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Validation of a FEM model for the simulation of the cold roll forming process

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Abstract. Cold roll forming is a process for plastic deformation, which allows realizing profiles, with a defined section and established length, from the plastic deformation of a metal sheet. The sheet is induced to cross several stands of rolls, arranged along the same axis of advancing. The rolls induce plastic deformation in the sheet and then lead it to the desired geometric configuration. In order to control the geometric parameters of the plate during the profiling, it was created a FEM model to simulate the final stage of the technological process, developed by an industrial production line of a company located in Naples (Italy), that sells tubes with several cross sections. In this phase, the semi-finished product, having a circular cross section, is forced to cross through four stands of rolls. In this way, it changes the geometric condition of the cross section from circular to square. The model was carried out using a non-linear calculation code, which allows analyzing the parameters of interest in the different process steps. The results, obtained numerically, were compared with the experimental ones through the measurement of five specimens, obtained directly from technological process. The values of percentage deviation, regarding the external dimension and the thickness, for each step of advancement, do not exceed the 3% of error. Then, the analysis results denote the capability to simulate the cold roll forming process using finite element method.

Introduction

Plastic deformations [1,2] are obtained by particular technological processes, which can be carried out either hot or cold, and are characterized by a defined condition of the load. The hot plastic deformation requires the use of fewer forces [3] compared to the cold one and it may have also considerable deformations without breakage or cracks; conversely, the cold deformation requires the use of high forces even for small deformations, but the obtained product has greater dimensional accuracy and resistance, as a consequence of the hardening. The materials, subjected to these processes, must have special technological properties such as malleability, ductility and bendability. These characteristics allow the structure to support the acting load avoiding phenomena of breakage. Indeed, the arising of defects in the material, does not allow the subsequent using. These processes take place at constant volume [4] and then from the starting material, having a certain shape and size, a component is obtained, with different shapes and dimensions. This component is characterized by the same volume of starting material [5].

Cold forming is a plastic deformation process of transforming a flat sheet of metal into section profiles such as channel sections by using cold rolling, brake pressing or folding operations. Cold roll forming (CRF) [6,7] is the more widely used operation to manufacture cold-formed section profiles with large volumes and longer lengths. The necessary profile [8-9] is formed by passing the metal strip through successive pairs of rolls. Most of the commercially available cold-formed products are manufactured using cold rolling which provides consistent sections with a high degree of accuracy to any desired length. A typical cold roll forming process is shown in Fig. 1 [10]. The increase in the strength values across the cross-sections of the members was found to be largely dependent on the method of cold forming employed in the manufacturing process. In brake pressing and folding operations, strain hardening is restricted only to narrow areas along the formed corners of the section whereas, in cold roll forming, both the corners and the flat portions of the section undergo a level of strain hardening with the corners undergoing the greatest levels. CRF technology provides large technological advantages in thin-walled parts manufacturing compared to press forming, as it do not require too many auxiliary operations; the CRF equipment has no idle running and the length of the parts is not limited with the equipment any more [11]. CRF is increasingly used in modern sheet-metal industry because the process satisfies the modern requirements of high productivity, environmental quality, quality maintenance, high accuracy and uniformity of parts, consistency of properties and surface conditions.

