Manufacturing of thin-walled hollow screws and nuts by tube forming
Experimental and numerical study

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Abstract

In modern days, there has been a growing concern related to the production of components. Nowadays, it is said that the production methods must be more efficient, less pollutant and more sustainable. Thus, the present paper has the main goal to explain the implementation of a new process - the manufacturing of thin-walled hollow screws and nuts by tube forming.

This process has its bases in the plastic deformation of steel tubes, which were granted by the company MCG. The scope of this procedure was to conceive and fabricate the tools involved in this experiment, make a characterization study about the material used and perform the concept at experimental and numerical levels.

The process was implemented at a low level of industrial production to verify the applicability of the procedure in reality. The main propose of this method is to increase productivity and to reduce wastes, costs and time. In general, ensuring a growth in efficiency when compared to currently available process of manufacturing these components.

To study the process in detail, numerical simulations regarding the manufacturing process were made with the help of an existing in-house computer software called I-FORM2 and I-FORM3, developed in the Mechanical Technology Section of Instituto Superior Técnico.

This paper concludes with a section concerning the comparison between the experimental part and the numerical simulations in terms of results and an analysis related to the feasibility of this new procedure.

Keywords:
Compression beading; Experimental development; Finite Element Method; Thin-walled hollow screw; Tools manufacture; Tube forming
1. Introduction

In the last two decades, climate changes have been so aggressive that the United Nations had to put up some directives to reduce the emissions of greenhouse gases, which are dangerous for the environment and people's health. According to this and new philosophies of production management, like Lean Manufacturing, the industrial sector is beginning to reduce emissions and material resources, trying to improve its processes in terms of efficiency, costs and time.

Following this new way of thinking, the author began to intellect what would be an advance in the connection between materials. Nowadays there are basically three types of joining methods: mechanical, welding and structural adhesive bonding. Every one of those methods has its advantages and its disadvantages. The welding process is largely used because of its major applications and quick union, but it's not great assuming that all the heating-cooling cycles impose poor properties to the materials. The adhesives confer very good aesthetic properties to the union but it becomes weaker with time due to physical and chemical effects. The last type of joining – the mechanical way - uses screws, rivets, nuts, washers and so on, and has a very wide market because they are removable. It can be concluded that the most important, more used and more durable method of connecting materials is the mechanical way.

In this area the screw and nut association is the most used and is the scope of this paper. The main objective of this paper is to demonstrate a new and innovative process for the fabrication of thin-walled hollow screws and nuts.

However the upgrading in this technology may be small, in generalization it would be very far because, has it can be imagined, the number of screws and nuts produced daily is in the order of hundreds of millions. Making the screws and nuts hollow has many benefits in terms of applications like transportation, lighter structures, less use of resources, among others.

Unlike the commercially hollow screws, which are internally machined from solid screws, this new procedure fabricates the mechanical components by plastic deformation. The forming method has very advantages because it doesn't have the wastes involving in the machining, is far faster and has a reduction in costs and energy very pronounced. The base of the method was the production of ice screw utilized by mountaineers.

The aim of the present paper is to characterize the material used in terms of instability load and material law; introduce the concept of this new process in terms of experimental and numerical analysis and demonstrate the feasibility and advantages of the procedure.

2. Experimental Background

The material used in this investigation were carbon steel welded tubes with 13.90 mm of outer diameter, 11.50 mm of inner diameter and 1.2 mm in thickness, in the 'as-received' condition from the company Manuel Conceição da Graça. The mechanical characterization tests and the experimental apparatus were performed at room temperature on a universal testing machine with a constant speed of 10 mm/min.

2.1. Material Characterization

In order to identify the material, a well-known test called stack compression test was executed and the material law was determined. This test was performed due to the fact that it is able to validate when extensions are higher and doesn’t have the problem of necking (present in the tensile test). The uniaxial compression test simulates more accurately the material flow in accordance with reality. The stack compression test is a new method to evaluate the material law. It has the same characteristic results has the uniaxial compression test, but it utilizes much less raw material.

