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Effects of process parameters on the deformation energy in a sheet-bulk metal forming process for an automotive component

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Abstract

The present study investigates the effects of the process parameters on cold forming process of an automotive component in AISI 1006 low carbon steel. The material formability was characterised up to 250°C. The material flow behaviour and the related thermal distributions during the geometrical transformations were analyzed. Coining and forming operations were investigated by using a coupled 3D Thermo-mechanical FEM with different die geometries and friction conditions in order to optimize the final die geometry and to reduce the energy consumption. FEM simulation results were validated by comparison with the experimental trials. The detailed study of the component allowed defining the energy required by the severe bending of the initial thick plate. The FEM predictions led to a reduction of deformation energy of about 20%, a mass reduction of 28% on the final product and permitted avoiding secondary machining operations.

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Keywords: Sheet-bulk; Energy efficiency; Manufacturing control strategies; Coining; Metal forming

1. Introduction

The continuous market demand for lightweight products, together with the need for sustainable processes, has driven several scientific investigators towards the study of the energy consumption for the manufacturing processes, mainly in the production of automotive industry components.

In literature, different approaches are proposed to optimize the process chain by investigating and calculating the energy consumption related to geometrical transformations and material flow. Moses and Weinert investigated holistically the energetic efficiency, in a term of manufacturing control strategies, by mapping the product variant related energy profiles for each equipment [1]. Ohara et al. focused the research both on the energy required in sheet forming and related mechanical properties for hot-rolled products [2]. Differently, Shrouf et al. devoted their studies to create an analytical model for minimizing energy in process scheduling, using genetic and heuristic algorithms to find the best schedule for reducing energy costs [3]. In solving the problem by modelling, Ghadimi et al. created an MEFA (Material and Energy Flow Analysis) model representing a road map to optimize parameters in a real manufacturing process layout, considering the need to integrate material and energy flow to reach the final goal to optimizing the results [4]. In a complete overview of energy consumption in different processes, Polyblank et al. underlined the importance of considering a closed-loop control of metal forming properties, showing the example of a real case for strip and ring rolling and incremental forging and many others forming operations [5]. Also, Skelton and Allwood explore an input-output model to evaluate material saving, considering also taxes, incentives, and labour costs, depicting a wide concept of energy saving [6]. Eberspächer dedicated his research to the milling machine monitoring approach by creating a holistic model [7]. Salonitis and Ball presented an overview on energy saving approaches focusing both on machine tools and the relationship of the results during production processes, whereas Apostolos et al. discussed various energy saving approaches for conventional and non-conventional automotive processes, aeronautics and

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white goods by giving some practical suggestions on improving the efficiency [8,9].

Duflou et al. provided an important contribution by investigating a systematic and structured approach made up by system scale for different kinds of the industry, by focusing on a single unit to supply chain [10]. In order to consider an important contribution in terms of modelling, Bi and Wang proposed an explicit relational model between machining parameters and energy costs using an analytical approach to solve the problem [11]. Wen et al. considered an example of using a grinding case in their model-approach [12]. The interest in energy optimization is well described by Cheng et al. who introduced the concept of cloud manufacturing, including the analysis of costs and risks [13]. Arif et al. worked on energy optimization during machining operations by analysing single pass and multi-passes process parameters, giving interesting consideration on tool life [14].

In this paper, the authors created a 3D Thermo-mechanical FE model to describe a severe bending on an automotive component with complex geometry, considering the parameter effects in sheet-bulk metal forming [15] and the material workability model [16,17]. Similarly to Ghani et al. who focused on the optimization of dynamic properties such as torque and mass; the present work focus on the reduction of energy by optimizing material flow [18].

This aim is reached by implementing a method able to a self-combine some parameters, depending on the cost weight of each, to reduce deformation energy and to respect final geometrical tolerances. FEM simulations were performed to investigate the parameters set and their effects on the process; experimental tests to validate the model were carried out in conjunction with a deep investigation on material properties and friction conditions. An optimization rule on the energy supplied to the workpiece for deformation was proposed by considering energy and material flows during the geometrical transformations. The results show a 28% saving of the total initial workpiece mass and about 20% of the total energy supplied by the mechanical press; furthermore, secondary operations necessary to reach the final desired tolerances were avoided.

