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Flexible Incremental Roller Flanging process for metal sheets profiles

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Abstract

Metal forming processes usually require high investment due to expensive plants and machinery, and, above all, the need of tailored tooling, which often limits their applicability to medium or large size production batches. Such economic issues become even more critical as the shape complexity or the parts dimensions rise, due to increased costs for material and equipment. As a consequence, to play in the metalforming market companies have to be capital intensive, which means that they have a high financial exposition and are heavily exposed to changes in market demands. In such scenario, made even more complex by the Covid-19 pandemic, flexibility and cost reductions have become fundamental, especially because the short demand is pushing the production towards small batches and highly personalized products. With regard to metal sheet parts, incremental forming appears particularly suitable to accomplish the new market trends, thanks to the use of simpler and cheaper tools to obtain even complex shapes thought multiple passes deformations. The paper presents a novel incremental forming machine to manufacture metal sheets long profiles, which uses one or more couples of rollers controlled by a numerical control. The innovative forming machine is presented together with the numerical model used to assess the influence of the main process parameters. Finally, a case study is evaluated to quantify the economic benefits of the proposed process and machine.

Keywords: sheet forming, incremental forming, roller flanging

1. Introduction

Covid-19 pandemic has been a dramatic shock for the demand of many consumer goods, and, consequently, for the entire manufacturing supply-chain due to a limitation of people movement freedom that is unprecedented in human recent history [1]. Thanks also to the support of governments and institutions, industries reacted by developing new procedures and processes based on agile and flexible approaches. So, words as smart working, remote meetings, distancing in work environment have become more than familiar in few weeks, as alternative ways to grant the production continuity in corporate organization. On the other side, the pandemic boosted the already rising trend of mass-customization and small or micro sized batches, with shorter lead times [2]. As these trends represent an incredible challenge and opportunity, it has been necessary to develop new manufacturing technologies to satisfy the new market needs, and this has to be done in very short time. With regards to sheet metal forming, matching high quality standard of products by using traditional forming operations often requires too expensive dedicated dies, as well as complex and stiff machines [3], in particular in case of small

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batch sizes [4], large or thick components [5], and complex free form parts. So, the challenge is today represented by the manufacturers capability of offering high flexibility, high accuracy, restricted time-to-market as well as restrained production costs to be competitive [6].

A way to overcome these challenges is to develop new processes based on Incremental Forming (IF) approaches, which answer to these needs often using simpler and cost-effective tools [7]. Besides the differences in the specific set-ups, IF approaches apply a local pressure and then a local plastic strain on the components limiting the contact surfaces to reduce the applied forces. However, the tools usually require more complex kinematic, as they are moved over the workpiece to apply subsequent steps of deformation and to achieve larger cumulated values [8]. The incremental approach was already applied in multiple ways to design flexible forming processes [9], for metal sheets parts. However, the higher number of degrees of freedom led to an increased complexity [10], thus requiring several studies to investigate the roles of the toolpaths [11] and of the machine stiffness [12] on the final component characteristics [13].

The paper presents a new incremental forming process to produce elongated thick components together with the machine prototype that has been developed to demonstrate such technology. The proposed machine uses two rollers to form the workpiece, each one with three independent degrees of freedom. After the prototype and tool design, the new process named Incremental Roller Flanging (IRF) was numerically investigated and compared with a traditional V-bending process to assess its capabilities. Finally, a case study was evaluated from an economic point of view, to quantify the savings in case of a small size batch production.

2. Proof-of-concept of Incremental Roller-Flanging (IRF) process

Process	V-bend	Roll forming	Roller hemming	Roller flanging
Tools config.	Single	Multiple	Single	Single
Kinematic	1 axis	1 axis	3+ axis	3+ axis
Productivity	Medium	High	Low	Low
Forces	High	Medium	Low	Low
Stiffness	High	Medium	Low	High
Tool cost	High	High	Low	Low

Fig. 1. Single-step and incremental forming process for long metal sheets components.

