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ORIGINAL ARTICLE

Incipient and repeatable plastic flow in incremental sheet-bulk forming of gears

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Abstract This paper analyses the differences between incipient and repeatable material flow in the incremental sheet-bulk metal forming (SBMF) of gears produced by indentation along the direction perpendicular to the sheet thickness. The underfilling of the punch cavity during the first indentation, which prevents the production of sound disk gears, is explained on the basis of constrained material flow under material strain hardening. A solution based on the utilization of a tailored disk blank is proposed to overcome this defect. The geometry of the tailored disk blank is determined by means of finite element analysis, and the overall methodology involved material characterization and experimentation with DC04 mild steel. The discussion on the extent of the plastic deformation region under constrained and free-material flow during indentation is complemented by experimental results obtained with a flat punch in rectangular sheet blanks of aluminium EN AW-1050A.

Keywords Incremental sheet-bulk metal forming · Plastic flow · Strain hardening · Gears

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1 Introduction

The differences in plastic flow resulting from the plane-stress conditions of sheet metal forming and the three-dimensional stress conditions of bulk metal forming have long been utilized to classify metal forming processes into two different groups. Recent development of sheet-bulk metal forming (SBMF) processes introduced a paradigm in the above classification of metal forming processes because their main objective is to deform sheets (or plates) with intended three-dimensional material flow [1]. In fact, SBMF processes allow producing sheet metal components with local functional features such as teeth, ribs and solid bosses positioned outside the plane of the sheets from which they are shaped.

Earlier developments of special purpose processes to fabricate sheet metal components with functional features positioned outside the initial surface of the sheets are due to Greisert et al. [2], who introduced flexible rolling to produce sheets with periodically varying thicknesses. Further developments were made by Hirt et al. [3], who developed a new rolling process for producing uniformly shaped surface ribs in sheets and by Merklein et al. [4], who proposed the utilization of tailored blanks for forming sheet metal components with functional elements of different thicknesses. However, all these processes are not flexible enough to produce components that require local features rather than periodically varying features positioned outside the plane of the sheets from which they are shaped.

One important step towards flexibility was made by Klocke et al. [5] who developed an incremental rolling process for producing riblet surfaces for the reduction of drag in specific parts of fans, compressors and turbines. Later, Sieczkarek et al. [6] analysed the potential of incremental compression in the direction perpendicular to the sheet thickness to produce load-adapted functional features at the edge of the sheets without resorting to complex and expensive tool systems installed in large capacity presses.

Another important advantage of incremental SBMF is the potential to produce sheet metal components with high quality because the overall level of undesirable deflections of the tools and presses are much smaller than those caused by the high forming forces that are typical of standard SBMF [7]. However, and despite lessening the process-machine interaction, incremental SBMF is mainly suitable and advantageous for small batch, customized production, due to economic constraints derived from cost and production rate.

From a material deformation point of view, the local deformation characteristics of incremental SBMF give rise to problems and challenges diverse from those found in standard SBMF. In fact, the non-uniform loading conditions of incremental SBMF lead to differences between neighbouring plastically deforming regions that are not found in standard SBMF.

The practical consequence of these differences in material flow is observed during the incremental forming of gears by indentation along the direction perpendicular to the sheet thickness (Fig. 1a). As shown in Fig. 1b, the first indentation by means of the double-wedge-shaped gear tooth punch (hereafter simply designated as the 'gear tooth punch') leads to underfilling of the punch cavity. This defect prevents the production of a sound disk gear by incremental SBMF.

This paper is focused in understanding the causes behind the underfilling of the punch cavity, which is not exclusive of the incremental forming of gears, and is generally attributed to material volume less and/or improper material flow. For example, Feldhaus [8] combined two-dimensional analytical and three-dimensional finite element modelling to optimize the geometry of the rolls and to ensure an adequate material flow to produce riblet sheet surfaces. Merklein et al. [9] investigated the use of tailored blank layouts and surfaces to improve the filling behaviour of a deep drawn cup-shaped part whose geometry is calibrated by upsetting perpendicular to the sheet plane.

However, as it was also pointed out by Merklein et al. [9], there are no extensive investigations on the understanding of plastic flow in SBMF, despite being a key subject for the overall success of the processes. In fact, this will be the main focus of this paper, which combines three-dimensional finite element simulation and experimentation to investigate incipient and repeatable plastic flow in incremental SBMF of gears by indentation along the direction perpendicular to the sheet thickness (Fig. 1a).

The organization of the paper is twofold. The first part analyses and compares the incipient plastic flow of the first indentation with the repeatable (similar) plastically flow of the subsequent indentations performed along the direction perpendicular to the sheet thickness. The work is performed on the aluminium EN AW-1050A with a flat punch in order to minimize the dependency on the type of indenter and to obtain larger and deeper indentations without damaging the punch (if stiffer materials were utilized). During the first part of the paper, the analysis is centred on the extent of the plastic deformation region to the vicinity of the punch, on the influence of strain hardening in subsequent indentations and on the material sideway spread arising from indentations that are performed very close to the width edges. The indentations are performed with sheet thickening, and the overall experimental plan may be considered as the continuation of the work on the mechanics of sheet-bulk indentation that was previously published by the authors [10].