2. Experimental procedures

Experimental tests were performed to set the mechanical properties of the material used for the component under investigation an AISI 1006 low carbon steel.

The friction conditions, which play a very important role during the severe bending of a thick plate, particularly during the coining operation, were experimentally tested [19,20]. To validate the FEM model and to confirm the experimental results reached by the investigation, experimental validations were carried out assuming the same model conditions. Torsion tests were carried out on cylindrical samples machined from the plate at different orientations regarding the rolling direction, i.e. 0°, 45°, and 90°. Torsion tests permit to get equivalent strains higher than those obtainable by tensile and compression tests and are comparable with the strains occurring in real processes.

The samples were deformed up to rupture at different temperatures, from 25 to 250 °C, and a strain rate of 0.5 s^{-1}. Thus, it permits covering the temperature range of the workpiece. The increase in temperature during coining operations is related to adiabatic heating. The torsion test machine is shown in Fig.1a where the specimen position is in the rectangular in which the induction heating system is also represented. A representative flow curves is shown in Fig.1b. Material behaviour law, obtained by torsion tests, is described in Eq. (1), no significant effect of the temperature on the stress is observed up to 250°C.

$$\bar{\sigma}\,[MPa] = 160 \cdot \bar{\varepsilon}^{0,45} + 300 \quad (1)$$

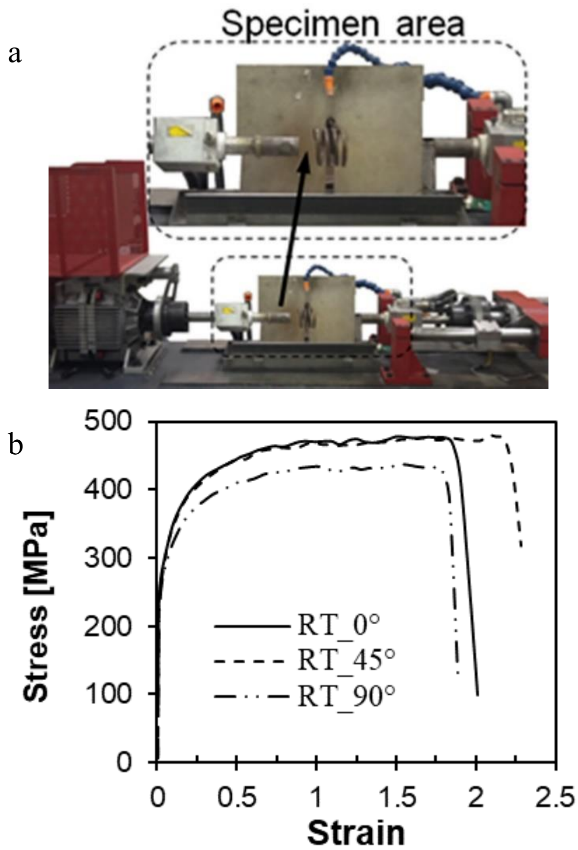


Fig. 1. (a) torsion test machine with induction system highlighted in the rectangular; (b) torsion test results at room temperature with specimens oriented with different rolling directions.

The part under investigation and an operation mock-up, formed in two steps, are illustrated in Fig.2a. The first step is performed by using a conical punch, the most relevant dimensions of which are reported in Fig.2b. The second step is a coining operation, necessary in order to obtain the final tolerances, especially on lateral surfaces, as shown in Fig.2c. These steps are carried out in a mechanical press with about 0,4 CPM and a maximum stroke of 450 mm. In the first operation, a severe bending deformation is obtained in order to give to the workpiece the final cylindrical shape; in the second step, the severe bending is considerably highlighted in the workpiece internal curvature, where it is high the breaking risk promoted from the very small curvature radius. To understand the problem and study the effects of the most important process parameters, a 3D Thermo-mechanical finite element model has been set up to analyse both the forces and energy during the process and to avoid the problems as well before the experimental validation. Force-stroke trends for the two forming operations were measured with a pre-calibrated load cell mounted on the die.