The stack compression test performs a compression of a pile of circular discs. This kind of test was proposed by Pawelski in 1967, however just in 2009 by the hands of Merklein and Kuppert, the use of this test to analyze curve flow of anisotropic materials was introduced.

The discs are created from the tube by some methods. Among them the one used in this particular case was electrical discharge machining of circular concave discs with 8 mm of diameter and 1.2 mm of thickness. The discs are piled and glued together and the test begins.

After the test was done and the consequent analysis was completed, the curve calculated for the material's law is observed in the next graphic (Figure 1).
The next equation is related to the material law of the tubes used in the process explicit in this paper.

\[
\bar{\sigma} = 667.7\bar{\varepsilon} + 324.4
\]  

(1)

2.2. Critical instability load

Another important data that must be computed experimentally regards the critical instability load. This is the load that demonstrates the value when the local buckling (instability) start to develop itself. This value was experimentally determined by compressing a tubular specimen between flat dies. The specimen was cut from the tube provided by MCG with a length of 29.20 mm. The following graphic (Figure 2) represents the load as a function of the displacement of the specimen.

The critical load determined was \( P_{\text{crit}} = 31.3 \, kN \). After this load value the tube starts to develop axisymmetric instability waves \( [2] \).

2.3. Experimentation

In the experimental analysis the new process of production was put in practice. To do this all the dies and preforms were machined to the correct dimensions and equipment from the Laboratory of Mechanical Technology were used for this performance.
Conducted experimental test of the screw were made first followed by the conception of the nut. After a few tests it was determined that the hollow screw had to be made in 3 stages: Reduction and jamb formation, Calibration and Creation of the hexagonal head. As for the production of the hollow nut, it acquires 2 distinct phases: Formation of the hexagonal head and Creation of the jamb.

The reduction and jamb formation of the screw is done using 2 dies (reduction die and a cylindrical die) and an internal mandrel. In the calibration phase is accomplished due to the fact that the reduction die in the previous step possesses a chanfer to make the entrance into the tube smoother. So the reduction die is put in the reverse way and by having a really small chanfer on this side the chanfer in the piece is removed. In the final stage an internal hexagonal punch is compressed into the tube end fulfilling the hexagonal head of the screw.

The first stage of the nut manufacturing is performed with 2 dies (internal hexagonal die and an external hexagonal die) and an internal mandrel. This stage allows the creation of the hexagonal head of the nut. Then at the other end of the tubular preform the generation of the jamb is due to the compressive force of the preform on an inversion die.

Finally the tools were mounted in the press’s base and the compression experiments were conducted in order to produce the components at issue and to obtain the results data to be compared with the numerical simulations.
3. Finite Element Method (FEM)

As it was stated earlier, numerical simulations were made to compare the results provided by the experimental part. Those simulations were made using the finite element method implicit in I-FORM2 and I-FORM3 created by Professor Paulo Martins in the 1980’s and developed by countless collaborators of Mechanical Technology Section of Instituto Superior Técnico in the past years.

This method is used as a way to simulate procedures in reality at a computer level, so it is used very often as the first approach to an industrial process. FEM was introduced by Ray Clought in the 1950’s in United States of America. But only in 1970 by the hands of Lee, Kobayashi, Cornfield, Johnson and Zienkiewicz the FEM was formulated to be applied to the flow formulation (which is the base of forming processes)\(^4\).