The second part of the paper draws from the understanding of the causes behind the differences in plastic flow during the first and successive indentations, to the proposal of a solution for avoiding the above-mentioned underfilling defect in the incremental forming of gears by indentation of DC04 mild steel disks along the direction perpendicular to the sheet thickness.

2 Experimentation

2.1 Material characterization

The investigation was carried out in two different materials. The experimental work on the influence of strain hardening and material sideway spread during the first and subsequent indentations was carried out on aluminium EN AW-1050A

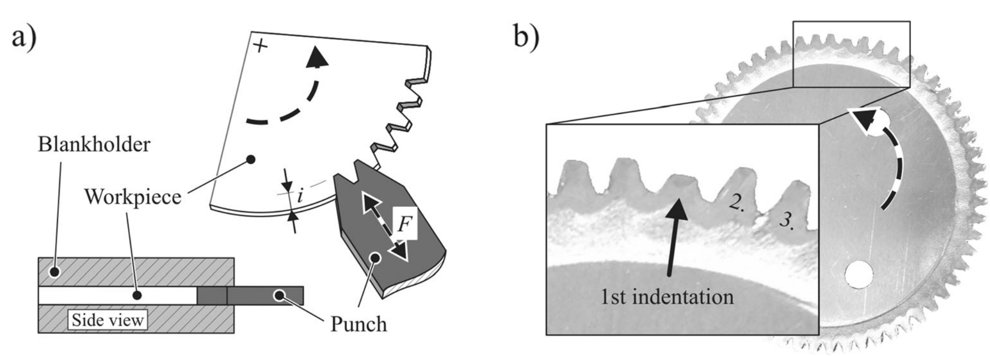


Fig. 1 Incremental forming of gears by indentation along the direction perpendicular to the sheet thickness. **a** Schematic representation of the process; **b** photograph of a disk blank with a detail showing the underfilling defect resulting from the first indentation

(WNr. 3.0255) rectangular blanks with 3 mm thickness. The experimental work on the incremental forming of gears by indentation along the direction perpendicular to the sheet thickness was performed on DC04 (WNr 1.0338) mild steel disk blanks with 3 mm thickness, at room temperature.

Both materials are appropriate for cold forming and its mechanical characterization was independently determined by the authors on a Zwick Z250 universal testing machine under quasi-static loading conditions. The tensile test specimens were cut out from the supplied sheets at 0°, 45° and 90° with respect to the rolling direction (RD), and the overall experimental procedure followed the ASTM standard E8/E8M [11]. The average stress–strain curves were approximated by the following Ludwik-Hollomon's strain hardening material models,

$$\begin{array}{l} \sigma = 535\,\varepsilon^{0.20}\ [\text{MPa}] - \text{DC04 mild steel} \\ \sigma = 125\,\varepsilon^{0.24}\ [\text{MPa}] - \text{EN AW}{-}1050\text{A aluminium} \end{array} \qquad (1)$$

Table 1 presents a summary of the mechanical properties for both materials.

2.2 Experimental methods and procedures

Figure 2 presents the experimental setup for the indentation of rectangular sheet blanks of aluminium EN AW-1050A along the direction perpendicular to the thickness. The tool consists of a flat punch, two die segments and two blank holders with suitable screws to clamp the sheet blanks firmly in position during the tests. The die segments are adjustable in order to control the amount of thickening during indentation.

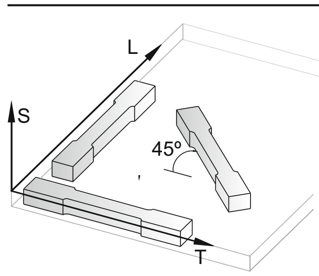
The punch and the dies segments were manufactured from a high-speed steel S6-5-2 (WNr. 1.3343) and the punch was plasma nitride with a depth of 600 μm in order to ensure a surface hardness of approximately 56 HRC. The blank holder was made from a pair of rectangular-shaped S 235JRG2 (WNr. 1.0038) steel plates.

Two different types of tests were performed. A first group of tests was aimed at determining the extent of the plastic deformation region undergone by the sheet during indentation and evaluating the influence of strain hardening on the evolution of the load with displacement during two successive indentations. A second group of tests was focused on evaluating the influence of material sideway spread on the evolution of the load with displacement.

Figure 3 presents the experimental setup for the fabrication of gears in DC04 mild steel disk blanks by incremental SBMF. The tool consists of a gear tooth punch and two circular blank holders that are fixed to a rotary table with a numerically controlled drive in order to ensure good positioning and repeatability accuracy. The punch was made from a powder metallurgy high-speed steel ASP 2023 (WNr. 1.3344) and it was vacuum hardened in order to ensure a surface hardness of approximately 60 HRC. The blank holders were made from S 235JRG2 steel plates and included screws to clamp the sheets firmly in position during the tests. Additionally, a vertical force was added to avoid the bending up of the setup.

Two different types of tests were performed. The first set of tests made use of disk blanks in order to replicate the previously mentioned underfilling defect of the first gear tooth. The second set of tests made use of tailored disk blanks with additional volume in the region where the first indentation will take place. The geometry of the tailored disk blanks will be given later in the manuscript and was determined by finite element analysis in order to account for strain hardening and material sideway spread between successive indentations.

