Boss Forming of Rods

Experimental and Numerical Analysis

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Abstract

Recent trends in manufacturing industries drive the development and research for more flexible metal forming processes, capable of meeting new customer demands, such as joining dissimilar materials.

The new process for producing annular flanges on rods is based on a previous process of boss forming of tubes. The overall mechanism that controls the process is boss forming, that was utilized to produce the bottom annular flange on the rod, with a cross section that can provide an adequate surface for supporting a sheet, for example.

In addition, a brief study on the joining by forming of rods to sheets is presented where boss forming was utilized on the rod to produce not only the supporting annular flange but also the top annular flange that allows to mechanically lock the two components.

This article combines experimental tests and finite element analysis in order to identify the modifications from the previous process of boss forming of tubes, that make possible to accomplish this new proposed boss forming process applied to rods, as well as the parameters that control its feasibility.

The results from this work are presented along the advantages and drawbacks of the new boss forming process. The efficiency of the new proposed mechanical joint is verified by a destructive pull-out test, which evaluates the force needed to separate the rod from the sheet.

Introduction

In recent years, manufacturing industries have been focusing on the development of metal forming processes, due to new customer demands. This recent trend lead to the development of the new Boss Forming process, which is an extension of Sheet-bulk Forming[1], to produce annular flanges in thin-walled tubes [2].

Boss forming involves partial compression of the wall thickness of a tube in order to pile-up material along its axial direction to produce localized annular flange (Fig. 1a). This process was improved by Alves et al[3] and it was proven to be successful in producing more robust annular flanges in tubes. The results of this study presented the opportunity to expand its use to produce annular flanges in rods (Fig 1b), which is another common structural element.

The goal of this dissertation is to expand the boss forming process to rods, by identifying its major parameters and introducing the necessary modifications in the previous tool design in order to produce viable flanges. Furthermore, by controlling the process parameters, boss forming can be purposed to mechanically join rods to sheets, as a more environmentally friendly and cost effective alternative than conventional joining methods [4].

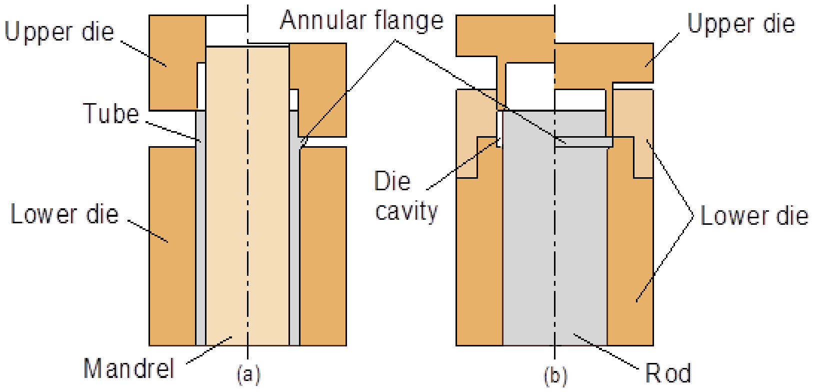


Fig. 1 – (a) Boss forming of annular flanges in thin-walled tubes (b) New concept of boss forming to produce annular flanges in solid rods.

Experimental work

The development of the new boss forming process was carried out on AW6082-T6 aluminium rods and AW6082-O aluminium rods. The AW6082-O rods were obtained by annealing AW6082-O rods. The details of the annealing process can be found in Torca et al.[5].

The application of joining sheets to rods utilized AW6082-O aluminium rods, DC04 mild steel sheets with 1.5mm thickness and an AA1050 AH14 aluminium sheet with 1mm thickness.

The mechanical characterization of the AW6082-T6 and AW6082-O aluminium was performed by means of compression tests in cylindrical specimens machined out from the respective rods. The mechanical characterization of the DC04 steel was performed by means of stack compression test. The material of the AA1050 AH14 aluminium sheet was sourced from the library of materials included in the software for the corresponding numerical analysis. The average stress-strain curves resulting from the mechanical characterization tests are shown in Fig. 2.