The mathematical bases that govern the finite element method are described by the next equation:

\[
\prod = \int_V \bar{\sigma} \dot{\varepsilon} \, dV + \frac{1}{2} K \int_V \dot{\varepsilon}_c^2 \, dV - \int_{S_t} t_s u_s \, dS + \int_{S_f} \left( \int_0^{u_s} \tau_s \, du_s \right) \, dS
\]

where \(\bar{\sigma}\) is the effective stress, \(\dot{\varepsilon}\) represents the effective strain rate, \(K\) is a large positive constant imposing the incompressibility constraint, \(V\) is the control volume limited by the surfaces \(S_t\) and \(S_f\), \(t_s\) represent the surface tractions on \(S_t\) and \(\tau_f\) are the friction shear stresses on the contact interface \(S_f\) between material and tooling. Friction is modeled as traction boundary condition and additional power consumption resulting from the rightmost term in equation (2) is determined through the utilization of the law of constant friction\(^3\). The friction factor utilized was set to 0.2 after checking the finite element predicted forming loads that best matched the experimental results.
The computer assisted design was fulfilled with SOLIDWORKS 2012, the construction of the mesh grid was performed in GiD 7.2 and all the computation analysis was accomplished using the software I-FORM.

In the domain’s discretization of the tubular preforms it was employed linear hexahedral elements, because it showed a great adequacy to the major field variables. A mesh with a total of 1400 elements was used in the domain’s discretization of the hollow nut preform and 2800 elements in the case of the screw. As for the tools, they were regarded as rigid and therefore discretized by triangular linear contact-friction elements.

4. Results and Discussion

4.1. Production stages of the Hollow Screw

As stated previously the production of the screw is composed by 3 stages, so in this section they are going to be studied in a graphical way.

The first stage involves the reduction and the jamb formation and is plotted in the next graphic.

![Reduction and jamb's formation process characteristic behavior](image)

Figure 7 – Reduction and jamb’s formation process characteristic behavior

The first rise in the load is due to the beginning of the tubular reduction. After that the load stabilizes thanks to the chanfer in the reduction die that allows a soft deformation of the preform. The new spike in the load develops around 2 mm and can be explained by the increase of material being deform therefore the reduction task, up to 12 mm in diameter, truly begins.

After that growth around 3 mm and until 12 mm the load stays almost constant, 8 kN, regarding the continuation of the tube’s reduction. The last increase in the load occurs approximately at 21 mm of displacement which states the end of the tube’s reduction and because the compression continues, the tube suffers a local instability in order to create the jamb required. The material flows outwardly thanks to the presence of the internal mandrel[^8].

The next image demonstrates the displacement-load progress in the calibration phase.

![Calibration process characteristic behavior](image)

Figure 8 - Calibration process characteristic behavior
As it can be seen in the graphic, the load increases from the beginning and continues raising while the chanfer is removed from the tube in the last stage. This may be explained by the friction between the tool and the preform that instead of flowing inwardly, the material tends to stay in the edge of the tool and not proceeding with the chanfer removal. It can still be noted that the diameter along the chanfer removal is slightly increasing which means a rise in the load.

At a displacement around 2.1 mm a new spike in the load is noted and occurs due to the contact between the reduction die inverted and the jamb already created - which has a greater area of contact - and because the compression continues the load must increase.

The final period on the screw manufacturing is visualized in the following picture.

![Figure 9 – Formation of the screw's hexahedral head process characteristic behavior](image)

The beginning of the deformation of the preform is due to the soft penetration of the hexahedral punch in the region of the formation of the screw's head. Like the reduction, after this, the deformation becomes more controlled.

Approximately at a displacement of 7 mm the load starts to intensify because the deformation area becomes in contact with an area that has been already deform. That deformed area is hardened and makes it difficult to maintain the deformation without an increase in the load.

### 4.2. Production stages of the Hollow Nut

![Figure 10 – Hexahedral nut's head formation process characteristic behavior](image)

Half of the nut production phases is the formation of the head and is displayed in the
preceding graphic. This stage commences with a growing load followed by a slight diminishing. That kind of occurrence is explained by the local instability of the tube in order to create the head of the nut.

The last peak in the load arises from the contact of the compression bead with the hexahedral walls of the outside die, which allows the creation of a hexahedral head.

Lastly, the analysis of the jamb’s formation of the hollow nut is expressed in the graphic below.

![Graph showing load and displacement](image)

**Figure 11** – Jamb’s formation process characteristic behavior of the nut

From the point where the tube contacts with inverted die, the load starts to grow. This rise occurs while the tube moves along the inverted fillet.