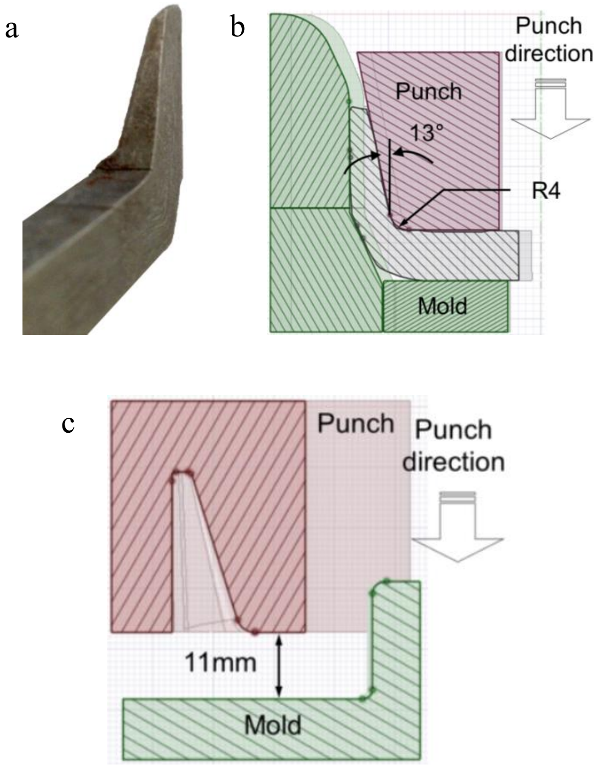


Fig. 2. Simplified scheme of the forming operations performed: (a) on the workpiece; (b) coining operation and die design; (c) lateral profile forming step scheme.

2.1 Finite element modelling and analysis

The initial geometry of the product analyzed in this work was obtained by a thick plate of 10 mm with a triangular profile as shown in Fig.3, where the most important dimensions are indicated. Fig.3a shows a plane profile of the initial unoptimized workpiece, where the central zone is represented by a dotted rectangle. The upper part of Fig.4a shows a real workpiece while, in the lowest part, the CAD model that was used for FEM discretization. This profile, which provides an excessive material flow in the coining cavity operation, is then optimized by analyzing deformation energy during the complete process. In Fig.3b, the lateral view of the initial workpiece is also evidenced, which focuses on the surface roughness; in the central area, as highlighted in the black rectangle in Fig.3b, the blanking profile for FE simulation was measured directly from the real trimmed workpiece. To get a reliable model, the initial geometry was divided into about 100.000 tetrahedron elements of 0,06 mm^3 each. The initial meshed workpiece is shown in Fig.4, a symmetry plane was considered to reduce the computing time.

The element distribution was increased in the bending zone for which it was relevant to assess stresses and deformation as well as the final curvature radii responsible for potential crack initiation.

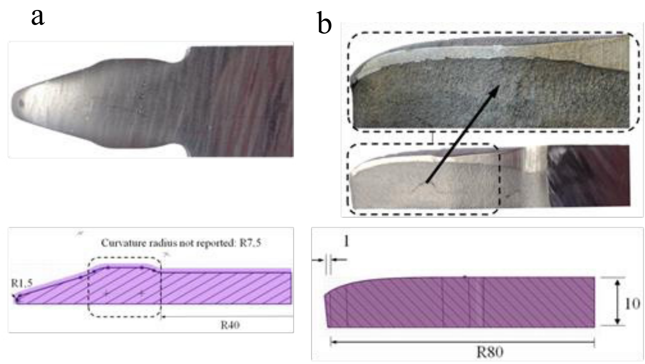


Fig. 3. Initial workpiece geometry for the severe bending operation: (a) plane profile and lateral side (b) (units are in mm).