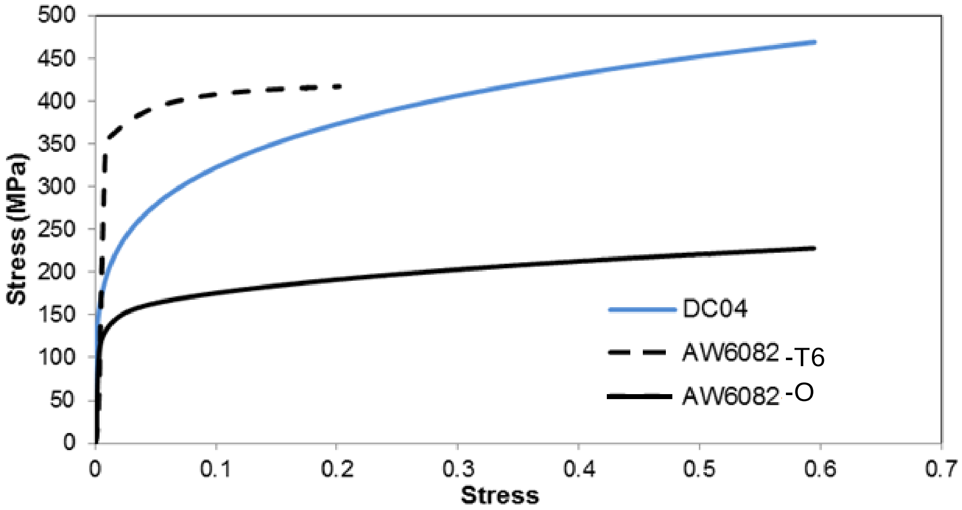


Fig. 2 - Stress-strain curves of the AW6082-T6 and AW6082-O aluminium rods and DC04 steel sheets.

The experimental work plan consisted of 2 sets of experiments and a final experiment of a destructive pull-out test.

The first set of experiments was focused on the development of the boss forming and made use of two different tool designs. The main parameters of the boss forming of rods were identified as the material pile-up thickness a, the material pile-up length b and the rectangular cross-section $c \times d$ of the annular die-cavity, as shown in the figure of Table 1.

The experiments were carried out, with different values of material pile-up thickness a and the material pile-up length b was calculated to ensure the complete filling of the annular die-cavity with a rectangular cross-section of $c \times d = 3 \times 3\text{mm}^2$. The relevant case studies of the process parameters are summarized in Table 1.

In the experiments using the first design (left side of the figure included in Table 1) the upper compression die pushes the material along the longitudinal direction that is then piled up to obtain the annular flange. The geometry of the upper die is a straightforward extension to solid rods of the boss forming of thin-walled tubes concept [2]. The lower die was modified to include a die cavity for controlling the final cross-section geometry and size of the annular flanges. A two-half die concept is utilized to allow removal of the rod after boss forming. Cases i, ii and iii were tested with both AW6082-T6 and AW6082-O aluminium rods with identical results.

The second tool design (right side of the figure included in Table 1) was developed after concluding that the first one was not viable for producing acceptable boss formed rods. To this end, the upper die was redesign to include a pressure ring, with a relief angle and appropriate inner r_{pr}^{i} and outer r_{pr}^{o}radii, which imposes compression on the material adjacent to that undergoing pile-up deformation. The new design was tested on AW6082-O aluminium rods (case iv of Table 1).

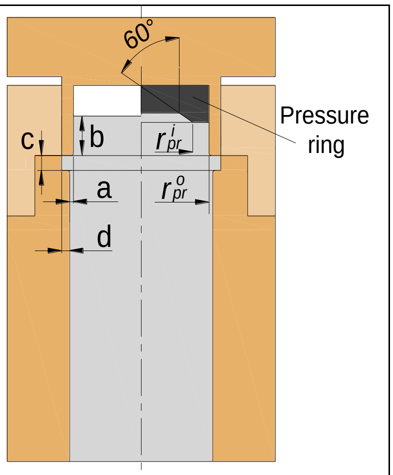
Case	a(mm)	b(mm)	r_{pr}^{i}	r_{pr}^{o}	
i	0.4	11.9	-	-	
ii	0.6	8.0			
iii	1.0	4.9			
iv	.0	4.9	8.5	11.5	

Table 1 Summary of the relevant case studies of the boss forming process parameters in rods

The second set of experiments utilized the new boss forming process to join DC04 steel and AA1050 AH14 aluminium sheets to AW6082-O aluminium rods by plastic deformation with mechanical interlocking.

As previously mentioned, the final experiment consisted in a destructive pull-out test to determine de maximum force that the new joint, obtained by boss forming, is capable of withstanding before failure.