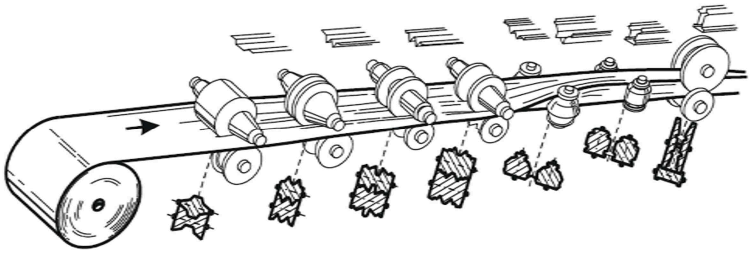

Fig. 1: A typical CRF process

An analysis, using finite element simulation, was carried out in this paper. The analysis was performed on a specific phase of a roll forming process, conducted at the company IMI SUD S.r.l., located in Casoria (Italy). The analyzed phase is the plastic strain suffered in the last step of the process, i.e. before the product is cut off and placed on the moving pallet. In this phase, the semi-finished product, having a circular cross section, is forced to cross into four stands of rolls, varying the geometric condition of the section from circular to square. The process involves the gradual deformation of the steel tube that is transformed in a square tube. By this stage of the process the company has the ability to market tubes with square section (30 mm of edge), having a thickness of 3 mm. Each of these stands of rolls have a particular shape, in order to incrementally increase the deformation of the tube by passing it through a series of idle rolls. The technological process takes place thanks to the push of a reel, disposed upstream of the process, that forces the tube to pass in the four stands of rolls. Previously, several authors [12-18] analyzed how to simulate, using non-linear FEM code, a metal strip behavior in the CRF process. The developed models take into account all of the non-linearities present in the rolling problem: material, geometric, boundary, and heat transfer. The FE-Model results are an improvement over the results obtained through the classical theory of rolling. The model also demonstrates the role that contact, plastic heat generation and friction generated heat play in the rolling process. In most of such works the sheet metal strip, that evolves in the rolls to create a bar of constant section, has always been analyzed. Unlikely the profiling of tubes was studied with a comparison of numerical and experimental results.
The simulation was carried out in order to evaluate the geometric parameters of the semi-finished product during the profiling phase, to compare numerical data with those measured experimentally from samples derived directly from the manufacturing process. Moreover, by FEM results the pressure distribution and Von Mises equivalent stress were analyzed. The preprocessing and postprocessing phase were performed using LS-PrePost-4.0, instead the used solver was Ls-Dyna 971. The obtained result helps to improve both the simulation process and the actual cold roll forming process especially when new or different metals are being introduced.

Fe-Model

FE-Model was set up in order to assess the geometric parameters of a semi-finished product during the profiling phase. In this process, a steel tube with circular section, having an outside diameter of 38 mm and a thickness of 2.7 mm, passes into four stands of rolls that induce a plastic deformation in the semi-finished product. The final product consists of a tube with a square section having the dimensions of 30 mm x 30 mm and 3 mm of thickness. The material, object of the CRF process, is a typical steel supplied in rolls: S235JR + AR which, by EN 10025-2 2004, corresponds to the class material Fe360B. Table 1 shows the main mechanical properties of the used material.

Table 1: Mechanical characteristics of the Fe360B

Fe360B Properties	Value	Unit
Yield stress	265	[MPa]
Modulus of elasticity	210	[GPa]
Tensile strength	360	[MPa]
Elongation at break	38	[%]
Poisson ratio	0.3	[-]
Density	7850	[kg/m^3]

In order to simulate the process, the rolls geometry used in the manufacturing plant of the company was reproduced. The rolls, in every single stand, are assembled with a radial clearance of 1 mm and they are idle with respect to the advancement of the semi-finished product. Starting from the construction drawings of each roll involved into the process, the 3D model was designed by the parametric CAD software CATIA V5 R21. It is well to highlight that the geometry of the rolls relative to the third and fourth step is equal to each other. The reason is found in the need to ensure the calibration in the terminal phase of the process. Since the technological process, simulated by the software Ls-Dyna 971, provides the contact between the semi-finished product and the outer surface of each roll, only the surfaces in question were modeled. Furthermore, in order to model the process by considering the real case, the rolls were suitably fitted with a 1 mm radial offset to simulate the presence of the clearance.

After importing the CAD surfaces, the FE-Model was realized (Fig. 2) using the LS-PrePost 4.0 software. In order to simulate the behavior of the semi-finished product in different stages of progress, the same was modeled with SOLID elements (8-node brick) with a material having plastic behavior: MAT24_PIECEWISE_LINEAR_PLASTICITY, having the parameters described in Table 1. The surfaces of the rolls were modeled with SHELL elements (4-node quad), characterized by the MAT_RIGID. For this material code, the characteristics of a common steel were updated. For the nodes arranged at the rear end of the semi-finished product, a law of linear displacement, which ensures a displacement of 1000 mm in 10 seconds, was assigned.

In order to simulate the relative sliding between the semi-finished product and the rolls, the CONTACT_CONSTRAINT_NODES_TO_SURFACE was defined using the nodes of the outer surface of the semi-finished product (slave) and identifying the surfaces of the rolls (master). For this contact code, the coefficients of static and dynamic friction were limited to a small value (FD=FS=0.05) in order to take into account that the rolls rotate in the idle way.

