New Process of Elastomer Compression Beading Tubes
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ABSTRACT
The purpose of the present work is to present a new alternative bead forming process designated as “Elastomer Assisted Compression Beading” (EACB). In this process, a local expansion is produced by elastomer forming before the conventional pressworking compression beading.

The study includes experimental tests under laboratory conditions and finite element analysis in order to identify the parameters that govern the process, as well as understanding the deformation and failure modes. The results show that with the EACB process it is possible to increase the formability limits beyond the minimum and maximum achievable by the conventional process. This new process allows to extend the range of industrial applications involving tube forming as the attachments of tubes to sheets and tubes to tubes.

This paper also presents structural and dynamic studies of a horizontal press tool with the capability to transform the vertical movement of the slide in two symmetrical horizontal movements. Such tools have a high industrial interest due to their ability in forming tube attachments with a single operation.

The structural analysis involves the evaluation of critical areas, using for this purpose finite element simulations. Finally it presents axial compression tests and relations that allow the validation of the results obtained when using the mentioned tool.

Keywords: Forming tubes, Compression beading, Plasticity, Finite element method, Horizontal tool

1. INTRODUCTION
Compression beading is a tube forming process that is accomplished by forcing one tube end towards the other (or the two tube ends towards one another) while leaving a gap between the dies that hold the tube, \( l_{\text{gap}} \), causing collapse by local buckling that leads to the development of a compression bead. Previous investigations have used compression beads for attaching tubes to sheets (Alves & Martins, 2012) or tubes to other tubes (Alves & Martins, 2012). The procedure requires the use of two dies, and an internal mandrel. By subjecting the specimen to an axial load, allows the creation of a local instability forming a well-defined bead, coincident with the geometric shape of the dies. On this compression bead will settle the component to attached (tube or plate) previously holed. In the final phase there are two possible operations: creation of a new instability and respective bead over the component to be fixed (Gonçalves, et al., 2013), or it is also possible to use an outer end inversion of the tube (Alves, et al., 2011) in order to restrict the movement and ensure a secured fixing of the component. These bonding processes can present structural, chemical, functional and aesthetic advantages when compared with the conventional joining processes such as welding, riveting, used of nuts and bolts or adhesives. Despite of the good results obtained, this alternative joining process has some limitations regarding the size of the maximum and minimum width of the bead, \( w_{\text{cb}} \), that it is possible to achieve with this method.
The aim of this paper is to introduce a new “Elastomer Assisted Compression Beading” process (hereafter referred to as “the EACB process”) that makes use of elastomers as pressure-transmitting medium for the bulging in order to meet the challenge of producing compression beads in a broader range of width. To accomplish that, numerical and experimental tests were made.

This paper also presents a study of a double-effect tool capable of transforming the vertical movement of the slide into two horizontal symmetric movements, developed in DEM at Instituto Superior Técnico. Nowadays, horizontal tools have a high industrial interest in this field, once it is possible to perform tube attachments through a single operation.

The aim of this second part concerns the structural and kinematic analysis of the tool. It was performed a dimensional survey of all tool components and modeled the set using the CAD software SolidWorks 2013. This modeling allowed to carry out a numerical finite element analysis of the tool structure with SolidWorks 2013. After completed this analysis, axial compression tests were performed in order to evaluate the performance of the tool. Fig. 1 shows the mentioned tool.

![Double-effect tool with the capacity of transforming the vertical movement of the slide into two horizontal symmetric movements: (a) Photograph, (b) 3D CAD and (c) Finite element mesh.](image)

2. EXPERIMENTAL BACKGROUND

The tubular specimens utilized in the experimental work were cut from commercial S460MC (carbon steel) welded tubes with an outside radius $r_0 = 16$ mm and a wall thickness $t_0 = 1.5$ mm. The stress-strain behavior of the material obtained in (1) was determinate by means of tensile and stack compression test performed at room temperature.