As highlighted in the analysis of the scientific literature, the use of an incremental approach allows overcoming several limitations of the single-step forming processes in terms of minimum batch size, maximum load, strain distribution or obtainable geometries. In the case of elongated bent sheet components, different bending processes are available to manufacture a bend in a single stroke. Fig.1 shows as reference, the V bending process, where one or multiple tools are used to bend the sheet along its entire length [14]. Despite the high productivity, this process requires a different toolset for every different bending radius, limiting the economic feasibility of small batch productions [15]. While the maximum length and thickness of the workpieces depends on the machine maximum load capability and stiffness. Then, in the roll forming process [16], multiple rollers with different geometries are used to incrementally form the desired profile. Despite the high number of rollers still limits the minimum batch dimensions, this process has a higher productivity with lower applied forces and required stiffness. However, both processes are not suitable to bend profiles along non-straight trajectories. In this case, the roller hemming process uses a single roller moved by a robotic arm along the component hedge to bend its profile [17]. Despite the high flexibility given by this system, its stiffness is not sufficient when thick or high strength components need to be formed. Finally, Fig. 1 shows the characteristics of IRF process where two or three idle rollers are used to incrementally bend an elongated profile, on a high stiffness system, with multiple strokes along its length. Fig. 2 shows the possible roller and kinematic configurations. In the simplest one, the workpiece hold by a blank-holder is formed by a single roller moving along its length (y-direction) and increasing it vertical coordinate (z-direction) at each forming step. To have a better control of inner bending radius and to increase the stiffness of the workpiece constrains, two or three rollers with different rotation axis can be used. At the same time, a horizontal (x-axis) and tilting movement can be added to each tool to control their contact points with the workpiece.

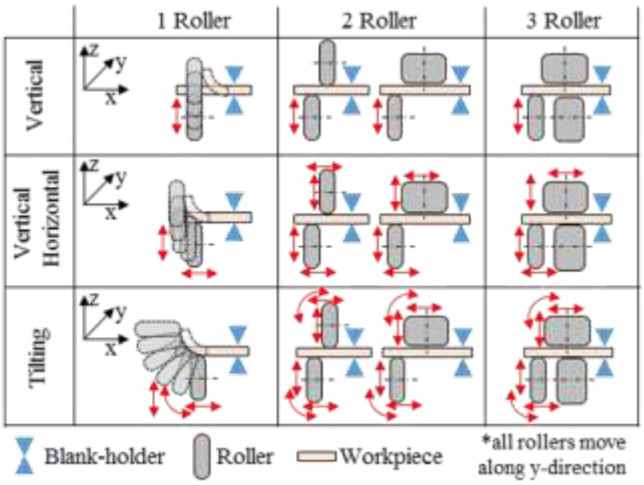

Fig. 2. Possible rollers configurations for Incremental Roller Flanging operations of metal sheets.

The IRF process allows to manufacture complex profiles using simple and cost-effective tools with standard profiles, making this technology suitable for low batch productions, customized workpieces on a wide range of materials and thicknesses.