Table 1 Summary of the mechanical properties of EN AW-1050A aluminium and DC04 mild steel sheets with 3 mm thickness



		Modulus of elasticity (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation at break (%)
EN AW-1050A	0° RD	64.3	33.6	70.7	31.1
	45° RD	67.2	33.9	72.5	36.4
	90° RD	70.4	34	69.9	32.6
	Average	67.3	33.9	71.4	34.1
DC04	0° RD	218	205.4	327.2	20.8
	45° RD	238	216.6	338.6	19.3
	90° RD	224	208.2	327.0	20.8
	Average	229	211.7	332.9	20.0

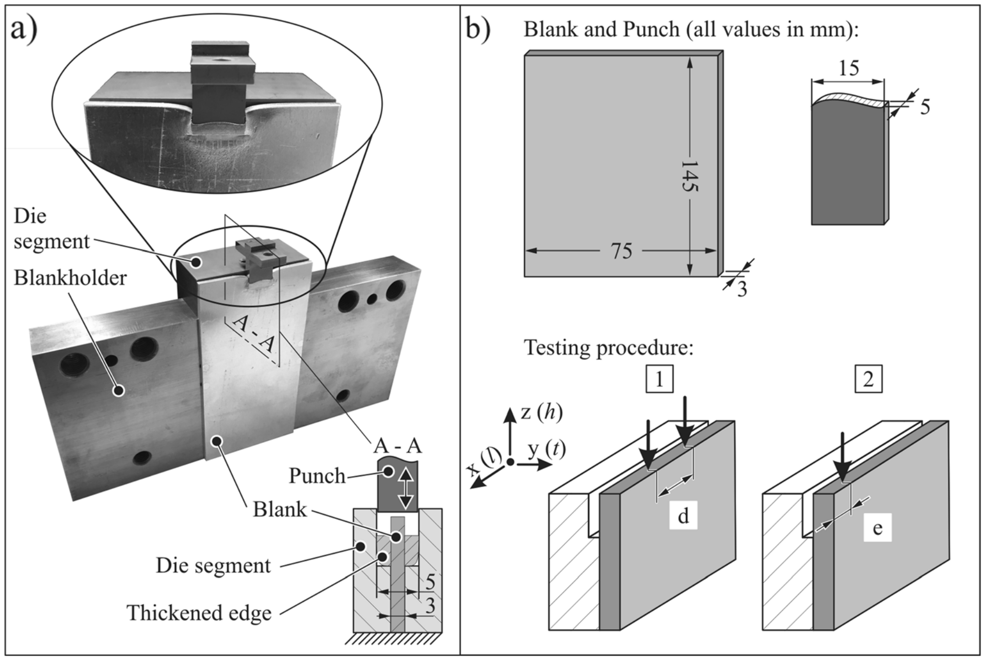


Fig. 2 Indentation of a rectangular sheet blank by a flat punch along the direction perpendicular to the sheet thickness. **a** Photograph of the experimental setup (one side open) with a detail showing the working area and the region adjacent to the punch; **b** schematic representation of the punch, rectangular blank and testing procedure

3 Finite element modelling

The incremental forming of gears by indentation along the direction perpendicular to the sheet thickness was simulated with the commercial finite element computer program Simufact.forming12.

The models made use of the rotational symmetry conditions of the process in order to discretize only a circular sector of the disk blanks (Fig. 4). The disk blanks were modelled as elastic–plastic deformable objects, and their geometry was discretized by means of approximately 340,000 hexahedral elements. The mechanical properties of the material are given in Eq. (1) and Table 1.

The punch and tools were modelled as rigid objects, and their geometry was discretized by means of triangular spatial elements. Contact with friction along the surface of these objects was modelled by means of the Coulomb friction law ($\mu = 0.15$) [12].

The numerical simulation of the process made use of an updated Lagrangian description of motion, and the required deformation was accomplished through a succession of punch displacement increments each of one corresponding to