The decreasing of the load around a displacement of 3 mm is due to the contact of the preform with the horizontal part of the inverted die which provides fewer restrictions to the deformation allowing the material to flow easily.

The new spike in the load is related with the increase of the material in which the press plate is in contact. This material makes the area of compression bigger – which provides an increased load – allowing the edge of the tube to be as horizontal as possible. This way the main goal in this part, the creation of the nut’s jamb, is accomplished.

### 4.3. Numerical vs Experimental results

One of the main points of this paper was to expose the comparison between the numerical part done at a computational level and the experimental part performed in the Laboratory of the Mechanical Technology Section in IST.

![Graph showing load and displacement](image)

**Figure 12** – Experimental and finite element predicted evolution on the first stage of the screw’s production

In general the results were very satisfactory because as it can be observed in the graphic above the curves are almost identical. Those results were obtained for nearly all the
stages of the components production, so because of that no other visual comparison will be presented.

In the phases regarding the hollow screw (one of them exhibit in the Figure 12) the course of the load vs displacement are similar as well as the values of the load for the same displacement.

During the manufacturing of the hollow nut the results were similar but a bit different in the last stage, in terms of load’s value. Those differences may be interpreted as a result of the friction factor. The determination of the friction factor is done using the ring compression test, however is difficult to implement it in a sheet. So, for this work, the determination of the friction factor was done by countless test cases with different friction factors. The assumption used in order to facilitate the numerical analysis, which correspond on assuming that the tools are rigid and don’t deform in the compression process is false, however its relevance is negligible.

This explanation could denote the clearance around 10% between the load values in the jamb’s formation of the nut. Yet it must be said that all the stages possesses similar behavior in experimental as well as in numerical way.

4.4. Comparison between 2 and 3 dimensions

After making a lot of tests at a numerical approach it was verified that the computational time was exceeding the normal time to simulate the manufacturing process of the hollow screw.

So a new path was taken into account, making the first two stages (Reduction and Calibration) in 2 Dimensions and then transform them into 3D. Finally, the last stage was execute in 3D.

![Comparison pictures between the experimental components (on the left) and the components obtained from the numerical analysis (on the right)](image13)

![Finite element predicted evolution between the approaches in 2D and 3D on the last stage of the screw’s production](image14)
The task proved to be a bit more difficult than expected but it was rewarded with a computational time improvement from 14 hours to 1.50 hours. The transition between 2D and 3D must be done carefully because it is an unusual task and some errors can come from it.

In the figure above (Figure 14) it is explicit the progresses of the 2 approaches for the formation of the hexahedral head of the screw. One thing that can be observed in the two approaches is that the 3D possesses a more continuous graphic than the 2D, because the 3D consists of more elements and so the calculations are done in shorter intervals. As it can be seen the similarity is well noted and the results were taken has reliable.

5. Conclusions

This work was developed with the purpose to determine the viability of a different and innovating kind of process to produce hollow screw and hollow nut from a tubular preform.

In the beginning it was discussed the material characterization in terms of mechanical behavior and the possibility to implement the deformations required in the project phase, namely the possibility of inversion and the applicability window of local instability.

The first thing to conclude is that it is possible to implement those processes in reality because the results were very similar between the experimental approach and the numerical approach.

All the numerical analysis was implemented successfully in I-FORM 2 and I-FORM3, an in-house computer program developed in Instituto Superior Técnico.

The improvement related with weight is around 59% for the screw and 56% for the nut, relatively to the conventional production of the same components. The upgrading in terms of costs is around 57% when one meter of tube is used instead of one meter of rod. Those statements will introduce an advance in lighter structures, a minor consume of raw material, less energy’s consumption and fewer pollutant emissions regarding the component’s transportation as well as its use in any moving technology.

It can be concluded that easy and costless processes can be projected in order to decrease costs and improve the environment and people’s lives in our society.

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References