3. IRF prototype

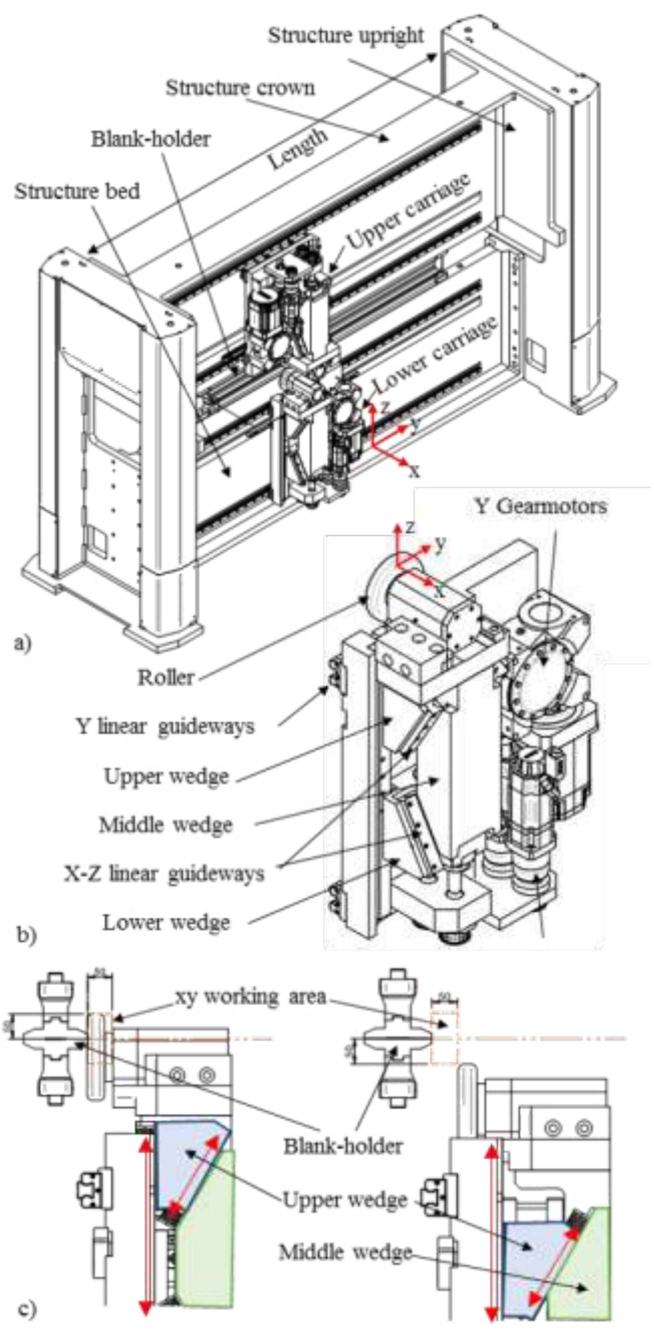

Fig. 3. IRF prototype and details: a) machine, b) carriage, c) vertical and horizontal movements.

On the basis of the above-mentioned configurations, a first prototype of the IRF machine was designed. Fig. 3a) shows the machine frame and its main parts, with the structure crown and bed sustained by the two upright elements. While the structure bed is fixed, the crown can vertically translate thanks to 4 hydraulic-actuators to close the blank-holder. The machine structure is symmetric with respect to both the xz and yz planes, and its length is modular according to the production needs. The first prototype total length is 4100 mm, while the blank-holder length and the total height are respectively equal to 2000 and 2500 mm. Each machine side can have two or more carriages moving the rollers along the three x, y and z directions. Each one can translate along the y directions, while an internal double wedge mechanism allows to translate only the roller in the x and z directions. As show by Fig. 3b) the carriage has three independents electrical gearmotors to control the motion axes. In particular, it slides along two linear guideways while the traction force is given by a rack-pinion coupling. The maximum speed along the y-axis is equal to 60 m/min with a maxim linear force (F_Y) equal to 22 kN. On the other hand, two gearmotors are used to independently move the two wedges making possible the horizontal and vertical movements. Each gear-motor, through a belt and a ball-screw transmission system, can move a single wedge with a maxim speed of 1 m/min and a maxim linear force of 138 kN. In this way, by changing the relative position between the upper and lower wedges, the roller fixed on the middle wedge moves inside a 50x100 mm area. Fig. 3c) shows the roller in two limit positions at the stroke-ends. Both the upper and lower carriages can work both independently and synchronously to form the metal sheet according to the different approaches presented in Fig. 2.

4. IRP prototype kinematics

As mentioned in Section 3, each carriage can independently move along the three x, y, z directions to form the metal sheets with different approaches. Fig. 4 shows a possible kinematic with two rollers, both moving synchronously along the axial direction. Fig. 4a) shows the position of the upper roller over the process time, while Fig. 4b) shows the position of the lower roller in the case of a 90-degree bend.

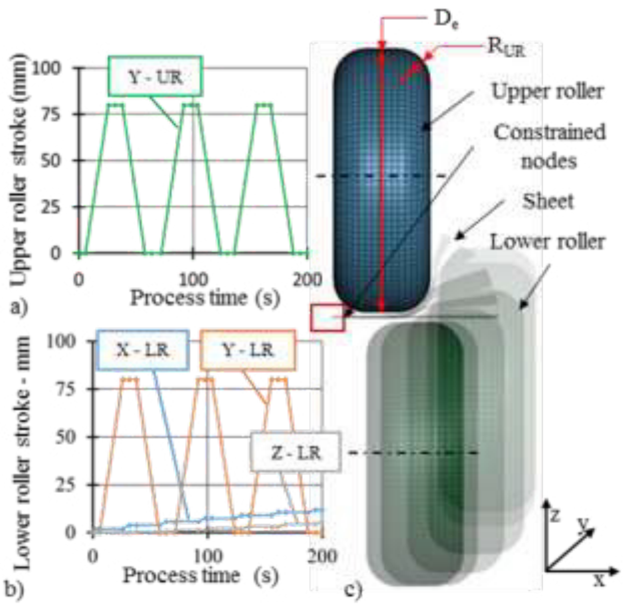

Fig. 4. Prototype kinematic: a) upper roller (UR) xyz-path, b) lower roller (LR) xyz-path, c) numerical model and forming flower.