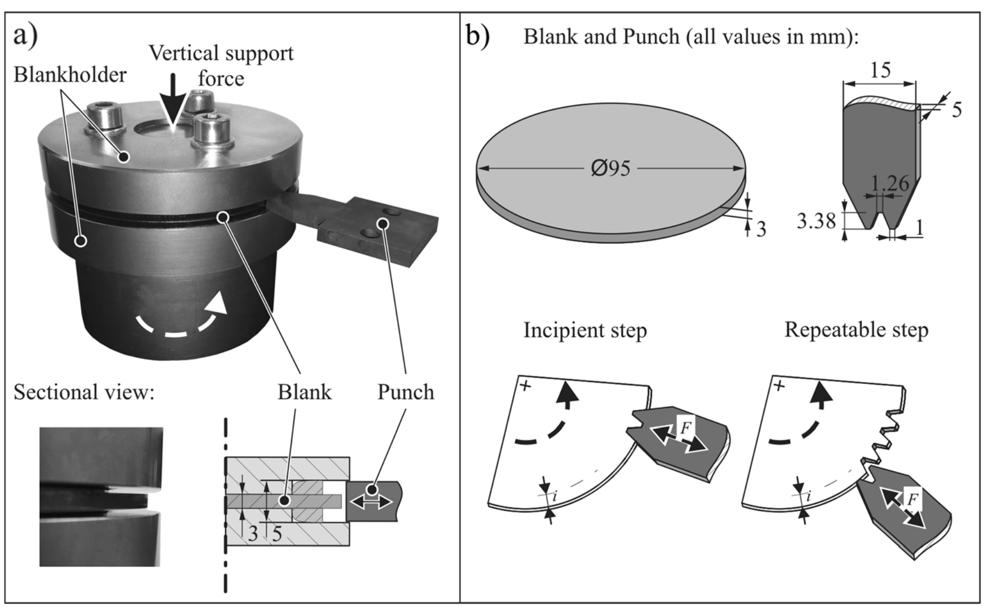


Fig. 3 Incremental SBMF of gears by indentation along the direction perpendicular to the sheet thickness. **a** Photograph of the experimental setup with a detail showing the working area; **b** schematic representation of the punch, disk blanks and testing procedure

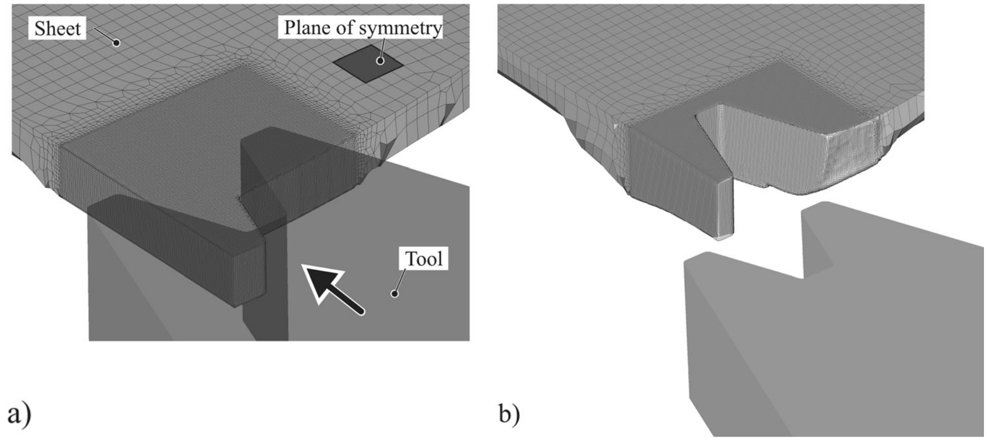


Fig. 4 Finite element model of a circular disk blank **a** before and **b** after being compressed by the gear tooth punch

0.014 mm in the radial direction. Automatic remeshing was used in order to control mesh distortion and to minimize the geometric interference between deformable and rigid objects.

The overall central processing unit (CPU) time for a typical analysis consisting of a finite element model similar to that shown in Fig. 4 was approximately 6 h on a computer equipped with two Intel Xeon CPU (3.4 GHz) processors and making use of 12 physical cores.

4 Results and discussion

4.1 Indentation of a rectangular sheet blank with a flat punch

The evolution of the force with displacement during the indentation of a rectangular sheet blank along the direction perpendicular to the thickness is influenced by the distance between successive indentations and by the distance from the indentation to the edge width. The first influence is controlled by the extent of the plastic deformation region and by the material strain hardening resulting from the previous indentation. The second influence is due to material sideway spread effects (free flow) at the edge width.

In general terms, the overall requirements should be similar to those specifying the minimum distance between the centres of two adjacent indentations and between the centre of any indentation and the edge of a test piece during hardness measurements [13].

As seen in Fig. 5a, the force grows monotonically with displacement for all test cases. The upper tails associated to the higher growing rates start at approximately 5.5 mm displacement and correspond to the transition from free to constraint thickening due to the filling up of the die cavity, as it was previously explained by Sieczkarek et al. [10]. The final decrease in force is due to unloading after finishing the indentations.

Under these circumstances, the new information generated by the present investigation is the observation that strain hardening resulting from the first indentation may increase the maximum indentation force by as much as 24 % whenever the distance d between the centres of two adjacent indentations is very small. In fact, as seen in Fig. 5a, only for a distance corresponding to $d = 22.5$ mm, there is no influence from adjacent indentations.

The photograph in Fig. 5b shows the two extreme test cases and allows anticipating that indentations utilized in the incremental SBMF of disk gears will be influenced by strain hardening resulting from previous adjacent indentations.