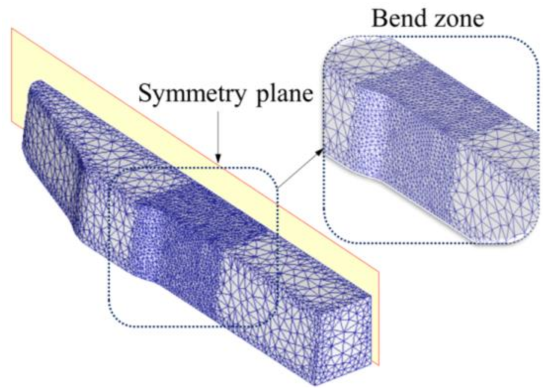


Fig. 4. Mesh and symmetry conditions of the simulated workpiece.

3. Results

To study both the material and energy fluxes, a first set of simulations was carried out to investigate the proper set of parameters and their effects on the properties of the part. After simulating with the parameters shown in Table 1, the comparison of the numerical results with the experimental values shows that a very low curvature radius is reached, and that the formation of a fold occurs at the end of the coining step. The results of the first set of experimental tests to produce the part are shown in Fig5a and 5b where a middle plane section of an unoptimized specimen is represented. To confirm the correct assembly of the part, some dimensions were measured. In particular, horn height and length were checked against the design tolerances. As observed in Fig.5a a lateral fold at the internal curvature was achieved. This fold in the 'non-optimised' workpiece represents a defect that must be avoided to preserve the part from rupture risk and save material. A stress concentration was evident in the area close to the fold (Fig 5c). To reduce the fold and optimize the whole process, the combined flow of material and energy was analyzed with the purpose of optimizing the workpiece profile and the die geometry, and to give a suitable shape for the second step where the reverse vertical material flow enhances the effect of the fold by reducing its radius. The analysis of the material flow and the specimen, while a larger profile was kept in the central tip portion. This permits better die filling in the coining step through changing circumferential displacements. By changing the lateral punch profile of the coining step, the optimized geometry was achieved: i) providing a reduced thickness at the top of the die cavity, the entrance of the specimen in the coining die is favoured, ii) with the simultaneous reduction of the bottom thickness, the burr is avoided. Consequently, increasing the circumferential thickness at the central zone of the specimen permits us to obtain a good filling of the coining die cavity. The aforementioned effects were attained by means of a coining punch with a three-angled lateral profile.

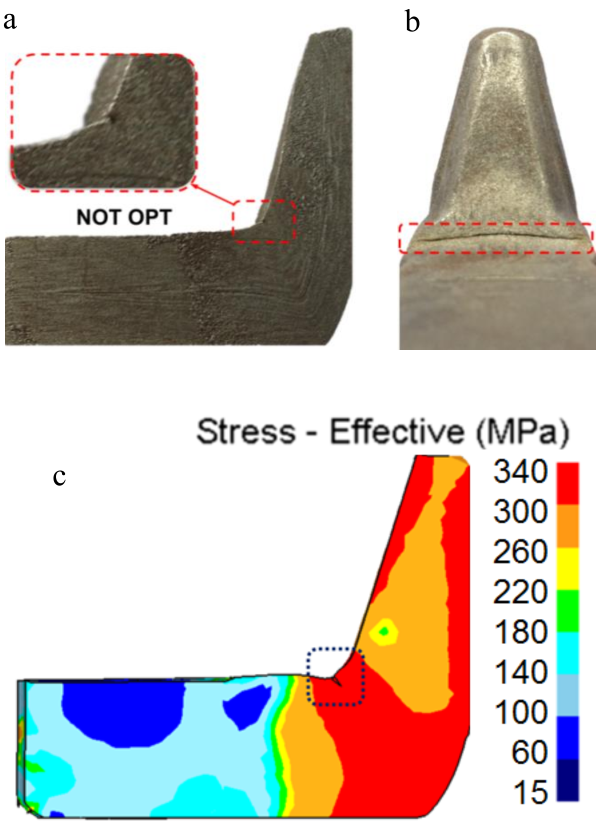


Fig. 5. Early simulations and experimental results: (a) particular of the fold in the inner surface of the horn; (b) real workpiece section with fold highlighted; (c) von Mises effective stress on the symmetry plane.