In this case, after an initial approach to bring the roller in contact with the metal sheets, at each step the lower roller moves along the x and z direction to change the contact point with the workpiece, and both the rollers move along the sheet length to bend it. Once the first stroke is made, the lower roller moves one step further along the horizontal and vertical directions and then both move to bend a second time the workpiece over its entire length. While the simplest kinematic, shown by Fig. 4, uses sequential movements, the machine CNC allows to manage interpolated movements for more complex geometries. Fig. 4c) shows the bending flower, and the subsequent positions of the lower roller for a 90 deg bend made in 5 steps, using two rollers with an outer diameter (D_e) of 125 mm having a fillet radius of 5 mm. It is worth to notice that with such simple tool paths the final workpiece bending inner radius is equal to the upper roller fillet radius (R_{UR}). However, by also moving the upper roller in the vertical and horizontal direction during the forming stage it is possible to control its contact point with the workpiece and obtain higher radii bending. Similarly, the prototype CNC allows to change the rollers x and z position over the y direction to obtain a non-uniform bending radius along the workpiece length. Finally, the carriages can be equipped with custom-shaped rollers or motorized cutting disc for cutting and embossing operations.

5. Numerical model

To assess the feasibility of the different configurations a numerical model of the IRF process set-up has been developed in LS-DYNA™ environment. The results of the IRF proposed model were compared to a standard V-bending case under the same conditions [19]. The reference material, for both cases, was AISI304L stainless steel alloy modelled with an elasto-plastic formulation according to the Hooke law (E = 195 MPa) for the elastic zone and the Hollomon equation ($\sigma = 780.5 \cdot \varepsilon^{0.126}$) for the plastic zone. The material model was experimentally calibrated with tensile tests, carried out according to the UNI EN ISO 6892 standard on an MTS servo-hydraulic dynamometer.

In both the cases, an initial 80x60 mm rectangular sheet was bent with a final angle of 90 deg and inner curvature radius of equal to the metal sheet thickness. Four different thicknesses were considered: 1, 3, 5 and 8 mm.

The workpiece was meshed with Belytschko-Tsay shell elements with 6 integration points, while the dies were meshed as rigid elements. A mesh size of 2 mm was used for the workpiece, while a narrower mesh was used for the roller curvature radius equal to R/2. Each roller was designed with an outer diameter De of 125 mm and a thickness of 35 mm. The boundary frictional conditions in the IRF process between the rollers and the metal sheet were selected according to literature, equal to 0.3 for the static friction coefficient and 0.2 for the dynamic friction coefficient. The same friction coefficients were adopted also for the V-bending simulation, for sake of comparison.

In the case of V-bending, the deformation was made in one stroke, at a constant speed of 20 mm/s, with an unload stage at the end of the process to allow the springback occurrence. In the IRF both the forming heads are moved along the Y direction, according to the tool path shown in Fig. 4a) and b). In this case, the nodes on the undeformed sheet edge were constrained in all the three directions to hold the sheet as done by the blank-holder (see Fig.4 c). In the IRF process at each step a 2 mm increment in the z-direction was considered. Therefore, the total number of steps change as a function of the sheet thickness from 7 steps for a 90 deg bend over a workpiece with a thickness of 1 mm, to 10 steps on a workpiece with a thickness of 8 mm.

6. Results and discussion

Fig. 5 shows a comparison between the forming load in the vertical z-direction between the IRF and V-bending processes.