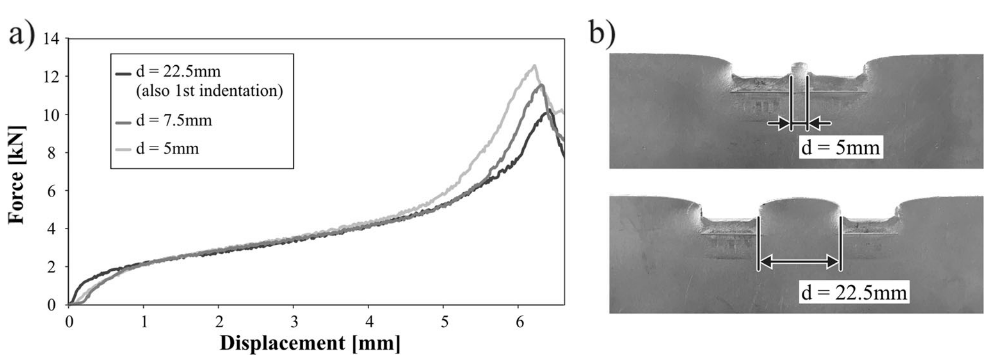


Fig. 5 Indentation of a rectangular sheet blank of EN AW-1050A aluminium with a flat punch. **a** Evolution of the force with displacement as a function of the distance d between the centre of two adjacent indentations; **b** photograph showing the two extreme test cases $d = 5$ mm and $d = 22.5$ mm

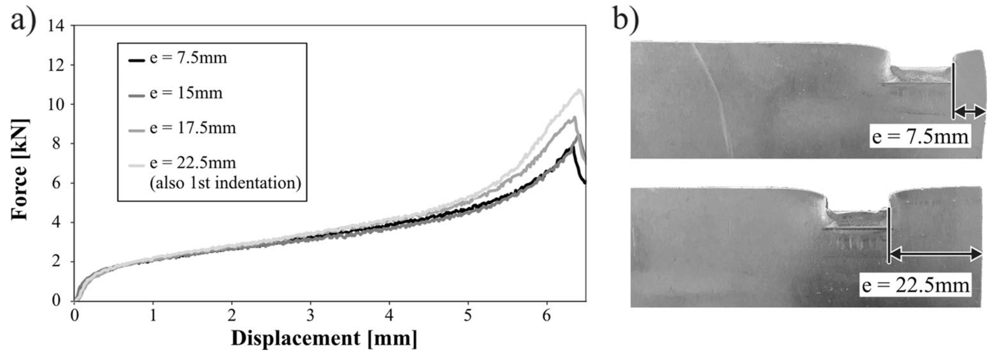


Fig. 6 Indentation of a rectangular sheet blank of EN AW-1050A aluminium with a flat punch. **a** Evolution of the force with displacement as a function of the distance *e* between the centre of an indentation and the edge width of the rectangular blanks; **b** photograph showing the two extreme test cases *e* = 7.5 mm and *e* = 22.5 mm

The influence of material sideway spread effects due to free (or near free) plastic flow on the evolution of the force with displacement is shown in Fig. 6a. As seen in the figure, as closer to the width edge the indentation is performed, as smaller the maximum indentation load becomes because material flowing sideways diminishes thickening and the constraint associated with the filling up of the die cavity. For distances e < 17.5 mm, the reduction of force can reach values above 28 %.

The photograph in Fig. 6b shows the two extreme test cases used in this investigation and allow anticipating that free flow and material sideway spread during the second indentation will also play a role in the deformation mechanics of disk gears produced by incremental SBMF. This will be analysed in the following sections of the paper.

4.2 Indentation of a circular disk blank with a gear tooth punch

Figure 7 shows the finite element predicted force-displacement curves for the first and second indentations of a circular disk blank with a gear tooth punch. As seen, the dashed curve obtained after dividing by two the force of the first indentation is comparable with that of the second indentation. The agreement between these two curves is understandable because the first tooth is formed by simultaneous indentation of the left and right punch wedges, whereas the second tooth is formed by the indentation of a single punch wedge (refer to the finite element insets in Fig. 7).

However, a closer observation of the two above-mentioned curves allows identifying some differences between the