The new set of parameters is shown in Table 1. where the three angles coining punch was considered in order to obtain the desired effects on the lateral specimen profile. The FE code could launch different simulations automatically by implementing a user routine in which a single parameter is fixed and the others are considered variable; the parameter was considered acceptable when the deformation energy reaches the minimum; subsequently, it is possible to repeat the energy optimization for another parameter. The routine ends after optimizing all the parameters.

The results of the second set of simulations are shown in Fig.6, where the optimized parameters are described, and the vertical positioning angles of the coining punch are illustrated.

In Fig.6a, a simplified coining punch section is represented with its parametric angles, indicated with Greek letters.

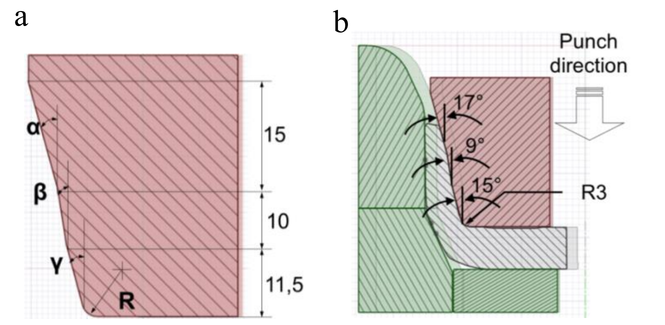


Fig. 6. Results of the second set of simulations without optimization: (a) coining punch model with parameters; (b) scheme of the coining operation at the end of the punch stroke.

Table 1. Parameters set analyzed through the simulations.

	N. sim.	1	2	3	4	5	6	7	8	9	10	11	12
Parameters	R	4	4	5	3	3	3	3	3	3	3	3	3
	α	13°	14°	14°	14°	15°	15°	15°	15°	15°	15°	15°	15°
	β						11°	10°	9°	8°	9°	9°	9°
	γ										15°	16°	17°

Moreover, in Fig.6b, the final optimized values indicate the results of the total optimization calculation, which are shown to indicate the final punch profile, used to obtain the optimized part. The flat punch surface is not influencing the specimen's inner surface and stress concentration in the fold.

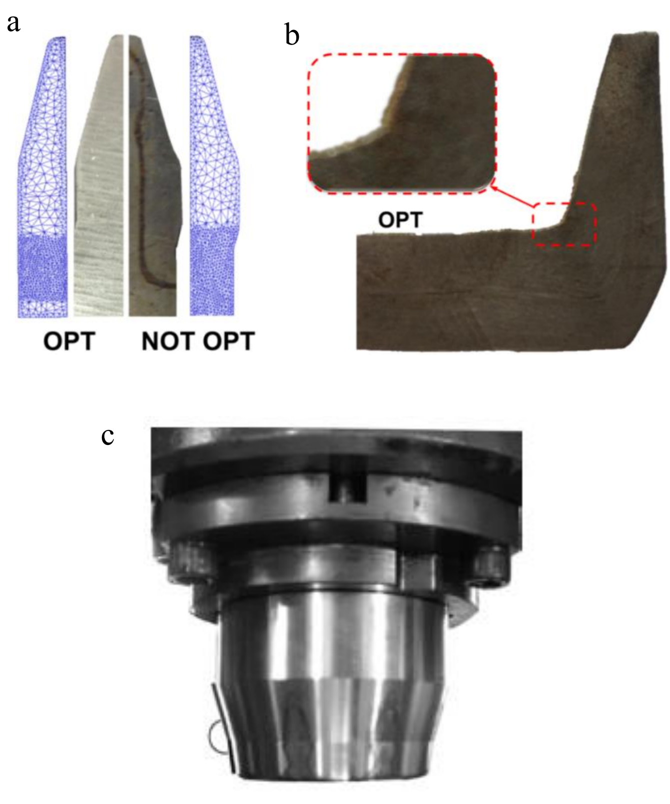


Fig. 7. (a) comparison between the optimized and unoptimized profiles; (b) detail of the central part in the workpiece highlighting the optimum curvature and (c) optimized coining punch.

