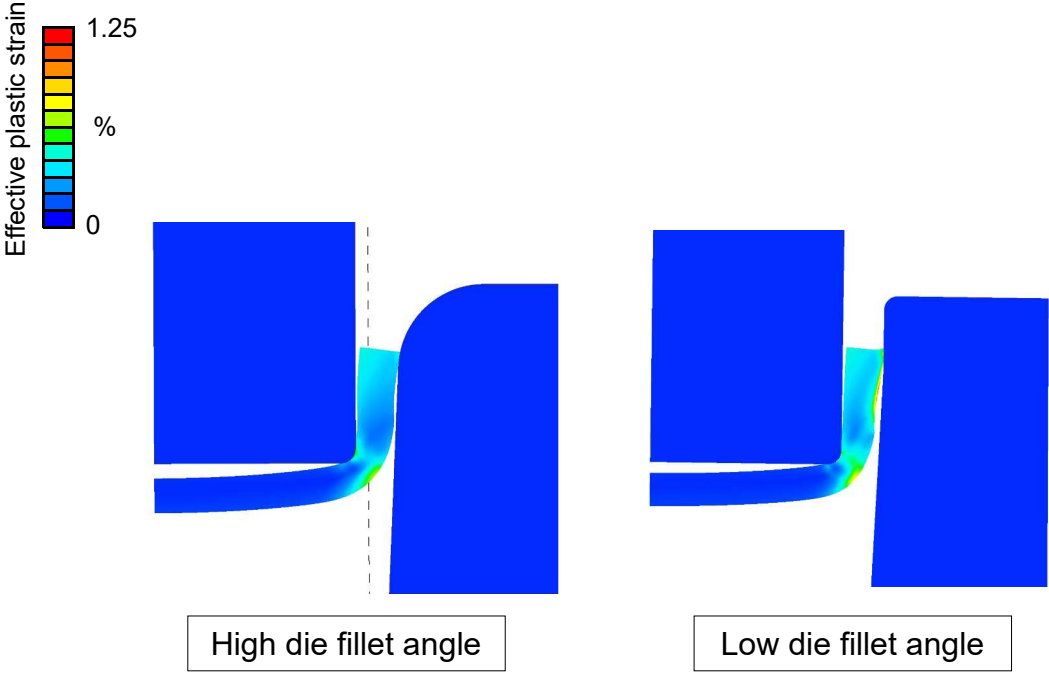


Figure 62: Effective plastic strain comparison as the forming die fillet vary

On the other hand, the die is probed during the process since it does not withstand the maximum stress in the final part. The die point of maximum stress is located at the end (Figure 63) of the die lean, therefore a more hardened and deformed part has more difficulties in the ironing process resulting in an increased stress on the die.

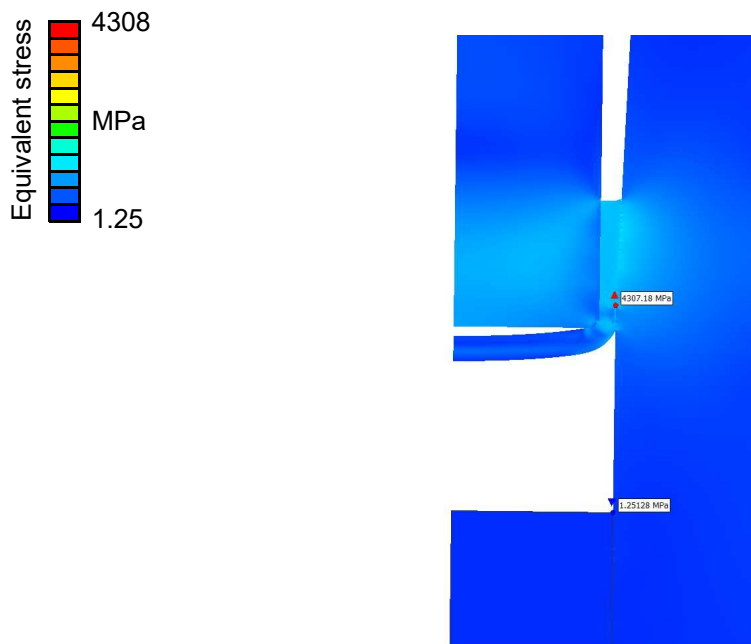


Figure 63: Forming die maximum equivalent stress position

On the die lean angle side, as it grows, it decreases the stresses in every tool because the deformation is less dramatic and diluted in more time.