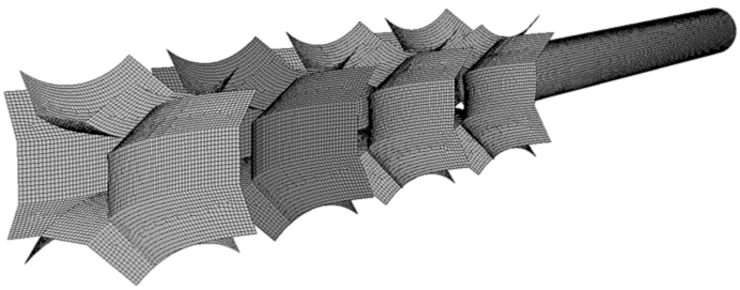

Fig. 2: FE-Model of the cold roll forming process

Results

Fig. 3 shows the result of the FEM analysis regarding the five advancement stages (0-1-2-3-4) of a section of semi-finished product in the simulated process. As shown, the semi-finished product undergoes a plastic deformation due to the presence of the stands of rolls, which involves a geometric variation of the cross section. Fig. 4 shows the pressure distribution (expressed in MPa) that acts on the semi-finished product at the time equal to 4.3 seconds. The choice of such a time instant guarantees the passage of the product in all four stands of rolls. The pressure distribution shows that in the first section, where the semi-finished product is changing its size and its section, the pressure distribution is more pronounced, having a typically parabolic shape. This trend is also justified by the geometrical configuration of the rolls in the first stage. In the second and third step the pressure distribution becomes similar while the fourth is practically nil because the latter have a geometry of the rolls equal to the previous one. The spatial distribution of the Von Mises equivalent stress (expressed in MPa), observed at the same time, is reported in Fig. 5. As can be seen, there are several points at which the semi-finished product has a stress that exceeds the Yield stress (265 MPa), then a plastic deformation has undergone.

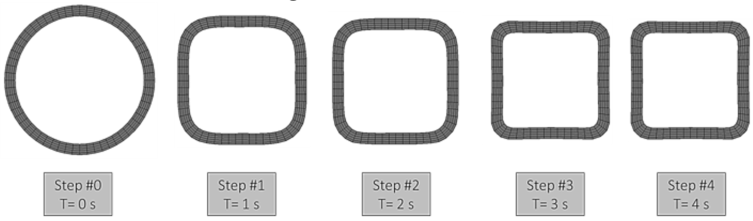

Fig. 3: FEM analysis on the five advancement stages in the technological process

Furthermore, the variation of the external dimension of the semi-finished product, which is the diameter in the initial process stage and the side in the other progress steps, was analyzed. The simulation starts from a tube of initial diameter of 38 mm; then, in the final phase of the process, the tube reaches a square section having a side of 29.4 mm. Similarly, it is possible to perform an investigation on the thickness: the tube starts from a thickness of 2.70 mm and reaches 2.79 mm.

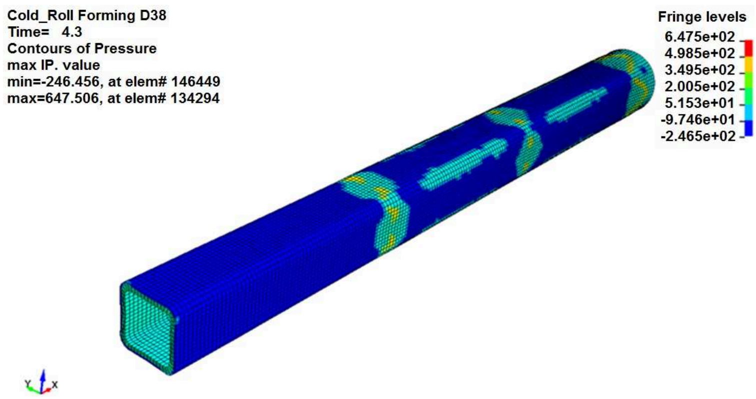

Fig. 4: Pressure distribution on the semi-finished product at 4.3 s

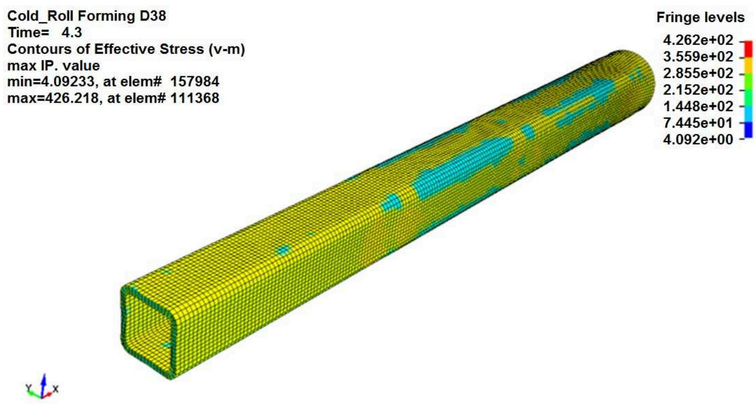

Fig. 5: Von Mises equivalent stress distribution on the semi-finished product at 4.3 s