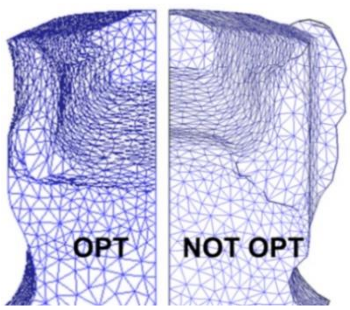
The same test plan used for FEM based simulations was reproduced experimentally by performing 5 repetitions for each parameters group. The results in terms of comparison between optimized and unoptimized shapes are depicted in the following discussions. Introducing the new punch geometry permitted differential strain distribution in the workpiece and allowed saving about 28% of the workpiece mass.

The saved material is located at half height of the workpiece and the new punch permits a larger circumferential material flow without burr formation. Initial workpieces for both optimized and unoptimized solutions are shown in Fig.7a, while in Fig.7b a mid-height section of the profile obtained with the optimized shape is shown together with the optimized coining punch used during experiments (Fig.7c). As described above, the optimized profile gave the possibility to get a larger curvature in the inner surface, avoiding critical zones for crack initiation.

Using a 3D Thermo-mechanical FE model, an optimal solution was automatically calculated, in terms of deformation energy to provide by the mechanical press, leading to change the die geometry and consequently the workpiece profile. Conduction and natural convection mechanisms were considered for heat exchanging. The temperature profile was calculated for both optimized and unoptimized simulations to validate the effects of modeling in terms of friction forces reduction on the optimized workpiece.

The new initial profile was tightened near to the bend zone and this condition, because of a better material flow direction, allowed to avoid burr formation in the final workpiece, as shown in the comparison reported in Fig.8a. Minimizing material and optimizing flow direction and deformation energy allowed to reduce the fold in the internal curvature profile (Fig.8b) and permitted to increase the mechanical strength of the part. The lateral surface roughness is consistently reduced after optimization, due to the complete mold filling. Material flow lines, in fact, better replicate coiner cavities and no flows directed perpendicular regarding the lateral surface were found.

a



b

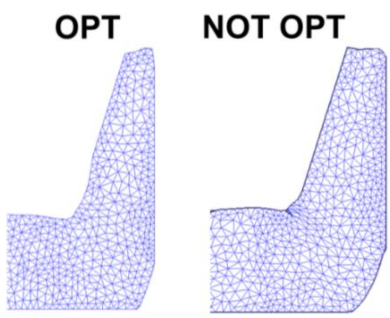


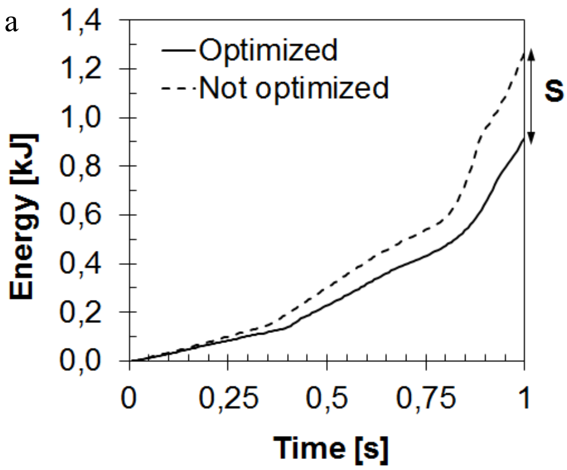
Fig. 8. FE simulations before and after the optimization: (a) plant profile from blanking punch side; (b) lateral profile at the end of the process.