All tests were carried out at room temperature in displacement control under a constant vertical velocity equal to 5mm/min.

Finite Element Modeling

The numerical modeling of the boss forming process was carried out with the in-house finite element computer program I-FORM [6]. The models made use of rotational symmetry conditions and discretized the longitudinal cross-section of the rods by means of quadrilateral elements. The same type of elements was utilized to discretize the sheets when simulating the joining of sheets to rods. Both rods and sheets were modeled as deformable objects and contact with friction along their interfaces was solved by means of a two-pass node-to-surface algorithm with penalization of the normal gap velocities in order to avoid penetration. The upper and lower dies were modeled as rigid objects and their geometries discretized by means of linear contact-friction elements.

Fig. 3a shows the initial finite element mesh utilized in the numerical modeling of boss forming with a detail of the fine mesh employed in the outer radius where the material of the rod is compressed and piled up.

Results and discussion

Fig. 3 illustrates two extreme modes of deformation that are observed in boss forming of rods with the first tool design (without pressure ring). Fig 3b corresponds to case i of Table 1, where material is removed from the outer radius of the rod by cutting and the die-cavity is not properly filled out. Consequently the resulting annular flange is unacceptable.

In Fig 3c, corresponding to case iii of Table 1, material is displaced and piled up with no separation into a chip. This mode of deformation is what is aimed for in boss forming and will later be applied to the joining of sheets to rods by mechanical interlocking.

The test case, corresponding to case ii in Table 1, with operating parameters between these two modes of deformation, experienced transition modes of deformation from cutting to piling up with chips being formed at larger or smaller extents.

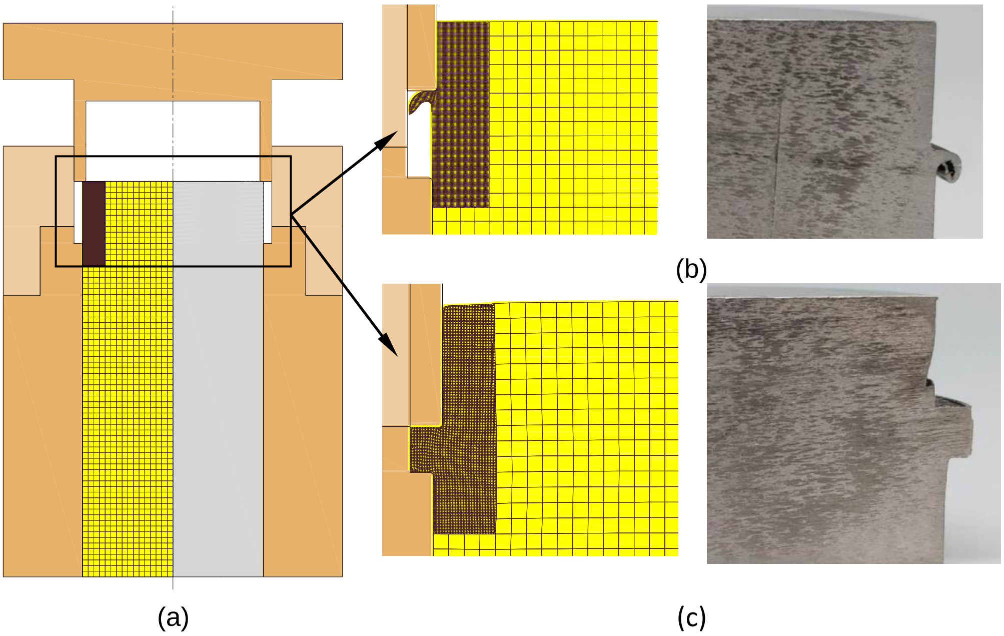


Fig. 3 – Boss forming of rods with the first tool design (without pressure ring) (a) Main geometry of b the boss forming process and finite element model. (b) Computed and experimental cross sections for case i (Table 1) (c) Computed and experimental cross sections for case iii (Table 1)

Despite case iii ensuring the formation of annular flanges by material pile-up with no separation into a chip, there are grooves typical of ductile fracture along the material pile-up length b (Fig 4a). The morphology of the grooves is typical of cracks that opened by tension.