$$\sigma = 616.4\varepsilon^{0.06} \text{ (MPa)} \quad (1)$$

Fig. 2 presents a schematic representation of the active tool components that were employed by the new proposed EACB process at the open and closed position. As seen, the overall process is accomplished by a sequence of two different forming stages. In the first one, a cylindrical rubber is placed inside the tube and the tube is bulged (expanded) by compressing the rubber plug with two punches moving in opposite direction with the same velocity $v$ (Fig. 2a). The punches are then retracted and the rubber plug is removed after returning to its original shape. In the second stage, the local bulged tube is subjected to axial compression load by means of the upper die in order to form the desired compression bead (Fig. 2b). The active tool components are dedicated to a specific outside radius $r_0$ of the tube and the internal pressure $p$ together with the initial gap opening $l_{gap}$ between the upper and lower dies determine the final bulge with $w_b$ and length.
The tubes were first bulged by compressing the rubber plug with the upper and lower punches until failure in order to determine the pressure at the onset of instability $p_c$ and the maximum displacement $d_{\text{max}}$ at the onset of bursting for different values of the initial gap opening $l_{\text{gap}}$. Then different levels of displacement $d<d_{\text{max}}$ were applied to new tubular specimens in order to obtain the maximum allowable expansion before bursting for each value of $l_{\text{gap}}$.

At the end of tube expansion (first stage of the EACB process), the rubber plug was removed and the upper and lower punches were retracted. An internal mandrel was placed inside the bulged tube which was subjected to axial compression by means of the upper die in order to produce the desired compression bead. After finishing the second stage of the EACB process ad removing the internal mandrel firm the tubular parts, selected specimens were halved lengthwise in order to measure the wall thickness variation along the meridional direction of the cross section.

In view of the above, the experimental work plan in Table 1 summarizes the geometry of the tubular specimens that were used in order to determined the feasibility window of the proposed process.

<table>
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<th>Caso</th>
<th>$r_0$ (mm)</th>
<th>$t_0$ (mm)</th>
<th>$l_0$ (mm)</th>
<th>$l_{\text{gap}}$ (mm)</th>
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<td>5</td>
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<td>16</td>
<td>1.5</td>
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Table 1 – Geometry of the tubular specimens that were utilized in the experiments with the EACB process.

In order to study the behavior of the tool, numerical and experimental studies were made. First a dimensional survey was conducted for all the components of the tool, making use of a CAD software. Then a finite element analysis of the tool was performed in order to verify possible limitations and critical states for the maximum load allowed in the test machine Instron Satec 120ton, present in laboratory of Mechanical Technology. Finally, in the experimental development, the tool was mounted
in the press, and compression tests were conducted in order to evaluate the dynamic behavior of the tool and compare it with the results obtained when using only the vertical effect of the press.

3. FINITE ELEMENT MODELLING

Numerical modeling of the EACB process was performed by means of the computer program I-FORM. Being developed since 1980s in DEM at Instituto Superior Técnico, I-FORM is built upon the irreducible finite element flow formulation which is based on the following extended variational principle to account frictional effects (Alves, et al., 2011),

$$ II = \int \bar{\sigma} \bar{\varepsilon} \, dV + \frac{1}{2} K \int \bar{\varepsilon}_{ij} \bar{\varepsilon}_{ij} \, dV - \int_{S_T} \tau_1 \nu_1 \, dS + \int_{S_f} \left( \int_{u_i}^{l_{u_i}} \tau_f \, du_f \right) \, dS $$

where $\bar{\sigma}$ is the effective stress, $\bar{\varepsilon}$ is the effective strain rate, $K$ is a large positive constant imposing the incompressibility constraint, $V$ is the control volume limited by the surfaces $S_U$ and $S_T$, $T_1$ are 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 conditions and additional power consumption resulting from the rightmost term in equation (1) is determined through the utilization of the law of constant friction $\tau = mk$. The friction factor $m$ was set to 0.1 after checking the finite element predicted forming loads that best matched the experimental results.

The discretization of the tubular preforms that were utilized in the investigation was performed by means of four-node axisymmetric quadrilateral element. The utilization of four elements showed to be adequate for modeling the distribution of the major field variables and for getting a proper evolution of the load-displacement curve. The tools were considered rigid and were discretized by means of contact-friction linear elements (Fig.3).