4. Discussion

From the trend of the energy spent by the mechanical press for the two forming operations as a function of time, it results that about 20% of the total energy required for deformation can be saved, as shown in Fig.9a and marked with “S”.

In addition, a 28% of mass reduction is obtained, to which a further energy saving is achieved by avoiding secondary operations; the better shape achieved after optimization represents an excellent result from an economical viewpoint.

a



b

Fig. 9. (a) Energy vs. time trend for the studied case and saved energy for the complete process; (b) view of the optimized finished workpiece.

The final shape, where the optimized workpiece is in agreement with the design tolerances, is shown in Fig.9b. In particular, it can be seen as a slight roughness of the lateral surface and absence of burrs as well as the fold at the inner radius of the horn.

The optimization effect on the strain in the vertical directions was significant during the complete process as presented in Fig.10a and confirmed by observing the final cumulative strain at the end of the last operation, as shown in Fig.10b. Two different strain trends are observed, i.e. A and B in Fig.10 a, where A is for coining, and B is for the last forming operation. Confirming the energy trends, the strain in the vertical direction in Fig.10b also showed a material excess on the lateral horn basis underlined by the red rectangle and consequently causing the formation of the internal fold.

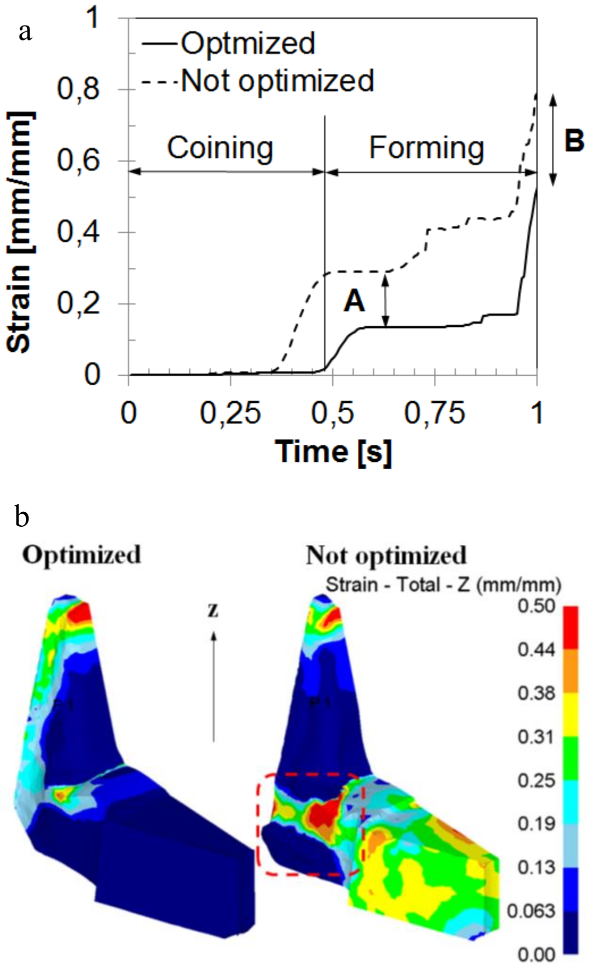


Fig. 10. (a) Strain as a function of time trend in both coining and forming operations; (b) view of the finished workpieces with burr highlighted.

Conclusion

The comparison of numerical modelling by experimentation has confirmed that the study permitted minimizing the energy consumption of the mechanical press and led to a new die shape able to favor the material flow as required by the designer. Modifying the material flow made possible the re-distribution of the workpiece mass and consequently the energy required to obtain the product. This approach, validated by the research on the material properties and friction conditions during the real process, led to a mass reduction of 28% on the final product which represents a very good outcome for an automotive component; moreover, it permits to minimize by about 20% the total energy supplied by the mechanical press. Finally, costs for finishing operations were avoided, with considerable benefit for the entire process chain.