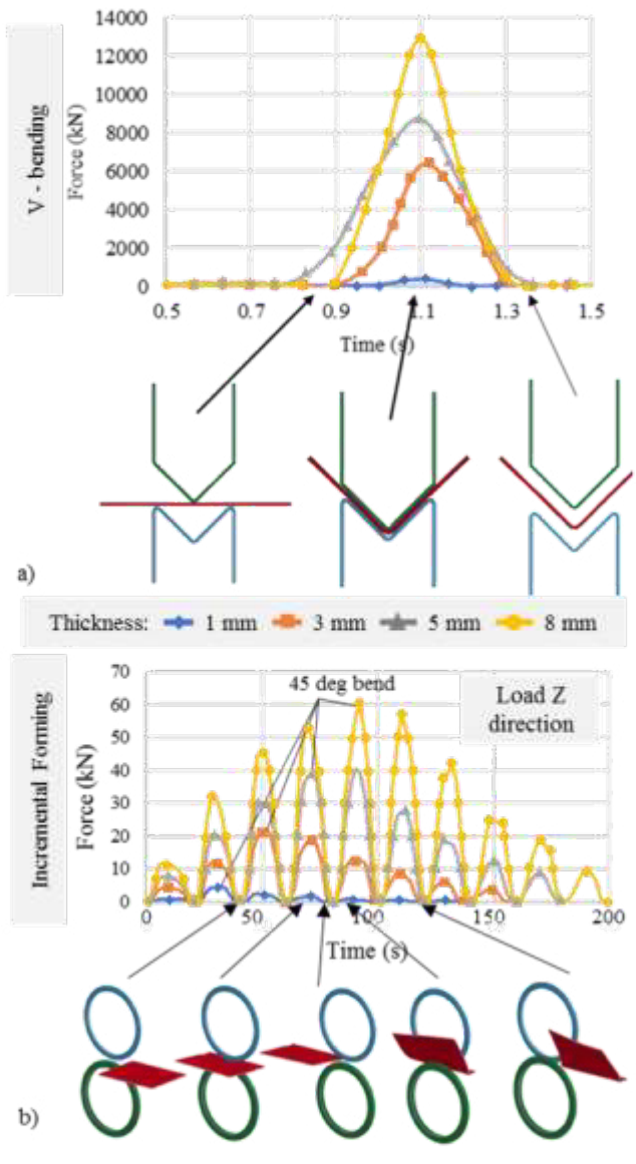

Fig. 5. Forces in the two processes: a) V-bending, b) IRF.

Fig. 5a) shows the force distribution over the process time for the V-bending process changing the workpiece thickness. In this case, as the process is done in one step and all the workpiece is bent at the same way, the maximum load is reached at the end of the forming stroke. The maximum load ranges from 1 to 1200 tons as a function of the workpiece thickness. Therefore, the machine stiffness and the maximum applied load may represent serious issues when large or thick components need to be manufactured. On the contrary, as shown by Fig. 5b), the maximum loads in the IRF process ranges from 0.5 tons to 6 tons for the same thickness values. In this case, as the total deformation is applied as subsequent steps, the load in the Z direction tends to increase up to a 45 deg angle, and then decrease as the 90 deg are reached. Then, the IRF process allows to manufacture larger and thicker components with lower applied loads, and it requires machine frames with lower stiffness values. It is worth to notice how the maximum force is reached earlier for thinner sheets, as in this case each step is made with the same 2 mm increase in the z-direction independently from the workpiece thickness. In this case, as shown by Fig. 6a), the thinner workpieces require a lower number of steps to be fully bent. At each forming step in the IRF process, the sheet section is incrementally formed along the length, therefore the force profile increases and decreases also within the single stroke. As each section is loaded and unloaded multiple times during the process, also the reached angle undergoes some variations due to the springback phenomena. While in the V-bending the springback occurs only at the end of the process when the dies are opened and the applied load released, in the IRF process it takes places after each step. Fig. 6a) shows the bending angle evolution over the process time of the reference middle section. In this case after each forming step a certain springback angle take places, however the following step can be used to overbend the profile and compensate the angle variation.

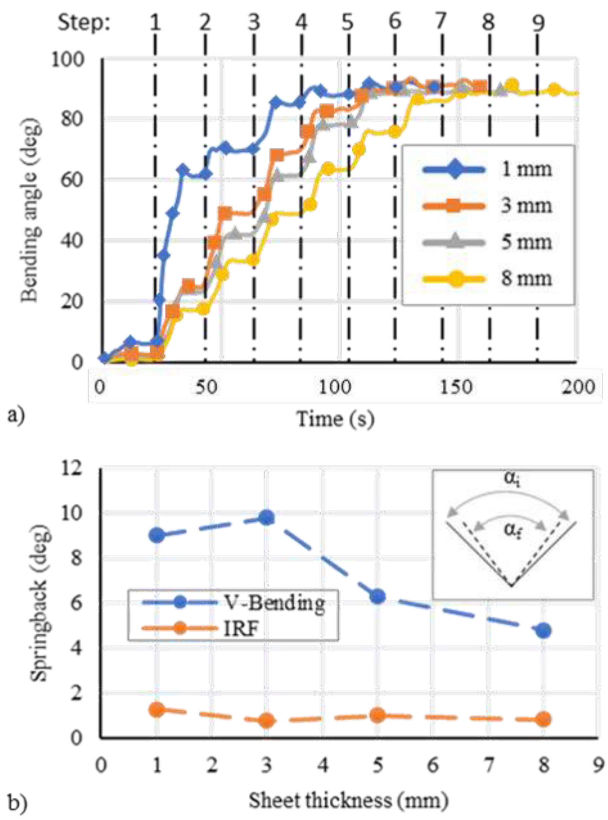

Fig. 6. Forces in the two processes: a) IRF, b) V-bending.