![Fig.3](image) – Numerical modeling of the EACB process showing the initial and finite element computed meshes at the end of the (a) first and (b) second stages of the EACB process (Case 4 of Table 1).

The internal pressure $p$ transmitted by the rubber was assumed as a normal distributed load per unit of area acting along the edges of the quadrilateral elements that are located at the inside radius of the tubes where the rubber plugs are paced. The numerical simulation of the EACB process was accomplished through a succession of pressure (first stage) and displacement (second stage) increments each of one modeling approximately 1% of the maximum applied pressure and 0.1% of the initial tube length, respectively. The convergence of the computational procedure was stable and the overall CPU time for a typical analysis containing a total number of 600 elements was below 3 min on
a standard laptop computer equipped with an Intel i5 CPU (2.5GHz) processor and making use of a single core.

In order to study the tool structure, numerical analysis were made using the finite element software SolidWorks 2013. For the analyses, sliding and no penetration conditions were imposed between the moving parts of the tool. The base and the tests plates were fully constrained. A vertical force of 1200kN was applied in the roof, representing the maximum capacity of the press which the tool was designed for. The mesh (Fig. 1c) was constituted by parabolic tetrahedral solid elements with base dimensions of 32 mm and a maximum tolerance of 1.6 mm, resulting in 14508 elements. The mesh chosen presented a good rate of results quality/analysis time, since it allowed to define all the tool components achieving an overall satisfactory results, with an analysis time below 3 minutes.

4. RESULTS AND DISCUSSION

4.1 Plastic flow and failure

First stage

The observation of crack morphology at bursting for the entire set of tubular specimens listed in Table 1 revealed the existence of two different plastic flow mechanisms during the first stage of the EACB process (Fig. 4).

![Graph showing influence of initial gap opening on bursting behavior](image)

**Fig. 4** – Influence of the initial gap opening \( l_{\text{gap}} \) on the bursting behavior for the specimens listed in Table 1: Experimental and analytical values of the internal pressure \( p_{\text{cr}} \).

For large values of the initial gap opening \( l_{\text{gap}} \) bursting occurs by failure along a vertical crack in close agreement with the behavior of thin-walled cylinder shell with open ends under internal pressure (refer to the rightmost specimens in Fig. 4). The internal pressure \( p_{\text{cr}} \) in this case can be calculated from the analytical expression (3) for a material following a Ludwik-Hollomon’s strain hardening model \( \dot{\sigma} = K \varepsilon^n \), where \( r_0 \) and \( t_0 \) are the radius and wall thickness of the tube respectively. However, the bursting behavior of tubes with small values of the initial gap opening \( l_{\text{gap}} \) exhibits failure along a horizontal crack (refer to the leftmost specimens in Fig. 4). The analytical model that is proposed for understanding plastic flow in such operating conditions is built upon an approximate solution for a thin-
walled toroidal shell under internal pressure. The corresponding expression for calculating \( p_{cr} \) as a function of \( l_{gap} \) is given by equation (4), where \( b_0 \) is the radius of the toroid. The approximation \( b_0 \approx \frac{l_{gap}}{2} \) is performed on equation (4) for calculating the internal pressure at the onset of instability as a function of the initial gap opening (Alves, et al., 2013).

\[
p_{cr} = K \frac{\left( \frac{2}{3} \right)^n}{b_0^{\frac{n}{3}}} \exp^{-n}
\]

(3)

\[
p_{cr} = \frac{2}{\sqrt{3}} K \frac{\left( \frac{n}{\sqrt{3}} \right)^n}{b_0^{\frac{n}{3}}} \exp^{-n}
\]

(4)

The agreement between the experimental values and the analytical predictions of \( p_{cr} \) is good and confirms the proposed plastic flow mechanisms controlling the first stage of the EACB process (Fig. 4). Major differences are due to the simplifying assumptions that were necessary to derive the analytical equations, to the influence of the geometric imperfections of the tubular specimens and to the influence of boundary constraints.