The press speed on the other hand, as it grows, makes the stresses to slightly increase since the deformation is the same but conducted in less time, the tool most influenced in this variation is the counterholder, that has to withstand all the pressure in the final part.

6.2.2 Maximum principal stress (MPS) SMF

The maximum principal stress is mainly influenced by the punch fillet radius and the forming die lean angle.

The punch fillet radius follows the same behaviour as before: diminish the maximum principal stress as it grows in the forming punch and die since the angle is less pronounced and deforms less, and augment it in the counterholder due to the smaller contact patch.

The die fillet radius barely influences any tools since the increase in maximum equivalent stress comes from the variation of the minimum principal stress.

The die lean angle, as it grows, diminishes the MPS in every tool, especially forming die and punch, due to the less and less dramatic ironing process.

The press speed has in margin of error influence on MPS, therefore is it possible to affirm that either there is no influence or if present is irrelevant to our purpose.

6.2.3 Minimum principal stress (mps) SMF

For what mps is concerned, it diminishes in forming punch and die and augments in the counterholder as the punch fillet radius grows. As before, because the deformation process is smoother but it creates a smaller contact patch on the counterholder, increasing its stress.

The die fillet radius, growing, barely influences the punch's mps but decreases it in the forming die and increases it in the counterholder. This behaviour, on the die, explains with the simultaneous decrease of the equivalent stress that, coupled with the MPS's irrelevant variation, forces the mps to decrease in order to comply with Von Mises' formula. In addition, since the counterholder has to withstand the deformations not performed from the die.

The die lean angle, as for the other quantities diminish every stresses since the deformation is less sudden, except for the forming punch that increases its mps of 50 MPa, a value that can be easily considered as simulation/probing error.

6.2.4 Maximum equivalent stress BMF

As for the variation of the punch fillet radius, as it grows, it augments the EqS on the counterholder and diminishes it in the punch, however there's no effect on the die.

The slight reduction in EqS on the punch is determined by the less deformation occurring: as a matter of fact, the sharper fillet forces more material on the wall and therefore determines higher radial displacement as visible in Figure 64.