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References

[1] Moses C, Weinert N. Process chain evaluation for an overall optimization of energy efficiency in manufacturing - The welding case. Robotics and Computer-Integrated Manufacturing 2015;34:44-51.
[2] Ohara K, Tsugeno M, et al. Process optimization for the manufacturing of sheets with estimated balance between product quality and energy consumption. CIRP Annals - Manufacturing Technology 2014;63:257-260.
[3] Shrouf F, Ordieres-Meré J, et al. Optimizing the production scheduling of a single machine to minimize total energy consumption costs, Journal of Cleaner Production 2014;67:197-207.
[4] Ghadimi P, Lia W, Karaa S, et al. Integrated Material and Energy Flow Analysis towards Energy Efficient Manufacturing. Procedia CIRP2014;15:117-122.
[5] Polyblank JA, Allwood JM, Duncan SR. Closed-loop control of product properties in metal forming: A review and prospectus. Journal of Materials Processing Technology 2014;214:2333-2348.
[6] Skelton ACH, Allwood JM. The incentives for supply chain collaboration to improve material efficiency in the use of steel: An analysis using input output techniques, *Ecological Economics* 2013;89:33-42.
[7] Eberspächer P, Schraml P, et al. A model-and signal-based power consumption monitoring concept for energetic optimization of machine tools. Procedia CIRP 2014;15:44-49.
[8] Salonitis K, Ball P. Energy efficient manufacturing from machine tools to manufacturing systems. Procedia CIRP 2013;7:634-639.
[9] Apostolos F, Papacharalampopoulos A, et al. Energy Efficiency of Manufacturing Processes: A Critical Review. Procedia CIRP 2013;7:628-633.
[10] Duflou JR, Sutherland JW, Dornfeld D, et al. Towards energy and resource efficient manufacturing: A processes and systems approach. CIRP Annals - Manufacturing Technology 2012;61:587-609.
[11] Bi ZM, Wang L. Optimization of machining processes from the perspective of energy consumption: A case study. Journal of Manufacturing Systems 2012;31(4):420-428.
[12] Wen L, Winter M, et al. Eco-efficiency of manufacturing processes: A grinding case. CIRP Annals - Manufacturing Technology 2012;61:59-62.
[13] Cheng Ya, Tao F, Liu Y, Zhao D, Zhang L, Xu L, Energy-aware resource service scheduling based on utility evaluation in cloud manufacturing system. Proceedings of the Institution of Mechanical Engineers, Part B: J of Engineering Manufacture 2013;227-12:1901-1915.
[14] Arif M, Stroud IA, Akten O. A model to determine the optimal parameters for sustainable-energy machining in a multi-pass turning operation. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 2014;228(6):866-877.
[15] Merklein M, Allwood JM, Behrens BA et al. Bulk forming of sheet metal. CIRP Annals - Manufacturing Technology 2012;61:725-745.
[16] El Mehtedi M, Gabrielli F, Spigarelli S. Hot workability in process modeling of a bearing steel by using combined constitutive equations and dynamic material model. Materials and Design 2014;53:398-404.
[17] Evangelista E, Masini M, El Mehtedi M, Spigarelli S, Hot working and multipass deformation of a 41Cr4 steel. Journal of Alloys and Compounds 2004;378(1-2):151-154
[18] Ghani U, Monfared RP, Harrison R. Energy optimisation in manufacturing systems using virtual engineering-driven discrete event simulation, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 2012, 226(11):1914-1929.
[19] D'Annibale A, El Mehtedi M, Di Ilio A, Gabrielli F and Panaccio L. Investigation on friction conditions during a severe bending deformation on a thick plate. Key Engineering Materials 2016;716:176-183.
[20] D'Annibale A, El Mehtedi M, Panaccio L, Di Ilio A, Gabrielli F. Investigation on process parameters affecting blanking of AISI 1006 low carbon steel. AIP Conference Proceedings 2016;1769,080013.