Fig. 6b) shows a comparison of the final springback angle α with the two modelled forming processes after a 90 deg bend as a function of the process and of the workpiece initial thickness. In this case, as the V-bending process does not allow to overbend the profile without changing the die design, the final springback amount cannot be compensated. On the contrary, the incremental approach of the IRP process allows to overbend the profile and to recover the final springback without changing the tools profile.

7. Case study economic assessment

The economic benefit of the proposed IRF process was evaluated taking as reference a simplified production case, considering the production batch of 100 pieces with the same geometry of the above-mentioned case study. The analyzed case study refers to a production plant located in South Europe, with an average man-power cost of 25 €/h. Three different processes are compared: the IRF process, the V-bending process on a 600 tons capacity bending machine, and the V-bending process on a 1000 tons capacity bending machine. Table 1 shows the cost details for the three cases. Despite the lower loads required in the IRF process, the machine hourly cost was calculated to be equal to a higher load bending press, as the higher number of axes required additional costs for the control and gear-motors systems. It is worth to notice, how the IRF incremental approach is more time-consuming, however, as the tools are simples and smaller, these require lower investment if compared with traditional V-bending tools. Then, in the case of small batch production, when the tool costs are not compensated by the higher productivity of the V-bending process the IRF allows to significantly reduce the total production costs.

Table 1. Cost detail for three different production cases.

Case	IRF	V-bend (600 ton)	V-bend (1000 ton)
Machine cost (€/h)	40	40	58
Production time (h)*	5.5	0.3	0.3
Tool set-up time (h)	0.1	0.3	0.3
Tool costs (€)	500	2000	2000
Total costs (€)**	864	2040	2050
*workpieces loading and unloading time included **Workpiece energy and material costs not included			

In this case, Fig.7 allows to analyze the effect of the batch size for the three different proposed process. As shown by the chart, the cost difference for a single-unit batch lies in the difference between the tools and set-up costs of the processes. However, as the batch size is increased the IFR costs rise with a greater slope if compared with the V-bend processes due to the longer required production time. Finally, the breakeven point is reached when the IRF total machine cost cover the difference between the initial tools and set-up investments required by the two technologies. In the presented case, such limit is reached for a batch size around 440 pieces.

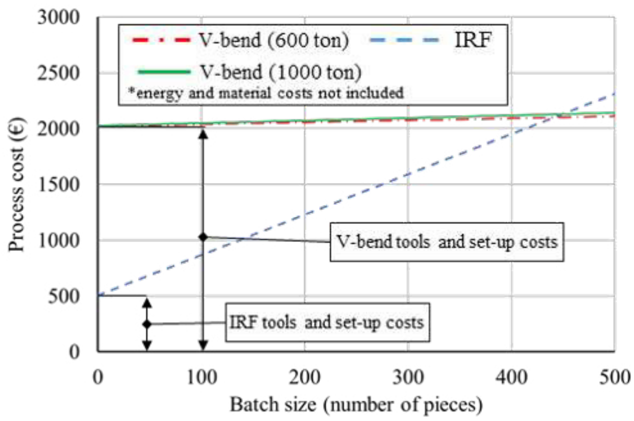

Fig. 7. Process cost as a function of the batch size.

8. Conclusions

The paper presents an innovative incremental roller flanging process and a newly designed incremental roller flanging machine. In the proposed process multiple rollers are used to incrementally bend a metal sheet, with a subsequent number of steps to reduce the forming loads and with the use of simpler axisymmetric tools. The proposed machine in the simplest configuration has seven degrees of freedom: three for each roller and one for the blank-holder. A numerical model of the IRF was developed in LS-Dyna^{TM} environment and compared with a V-bending reference forming process. The results show that, despite the lower productivity, the IRF process allows limiting the forming loads and a better control of the final angle of the bent profile. Finally, to fully exploit the capabilities of the proposed system and the advantages of a flexible and agile approach the process economic benefit was evaluated with reference to a case study.

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