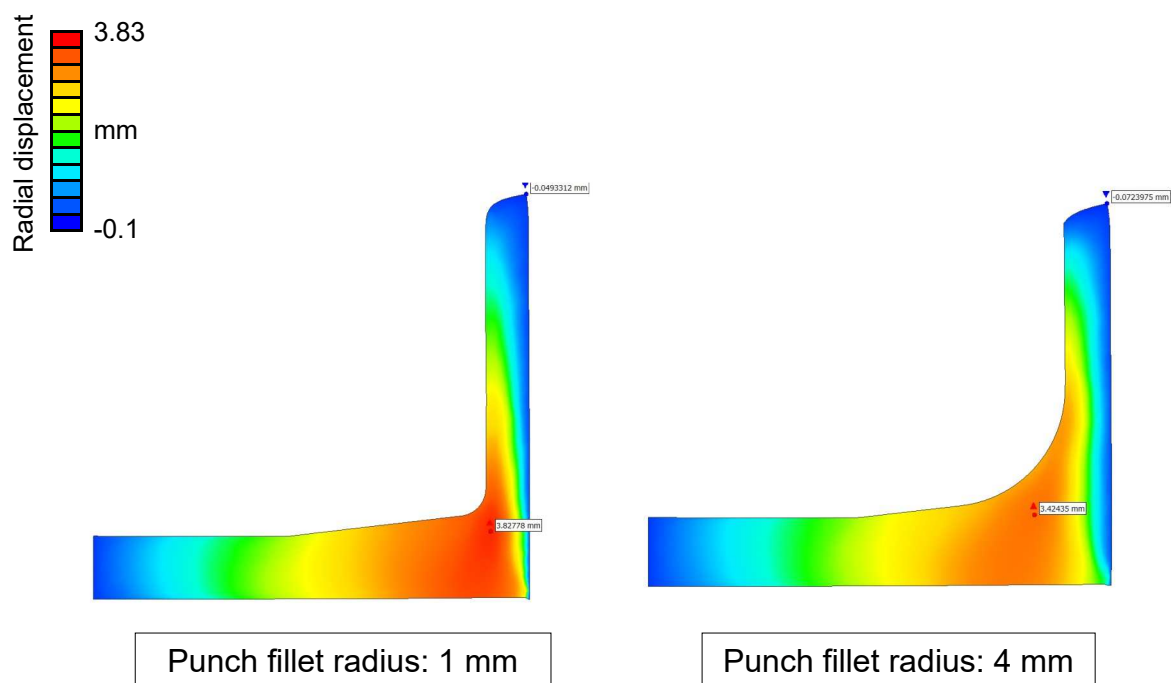


Figure 64: Radial displacement comparison with punch fillet radius variation

On the other hand the counterholder follows an opposite behaviour, in fact the bigger the fillet angle, the more the creation of a strong stagnation point is encouraged.

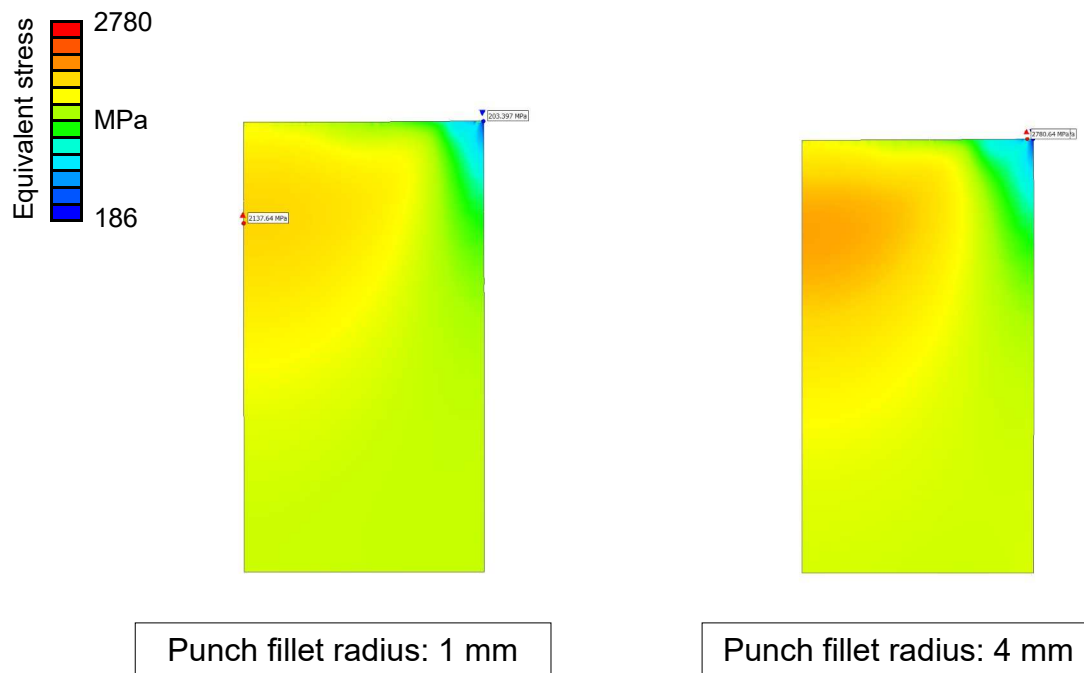


Figure 65: Microtextured counterholder equivalent stress distribution

As visible in Figure 65 the distribution is more or less similar but the maximum is situated on the stagnation point and not in the inner part of the tool. That's a clear sign of lower material flow in that region (as also visible in Figure 64) compared with smaller fillet radius.