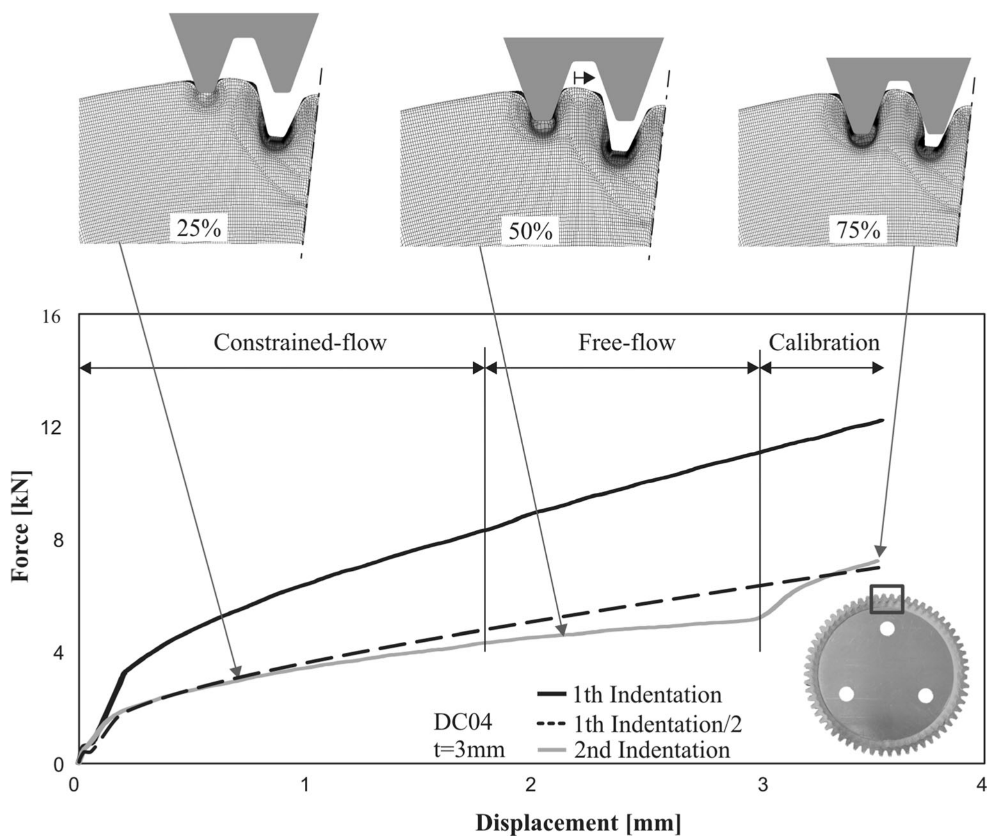


Fig. 7 Numerical evolution of the force with displacement for the indentation of a circular disk blank of DC04 steel with a gear tooth punch. Insets show the finite element predicted geometry at various stages of the second indentation (values in percentage of the required punch displacement)

deformation mechanics of the first (incipient) and second (as well as the following repeatable) indentations. In fact, three different forming stages may be distinguished: (i) the indentation stage with constrained sideway spread, (ii) the indentation stage with free sideway spread and (iii) the final calibration stage.

The evolution of the force-displacement curve during the first stage presents a monotonic increase of the force with displacement, which is identical in both first (refer to the black dashed curve) and second indentations. The second stage reveals some differences between the two force-displacement curves that are caused by free sideway spread occurring in the second indentation. This explains the smaller growing rate of the force with displacement in the second stage. During the third stage, there is a sudden force growth from a lower level that corresponds to the final calibration of the tooth geometry