The two different types of experimental results were observed for Case 3 of Table 1 allowed to identify the transition value of \( l_{gap} \) where plastic flow and failure mechanisms associated with thin-walled cylinder and toroidal shells are likely to coexist (Fig.5a). The details of the finite element predicted distribution of ductile damage according to the normalized Cockcroft-Latham criterion

\[
D = \int_0^{\varepsilon_f} \frac{\sigma_1}{\sigma} d\varepsilon
\]

for selected test cases with initial gap openings below and above \( l_{gap} = 15 \text{mm} \) corroborate the changes in plastic flow and the corresponding location and direction of failure by cracking (Fig.5b), showing that the region where the accumulated damage \( D_{\text{max}} \) is the greatest and failure by cracking is likely to occur, changes from the circumferential direction along the tensile region of the inner tube surface subjected to bending and pressure (refer to ‘A’ Fig.5b), to the equatorial region of the outer tube bulged surface (refer to ‘B’ in Fig 5b).

Although the above discussion, the essence of the first stage of the EACB process relies on the possibility of controlling the amount of compression of the rubber plug so that sound bulged tubes can be produced without failure.

Second stage

The second stage involves axial compression of the bulged tubes. As seen in Fig. 6, the formability limits of the EACB process successfully extend those of the conventional process by allowing the formation of compression beads with initial gap openings of \( l_{gap} = 5 \text{mm} \) and \( l_{gap} = 25 \text{mm} \).
At higher gaps opening ($l_{gap}>25mm$) the tubular specimens fail by cracking. Two types of failure are observed. One type is caused by cracking along the meridional direction (Fig. 7.1.a) and is attributed to high values of ductile damage at the equatorial plane of the specimens (Fig. 7.1.b). The other type of failure is caused by cracking along the circumferential direction (Fig. 7.1.c) and is attributed to meridional stresses emerging from the asymmetric propagation of compression beads whenever the initial gap opening is very large. In fact, when the unsupported free length of the tubes is very large, there is a change that local bucking starts developing naturally into an asymmetric instability wave until it comes into contact with the upper and lower dies (refer to ‘A’ and ‘B’ in Fig. 7.1.d). From this moment on, the compression beads are forced to bend towards the horizontal, axisymmetric, direction and the risk of failure along the horizontal cracks increase due the exposure to high meridional tensile stresses.

Fig. 7 – (1) Failure by cracking during the second stage of the EACB process (Case 6 of Table 1): a) Cracking along the meridional direction; b) Finite element predicted evolution of ductile damage; c) Cracking along the circumferential direction; d) Evolution of the compression bead present in (c).

(2) Experimental and finite element predicted variation of the thickness along the meridional direction for Case 4 of Table 1 in the cross section of tubular specimens corresponding to the end of the first and second stages of the EACB process.

The influence of plastic flow in the variation of thickness along the cross section of a tubular specimen at the end of the first and second stages of the EACB process is illustrated in Fig 7.2. The initial flat region of the graphic correspond to nearly unstrained material placed in the cylindrical region of the specimens and the final thickness in this region remains practically identical to the initial
thickness of the tubes. The subsequent sharp decrease in thickness that is observed at the end of the first stage on the EACB process, is due to tube bending around the corner radius $r_c$ in order to match the contour of the upper die. Further decrease in thickness towards the equatorial region that is observed at the end of the first stage is caused by tube expansion with the rubber. A maximum thickness reduction is found at the equatorial plane (refer to ‘A’ in Fig. 7.2). In the second stage there is a replacement of the equatorial plane by the adjacent zone placed immediately before (refer to ‘B’ in Fig 7.2), as the region of the tubular specimens where thickness variation is larger. This is attributed to combination of thinning due bending in ‘B’ and thickening at the equatorial plane corresponding to former point ‘A’.

4.2 Pressure and forming loads

Fig. 8a shows a typical experimental and finite element predicted evolution of the internal pressure with the radius of the bulged tube during the first stage of the EACB process. The internal pressure $p$ increases until it reaches a critical pressure $p_{cr}$ where instability starts and busting follows with further deformation. The increase in the tube radius is negligible during most of the first stage and only grows suddenly very close to its end.