The undercut angle has more clear influence, decreasing both punch and die EqS as the angle grows. The influence on the counterholder is barely measurable and can be considered as calculation error.

On the punch and die the correlation is clear: bigger angle means less constriction to the material flow, lowering the overall EqS maximum value and making the distribution more even.

Regarding the press speed influence, is quite strong on punch and counterholder meanwhile irrelevant on the die.

As the speed grows it increases quite drastically the stresses on the tools, since more speed becomes more hardening, turning the material into a harder one.

6.2.5 Maximum principal stress (MPS) BMF

The Punch's maximum equivalent stress is totally untouched from both fillet radius, undercut angle and press speed, all the variations are too small to be considered feasible of analysis.

The forming die's MPS is only influenced in a meaningful way from the undercut angle because, as explained for the EqS, the bigger angle encourage the creation of a stagnation region that generates a singularity point with a spike in stress.

On the counterholder, the only remarkable influence is located on the press speed that, as before, growing increases the hardening effect on the material and therefore the overall stress on the tool.

6.2.6 Minimum principal stress (mps) BMF

On the mps side of view, the influences are more evident, sign that the real driver for the variation of the EqS is actually the minimum principal stress.

The punch fillet influence on the punch, die and counterholder is quite mild. All these parameters are decreasing as the radius increases.

The punch it's influenced from the less material deformation and the die has to withstand more compressive stress due to stagnation point increase. On the other hand the counterholder suffers an increase in the compression forces since the smaller radius generates a flatter surface that allows the stresses to be spread evenly on the counterholder, while the bigger radius concentrates it in the centre resulting in a higher (or smaller if considering compression a digit) and pointy value, as visible in Figure 66.

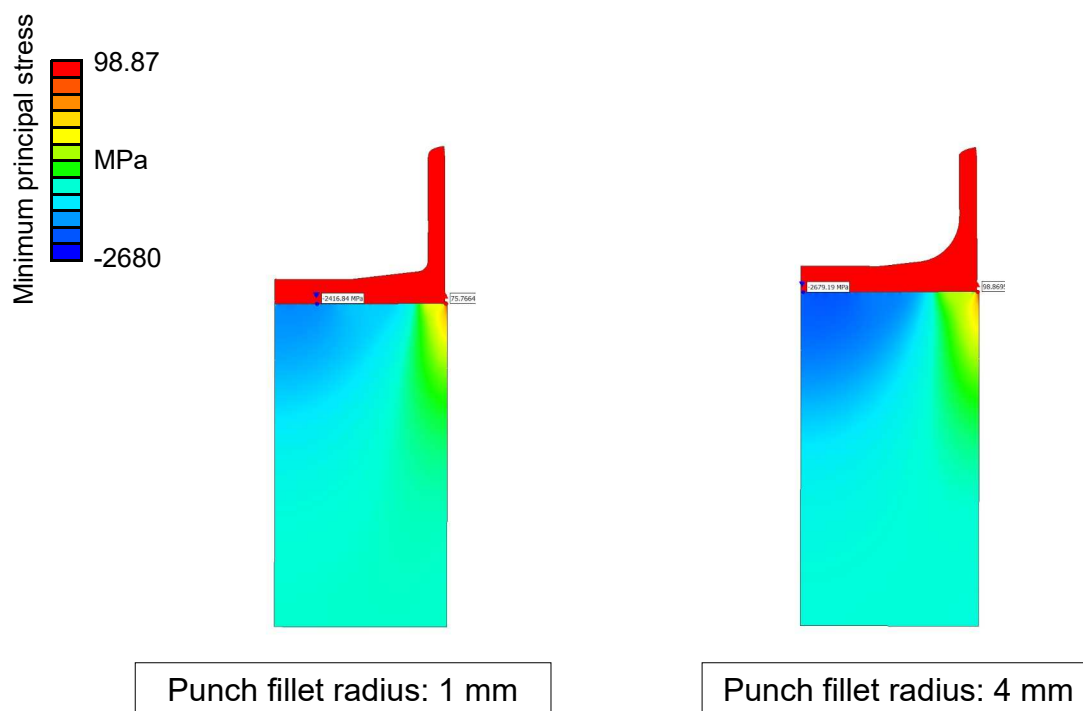


Figure 66: Microtextured counterholder minimum principal stress

For what the undercut angle is concerned, it influences the forming die decreasing the stress since, as explained before, the bigger the undercut the better the flow of

material. The press speed, as before, has just a severe influence on the counterholder, due to the hardening process.