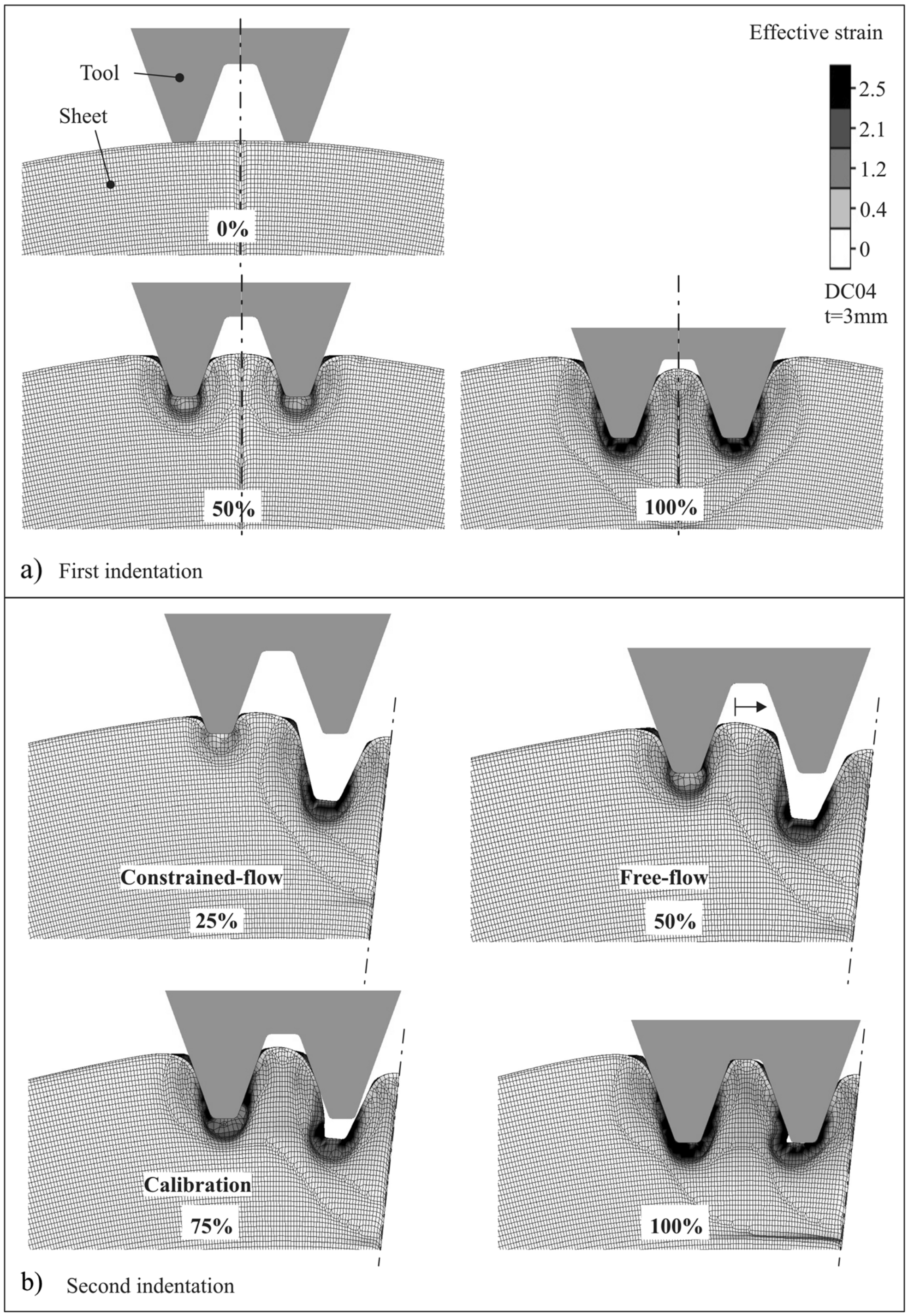


Fig. 8 Indentation of a circular disk blank of DC04 steel with a gear tooth punch. **a** Finite element predicted geometry and distribution of effective strain during the first indentation at different percentages of the desired punch displacement; **b** finite element predicted geometry and distribution of effective strain during the second indentation at different percentages of the desired punch displacement

by filling up the free space in between the left and right punch wedges.

The second and third stages are not observed in the force-displacement curve of the first indentation, which increases monotonically until the end of stroke. This evolution is attributed to the fact that simultaneous indentation by the left and right punch wedges is constrained by adjacent non-deforming material.

In addition, it is possible to explain the above-mentioned variations of the force-displacement curve in the light of the previous investigation on the indentation of a rectangular blank with a flat punch (Section 4.1). In fact, the decrease of force during the second stage is similar to that observed in Fig. 6 where the indentation force decreases with the closeness to the width edge of the rectangular sheet blank. The sudden increase of force during the last instants of the second indentation is mainly due to the resistance of material to flow into the region placed in between the left and right punch wedges as a result of strain hardening produced by the first indentation. In fact, this increase of force is identical to the final upper tails disclosed in Fig. 5 that are due to strain hardening resulting from the first indentation when the distance between the centres of two adjacent indentations is very small.

The differences between the deformation mechanics of the first (incipient) and second (repeatable) indentations are further illustrated in Fig. 8. The first tooth is shaped by simultaneous indentation of the left and right punch wedges with significant constraint from the adjacent volume of non-deforming material. This causes underfilling of the first tooth and a significant extent of the plastic deformation region (and strain hardening) into the neighbouring material (Fig. 8a). In contrast, the second tooth is shaped by indentation under a competition between constrained flow, free flow and strain hardening. Constrained flow prevails at the early stages of deformation, free flow at the mid stages of deformation and strain hardening effects resulting from previous indentation are mainly important at the last instants of the process (Fig. 8b). These differences explain the reason why the deformation mechanics of the first tooth of the disk gear is different from that of the second and remaining teeth.

4.3 Fabrication of sound disk gears by incremental sheet-bulk metal forming

The differences between incipient and repeatable plastic flow in the incremental SBMF of disk gears that were analysed in the previous sections of this paper allow understanding the reasons behind underfilling in the first indentation. The strategy to overcome the underfilling defect and produce sound disk gears consisted in utilizing tailored disk blanks with uniform initial thickness t_0 and additional volume in the region where the first indentation will take place. This ensured adequate thickening and filling of the first gear tooth.

The additional volume is schematically represented in Fig. 9a and is characterized by the thickness t_b of the bottom land, the thickness t_t of the top land, the height h from the bottom to the top land, the angle θ between the bottom and top land and the fillet radius where the inclined edge of the volume joins the bottom and top land.

Figure 9b–d show three selected results obtained from the systematic finite element investigation that was carried out in order to determine an appropriate geometry for the additional volume of the tailored disk blank. This methodology was selected in order to prevent trial-and-error procedures derived from a broader experimental work plan involving different geometries of the tailored disk blanks.

As seen in the figures, three different situations are likely to occur as a result of the material flow inside the punch cavity.