Fig. 8b show the experimental and finite element predicted load-displacement curves corresponding to entire set of test case listed in Table 1, for the second stage of the EACB process. As seen, all test cases apart from Case 1 show three different plastic deformation stages (refer as ‘A’, ‘B’ and ‘C’ in Case 3 in Fig. 8.b ). The first sate (‘A’) is characterizes by a steep increase of the forming load as the bulged tube is axial loaded and compression bead starts. In second sates (‘B’), the compression bead grows under a falling load. The third stage (‘C’), is characterize by a sharp increase in load requirements caused by the enclosure of the compression beads between the upper and lower dies. Case 1 only presents two stages due to the small value of the initial gap opening that leads to small width compression beads, being the second stage negligible.

4.3 Tool

Respecting the results obtained from the study of the tool Fig. 9 shows a variation of the region with maximum stress for different openings of the tool with and without the support of the risers. In
general, the lateral support and the vertical actuator are the components that verify higher stress values. The abrupt transition between point ‘A’ and point ‘B’ in both cases with and without risers is explained by two phenomena: for a opening of the tool around 460mm there is a transition in the maximum stress region, and the vertical actuator ceases its full contact with the inclined area of the car tool holding, resulting in a sharp change in the maximum stress. The load transmitted stops being primarily supported by outriggers, becoming also transmitted vertically to the car tool holding.

![Diagram showing stress variation](image)

Fig. 9 - Variation of the position and value of the maximum stress for different openings of the tool.

Numerical calculations were performed using the finite elements method, force projection and virtual work method in order to predict the transmission of the vertical force to the horizontal. Neglecting friction, it was calculated that the tool would have the capacity to increase the load 73%. However experimental tests showed that the friction has a relevant influence in the dynamic behavior of the tool. In fact, the force transmitted by the tool verify a decrease of approximated 50% due the lost of energy in friction. It was conclude that to achieve an acceptable result from a test performed with the tool, it was necessary to do some adjustments in the results obtain. The displacement needed a correction using the relationship $x = \frac{2y}{\tan 60}$, where $x$ is the true displacement and $y$ is the displacement registered from the test machine. The load could be corrected by two forms: using a global corrective coefficient $\frac{F_{\text{horizontal}}}{F_{\text{vertical}}} \approx 2$ or applying friction coefficients to each movement components. Fig. 9 display the test results, regarding the preferred corrections.

![Graph showing load vs displacement](image)

Fig. 10 – Experimental results obtain in the vertical test and in the horizontal test with the corrections needed: a) Compression test of a cylindrical aluminum sample; b) Compression test of a S460MC (carbon steel) tube.
5. CONCLUSIONS

The deformation mechanisms for each stage of the EACB process were studied through analytical model, numerical simulation and experimental tests. Plastic flow and failure during the first stage were explained with the classical solution of thin-walled cylinder shell with free ends under internal pressure and the approximate solution of a thin-walled toroidal shell under internal pressure. The approximate solution proved to be suitable for the understanding of the critical values of internal pressure $p_c$, and understanding the development of circumferential cracks at bursting when using small values of the initial gap opening. It was found that the formability limits of the overall process are dependent on failure by cracking along the meridional direction of the bead during the second phase of the process, due to high levels of ductile damage accumulated in the equatorial region of the tubes. For high values of the initial gap it may result in asymmetrical deformation modes causing failure of the tube by tearing along the tangential direction of the bead.

The structural study of the tool concluded that the critical regions differ with different tool opening. The lateral support and the vertical actuator are the components with higher stress values. It was found that the use of risers is indispensable in order to reduce the maximums stresses. The numerical study of the influence load transmitted, conclude that without the influence of friction between the moving parts, there would be an increased of the transmitted load about 73 %. However experimentally it has been found that friction have a determining influence on the dynamic behavior of the tool, causing a decrease of the transmitted load about 50%.

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