6.2.7 Final conclusions

To summarise all the influences of the features on tools stresses, the following table collects all the data (Counterholder is abbreviated as CH).

SHEET-BULK METAL FORMING									
	EqS			MPS			mps		
	Punch	Die	CH	Punch	Die	CH	Punch	Die	CH
Punch fillet	↓	0	↑	0	0	↑	↓	↓	↑
Die fillet	0	↓	0	0	0	0	0	↓	↑
Die lean angle	↓	↓	↓	↓	↓	0	0	↓	↓
Press speed	0	0	0	0	0	0	0	0	0

BULK METAL FORMING									
	EqS			MPS			mps		
	Punch	Die	CH	Punch	Die	CH	Punch	Die	CH
Punch fillet	↓	0	↑	0	0	0	↓	0	↓
Undercut angle	↓	↓	0	0	↓	0	0	↓	0
Press speed	↑↑	0	↑↑	0	0	↑↑	0	0	↑↑

6.3 Diameter investigation

6.3.1 Shape comparison

As visible in Figure 50 the shapes are clearly different due to the different external die diameter, therefore the one with smaller diameter has taller walls meanwhile the other has bigger tappet head with shorter walls in both SMF and BMF.

Therefore the overall shape is not influenced from the external diameter, that changes only the proportions between walls height and tappet diameter.

6.3.2 Force-stroke curve comparison

In the SMF analysis (Figure 51) it can be seen as the deep drawing and ironing parts engage almost the same press-force however the final microcoining region clearly differentiates the two diameter, the bigger of which evidently requires more force.

In the BMF analysis (Figure 52) the curves are identical but the one of the bigger diameter is shifted upwards.

The final conclusion about the force-stroke curve is that the bigger the diameter, the higher is the force required for the process, in both SMF and BMF.

6.3.3 Effective plastic strain

As visible in Figure 53 and Figure 54 the simulations of both SMF and BMF are completely overlapping in every parameter except shape. Is it possible to affirm that the internal tensions distribution is not influenced by the external diameter.

6.3.4 Material flow analysis

The material flow on the head surface of the tappet is one of the most important parameters to evaluate the feasibility of microtexture printing, the bigger the material flow, the more difficult and inaccurate is the printing process.

On the SMF side it is possible to see in Figure 56, Figure 57 and Figure 58 how the metal flow is really low compared to BMF and does not change much between 31 and 34 mm diameter of the tappet, or rather increasing the dimension of the tappet slightly decrease the radial displacement. In addition is important to note how the more points approach the external walls of the tappet, the more the material flow became remarkable. For example in the apex it reaches 0.1 mm, in the middle 0.3 and in the end around 0.8, therefore the region with the best quality of printing is the central one.

On the other hand BMF has way bigger radial displacement as visible in Figure 59, Figure 60 and Figure 61. As before the differences are not severe but this time linked with the region of interest: in the apex part the 31 mm diameter shows smaller displacements, in the middle part are basically overlapping and in the external region the 34 mm shows smaller displacement. Important to note as the value of the displacement is more dramatic than in the SMF: 1 mm for the apex, around 2.5 mm for the middle and 3.5 for the external part, so around 10 and 5 times the SMF ones.

In conclusion, the diameter of the tappet slightly influences the radial displacement, sometimes magnifying it and sometimes shrinking it so more investigation is needed on this field: wider diameter gaps between the simulations are needed to make the differences in radial displacement more clear. In addition the most important consideration on this topic is the better suitability of SMF in microtexture printing, decreasing visibly the material flow between 5 and 10 times, dramatically improving quality.

Therefore SMF is clearly a better suited microtexture manufacturing process for both use of cheaper material and better printing quality.

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