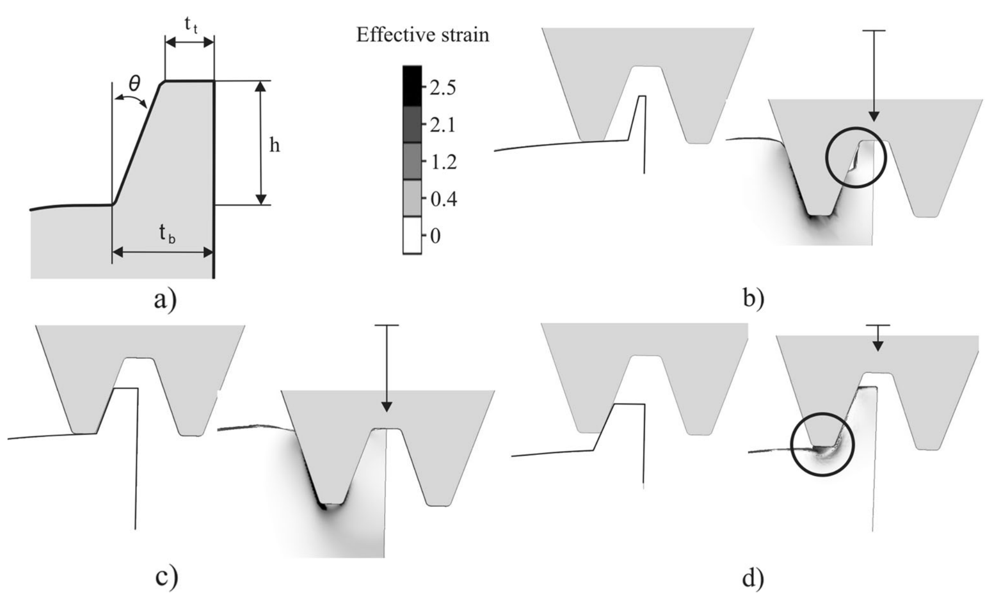


Fig. 9 Tailored disk blank of DC04 steel with additional volume in the region of the first indentation. **a** Schematic representation of the additional volume with notation; **b** initial and finite element predicted geometry for a test case corresponding to $t_b = 0.75$, $t_t = 0.27$, $h = 1$ (mm); **c** initial and finite element predicted geometry for a test case corresponding to $t_b = 1.5$, $t_t = 1$, $h = 1$ (mm); **d** initial and finite element predicted geometry for a test case corresponding to $t_b = 2.5$, $t_t = 1.3$, $h = 1$ (mm)

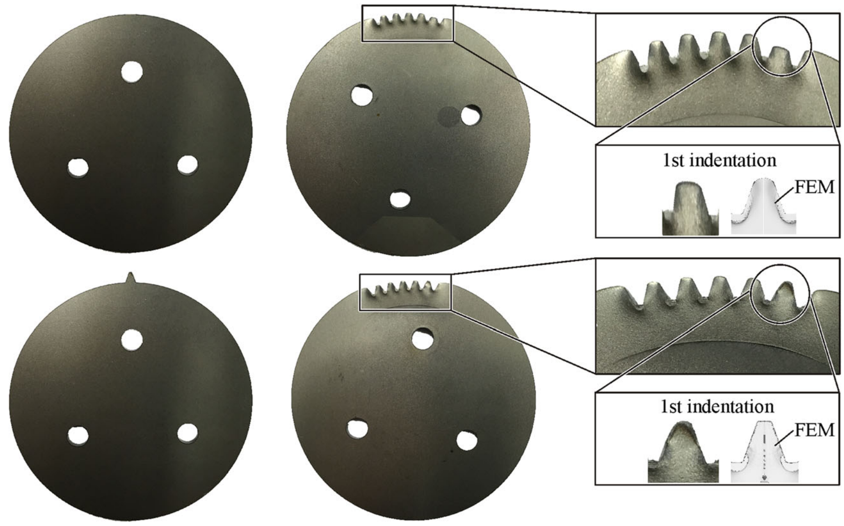


Fig. 10 Gears produced by incremental SBMF along the direction perpendicular to the sheet thickness. **a** Photograph showing gears produced from a standard disk blank and from a tailored disk blank; **b** detail of the teeth adjacent to the first indentation for both cases shown in (**a**) with a comparison between the experimental and the finite element predicted profiles of the tooth produced by the first indentation

For example, if the additional volume is slender and insufficient to fill the die cavity completely, the material will fold back on itself and create a defect (refer to the zone located inside the black circle of Fig. 9b).

On the other hand, if the additional volume is oversized, the excess material will flow around the fillet radius where the inclined edge joins the bottom land and will give rise to unacceptable material superposition (refer to the zone located inside the black circle of Fig. 9d). Both situations are undesirable and will give rise to forming defects during the first indentation.

In contrast, the finite element simulation conditions of Fig. 9c seem to be capable of ensuring the indentation of the first tooth without defects. In fact, by using a tailored disk blank with the additional volume ($t_b = 1.5$ mm, $t_t = 1$ mm, $h = 1$ mm, $\theta = 20°$) shown in Fig. 9c, it was possible to produce the sound gear that is pictured in Fig. 10a. The details of the teeth and the comparison between finite element predicted and experimental obtained geometries that are shown in Fig. 10b further confirm the absence of underfilling defects during the first indentation produced on the tailored disk blank.

To conclude, it is worth noting that the first tooth will have different properties from the remaining teeth due to differences in the amount of strain hardening resulting from the overall indentation process. These differences may be relevant for predicting and setting the final properties of the disk gear [14] but can be easily overcome if the product is subject to induction tempering after being formed.

5 Conclusions

This paper presents a new incremental SBMF process to produce disk gears by indentation along the direction perpendicular to the sheet thickness. The new proposed process is different from all the existing forming and cutting process where application of loading is mainly performed perpendicular to the sheet surface.

Experimentation and three-dimensional finite element modelling allow understanding the interaction between the multiple adjacent indentations that are required to produce the disk gears. Constrained material flow plays a key role in the first (incipient) indentation, whereas strain hardening and free-material flow are critical for the remaining (repeatable) indentations.

The investigation showed that the underfilling of the punch cavity during the first indentation may be successfully prevented by utilizing tailored disk blanks with additional localized volume in the region where the first indentation will take place.

The design of the additional localized volume was performed by finite element modelling. Results show that slenderness and oversized shapes should be avoided in order to prevent folding or material superposition around the fillet radius where the inclined edge joins the bottom land of the additional localized volume.

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