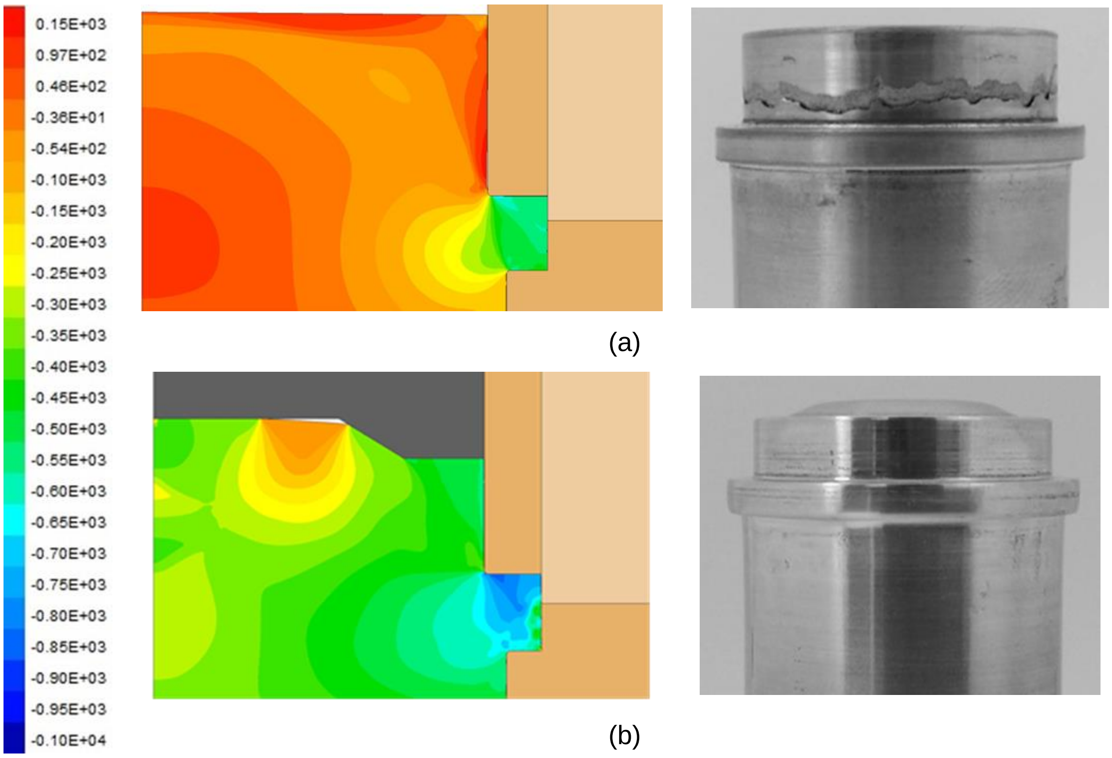


Fig. 4- Finite element distribution of average stress [MPa] at the last stages of boss forming. (a) Case iii, without pressure ring (b) Case iv, with pressure ring.

The first proposed solution to avoid crack formation was to anneal the aluminium rods and increase the formability of the material. This solution proved to be unsuccessful and the new results were identical to experiments using the non-annealed aluminium rods with the same operation parameters

The avoidance of cracks during boss forming of rods required changing the stress state of the material adjacent to that undergoing pile-up deformation. This was achieved by redesigning the upper die in order to include a pressure ring that imposes compressive stresses on the material next to pile-up thickness a (Fig. 4b).

Fig. 4 shows the finite element computed distribution of average stress σ_m at the rod end for both tool designs without (Fig 4a) and with (Fig 4b) pressure ring. The results confirm the avoidance of tensile average stresses σ_m when using the upper die with a pressure ring. The experimental results (photographs included in Fig 4) confirm the influence of the prevailing stress state in occurrence or prevention of ductile fracture along the material pile-up length b.

The utilization of the pressure ring also influences the force-displacement evolution of the boss forming process (Fig 5). The curves follow a trend typical of a closed die forging force-displacement evolution. Moreover, the occurrence of crack formation in the boss forming of rods without pressure ring (Case iii) is not explicit in the force-displacement evolution.