In order to validate the FE-Model, a comparison between the numerical values and the ones obtained from experimental measurements was carried out. The used reference consists of 5 specimens (Fig. 6) derived from the five different steps of the technological process. The samples were obtained by cutting from the semi-finished product five different sections, that represent every profiling step. The outer surface of the specimens was polished in order to allow the measuring of the geometric quantities of interest.

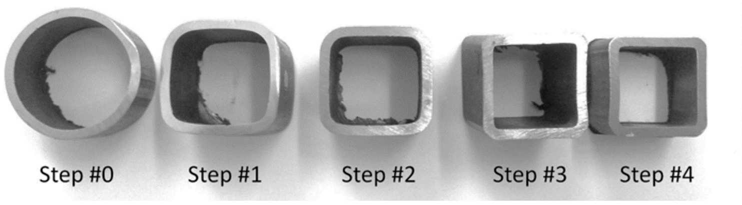

Fig. 6: Specimens of the semi-finished product

Both the external dimension and the thickness, for each process step, were analyzed. Table 2 shows the measurement of the geometric values obtained experimentally and numerically. In the same table, the percentage deviation between the numerical and experimental values (*D*) is reported. This feature was evaluated using the following formula:

$$\boldsymbol{D = \frac{EV - NV}{EV} \cdot 100.} \quad (1)$$

In the Eq. 1, EV is the experimental value and NV is the numerical value.With the comparison of the results, a very thrust correlation between the numerical data and those obtained experimentally is highlighted. The values of percentage deviation, for each step of advancement, do not exceed 3% error. The slight geometrical deviation of the semi-finished product in the first step of advancement (2.98%), compared to that obtained in the production process, may be due both to the numerical model that simulates the behavior of the material and the clearance between the rolls. This parameter cannot be evaluated experimentally in a direct way and it also affects the energy parameters of the process. The performed analysis shows the validity of the FE-Model to simulate the process of cold roll forming.

Table 2: Experimental and numerical geometric features of the five process steps

Step	Experimental values [mm]		Numerical values [mm]		Deviation [%]	
	External dimension	Thickness	External dimension	Thickness	External dimension	Thickness
#0	38.00	2.70	38.00	2.70	0.00	0.00
#1	33.50	2.80	32.50	2.78	2.98	0.71
#2	32.00	2.80	31.70	2.78	0.94	0.71
#3	30.00	2.80	29.40	2.79	2.00	0.36
#4	30.00	2.85	29.40	2.79	2.00	2.10

Conclusions

In order to assess the geometric parameters of a semi-finished product in the technological process of cold roll forming, a FEM simulation of the process was performed by using the non-linear computer code LS-Dyna 971. The analysis was performed on a specific phase, in which the semi-finished product is forced to pass into four passes of rolls. For this reason, the product varies the geometric condition of the section from circular to square. The steel tube have an initial circular section, with an outside diameter of 38 mm and a thickness of 2.7 mm. The final product is a bar having a square section (30 mm x 30 mm) with 3 mm of thickness.

By the FEM simulation, the geometric quantities of interest, in different progress stages of the semi-finished product, were analyzed. The results obtained numerically were compared with the experimental ones through the measurement on 5 samples, obtained directly from the technological process. The values of percentage deviation, regarding the external dimension and the thickness, for each step of advancement, do not exceed the 3% of error. The small deviation of the semi-finished product in the first step of advancement (2.98%) compared to the experimental data, could depend on the numerical material model and on the clearance between the rolls.

Moreover, the pressure distribution shows how the geometrical configuration of the rolls influences the loads and the wear on the rolls. Indeed in the fourth pass, the rolls are unloaded because the latter pass has a geometry of the rolls equal to the previous one. The distribution of the Von Mises equivalent stress denotes that there are several points at which the semi-finished product exceeds the yield stress, and then a plastic deformation has undergone. In the global analysis, the FE-Model denotes the capability to simulate the cold roll forming process using finite element method.

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