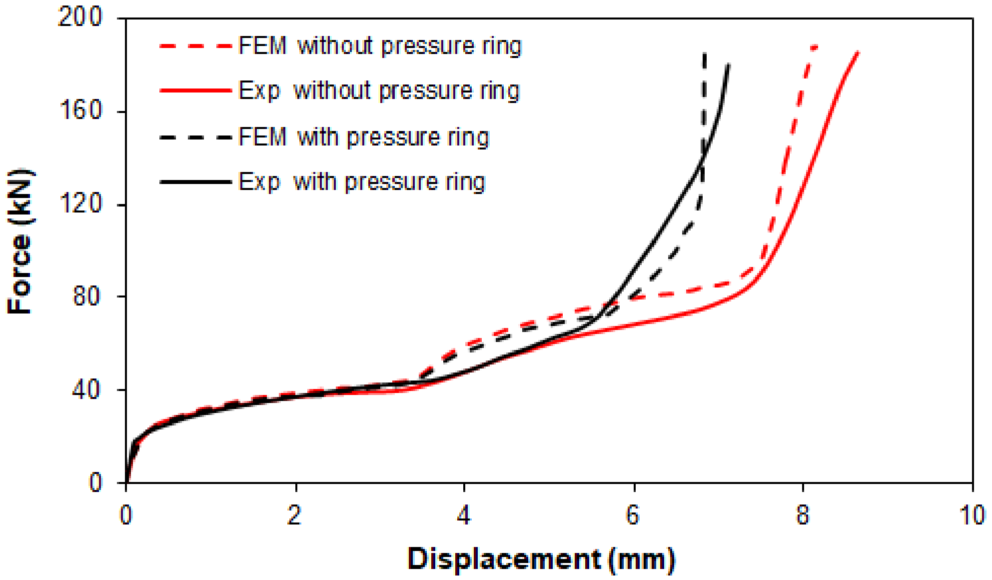
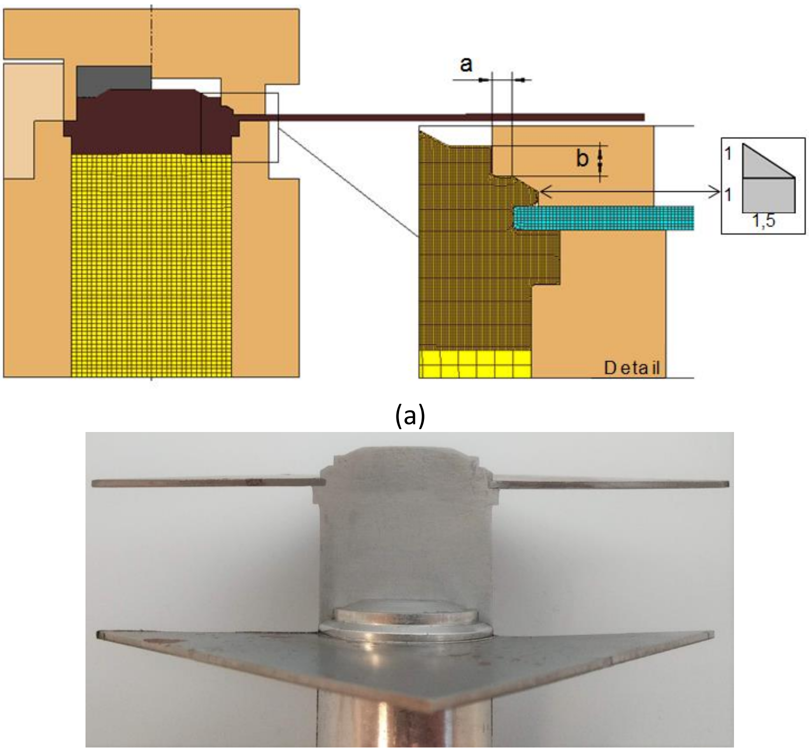


Fig. 5 – Experimental and finite element predicted force-displacement curves for the boss forming of rods, without (case iii of Table 1) and with pressure ring (case iv of Table 1)

The influence of the pressure ring is limited to the final stage of the boss forming process. Both force-displacement evolutions show a small monotonic force grow up to a point, beyond which, the force rises more steeply in the boss forming with pressure ring, due to the extra compressive stresses induced by the pressure ring. Still, the maximum force for the upper die with pressure ring is below 200 kN. Moreover, the occurrence of crack formation in the boss forming of rods without pressure ring (Case iii) is not explicit in the force-displacement evolution.

The boss forming with pressure ring concept was utilized to join sheets to rods by plastic deformation with mechanical locking. The operation conditions were retrieved from case iv of Table 1 as they proved to be adequate for producing sound annular flanges. This joining by forming process was performed in two stages (Fig 6a). In the first stage, boss forming was utilized to produce the bottom annular flange. The cross-section geometry of the annular flange was retrieved from the previous works of joining tubes to sheets[3] and ensures an adequate bearing surface for receiving the sheet. In the second stage, boss forming was utilized to produce the top annular flange that allows fixing the sheet to the rod by mechanical interlocking. Numerical simulations were performed in order to design the geometry of the new annular die-cavity with appropriate dimensions for joining the steel and aluminium sheets with different thickness. The photograph in Fig 6b shows the joint with the steel sheet and its cross section at the end of the process.



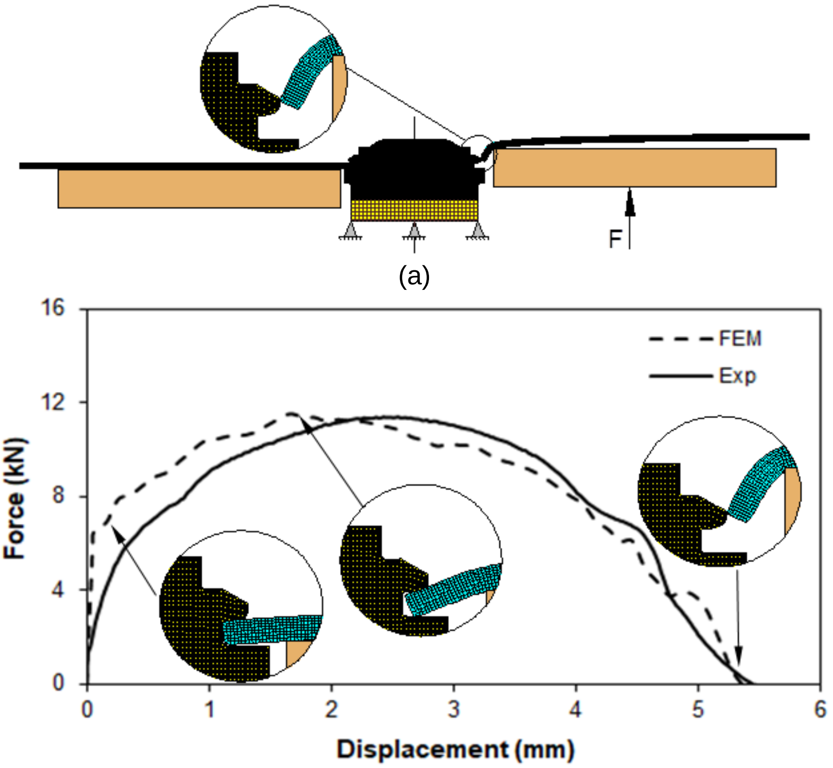
(a)

(b)

Fig. 6 – Two stage joining process (a) Finite element modeling of the joining of sheets to rods and die-cavity dimensions [mm] (b) Cross section of the joint of DC04 steel sheet and AW6082-O aluminium rod

Fig.7 shows the finite element and experimental results of the destructive pull-out tests aimed at detaching the steel sheet from the aluminium rod.

As observed from the finite element simulation (Fig 7a) and from the force-displacement evolutions (Fig 7b) the mechanical interlock remains mostly unchanged up to a force of approximately 7 kN. Below this force, deformation is essentially carried out by the sheet subjected to progressive bending. Above this force, the mechanical interlock starts to fail, reaching a maximum vertical force of approximately 11.8 kN. The sheet is eventually drawn and detached from the rod.



(a)

(b)

Fig. 7 – Destructive pull-out test (a) Finite element modeling (b) Predicted and experimental force-displacement evolutions for the destructive pull-out tests.

Conclusions

Boss forming of annular flanges in thin-walled tubes can be successfully extended to solid rods. The extension requires redesigning the upper die to include a pressure ring and building the lower die in two halves to include a die cavity. The pressure ring imposes a compressive state on the material of the rod adjacent to that being piled up along the material pile up length, in order to prevent cracking. The utilization of small values of the material pile-up thickness revealed to be inappropriate the material will be removed by cutting with formation of a curled chip. The transition between modes of deformation observed with intermediate values of pile-up thickness is attributed to loss of symmetry conditions during the process.

The application of the new boss forming process for joining sheets to rods has the advantage of allowing dissimilar materials while also being performed at room temperatures with simple tools and equipment.

Acknowledgments

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