Joining of overlap sheets by Sheet-Bulk Metal Forming

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Abstract

Several industry sectors, mainly automotive and aeronautic, have been promoting the development of new technological processes that provide high efficiency. Sheet Bulk Metal Forming (SBMF) follows this trend, being able to produce complex parts with less manufacturing stages. However, its applicability to join parts is not yet fully explored.

The research work aims to develop a new lap joint by plastic deformation (SBMF). The process combines a partial cut and bending with an upset compression in direction perpendicular to thickness.

The viability of the joint was evaluated through a theoretical model and the overall concept was validated by means of numerical and experimental tests. The destructive tests demonstrate a good mechanical performance of the lap joint.

Keywords

Overlap joint; Joining by forming; Sheet Forging; Numerical analysis; Experimental analysis;

1. Introduction

In today's industry, the need to optimize operations and technologies is a main focus. For example, in the automotive industry, research is being made into finding ways to handle lighter and cheaper materials and to obtain complex components withthe minimum amount of production operations possible. The development of SBMF processes aims to answer to that. This brand new technology can be used to combine sheet deformation characteristics with conventional mass deformation, being able to form local zones outside the plane of the sheet, allowing to obtain complex geometries in a few number of operations [1]. However, SBMF processes can achieve a wider applicability when used in joining processes.

Sheet joining is one of the most common joining processes existent and its finished products can be easily detected everywhere. Although well-known joining processes such as resistance spot welding, friction stir welding, mechanical fastening and adhesive bonding are mostly used, a new trend known as joining by forming emerged recently. This trend presents itself as the group of joining processes obtained by plastic deformation, being able to correspond to some of the defects and limitations of the more known sheet joining processes referred earlier.

The research work presents a new sheet joining method based in both SBMF and joining by forming, thereby obtaining a purely mechanical joint. The presentation describes thestages of the proposed process, as well as the major process parameters by means of a theoretical model developed for the case in study. The overall plastic deformation and applicability limitations was investigated by means of experimental and finite element simulative work. In order to test the performance of the newly obtained joint, an experimental destructive test was made to find out the maximum shear force that the joint can handle.

2. State of the art

2.1. Progress in SBMF

Processes inserted in SBMF can be classified by two parameters: changes in the thickness of the final product and by the acting of the deforming tool [1]. The existent forming loads depend highly on the contact areas between the acting tool and the deformed part. In order to avoid high loads, the use of rotational tool motion processes can be used, since these usually have relatively low contact areas. However, to use this kind of tools, the optimum control can be more difficult than controlling a simple linear tool motion, increasing the operation time for a given procedure.

Sheet forging can also be useful in producing components made by conventional stamping. Although this variant is not as well-known as stamping operations, current research shows that it can manufacture complex components obtained by stamping, but with less excess of material, reducing the weight of the component, and with fewer steps in the overall operation, highly increasing the productivity associated [2].

The main concerns involved in most SBMF processes are related to its characteristic high loads, essentially in the end of the forming process. When forging a sheet surface with details composed of tiny and complex geometries at very high pressures, the deformation of such details can easily create high localized plastic strains that may originate a differentmaterial flow than the one intended, since it tends to avoid certain regions of highly difficult material deposition [3]. It can be expected that a strict control of the material flow in SBMF processes is there by essential. Research has been made to improve the material flow in SBMF by studying and understanding the influence of the friction conditions by means of new developed tests [3] or tool-optimizingto increase its life performing and to study its chemical interaction with specialized lubricants tocreate favourable friction conditions by easing the material flow of a certain SBMF process [4].

2.2. Overlapsheetjoining processes

Overlap joints are produced by welding, adhesive bonding, mechanical fastening or joining by forming as shown in Fig. 1and are widely used to assemble continuous surfaces from individual sheets partially placed over one another without changing in their shape.

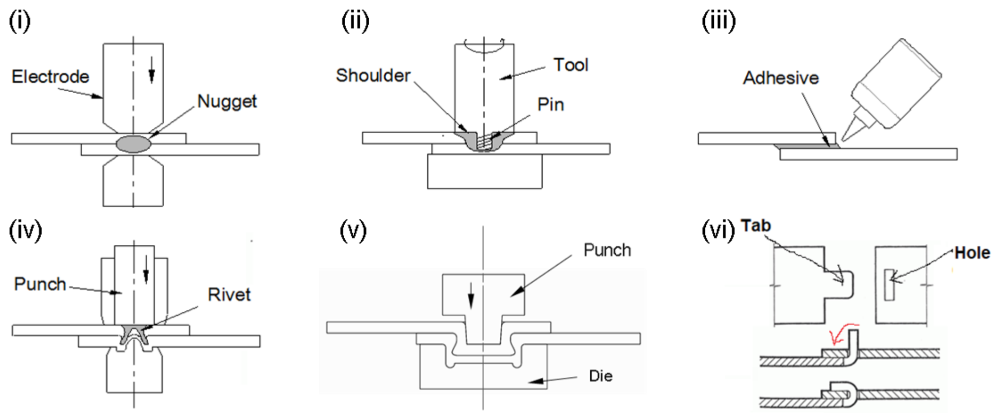


Fig. 1- Schematic representation of the mostly used processes to date into obtaining an overlap sheet joint: **(i)**Resistance Spot Welding; **(ii)** Friction Stir Spot Welding; **(iii)** Adhesive Bonding; **(iv)** Self-pierce Riveting; **(v)** Clinching; **(vi)** Hemming

Resistance spot welding (i) and friction stir welding (ii) are among the most commonly used welding processes to produce lap joints in metal sheets. However, their utilization is limited in case of dissimilar materials and is costlier than alternative processes due to the inspection of the welds. Lap joints produced by adhesive bonding (iii) can overcome the welding difficulties in joining sheets made from dissimilar materials but its utilization is constrained by temperature, ageing due to weathering, long curing times and cautious surface preparation.

Mechanical fastening comprises the utilization of threaded fasteners and rivets. This type of jointsare easy to assemble and disassemble, usefulto connect dissimilar materials of sheets and are free from thermal after effects and curing time requirements. However, fasteners and rivets are limited by the maximum force that they can safely support, aesthetic and dimensional requirements and corrosive working environments. Also, the pre-drilling hole made to joining sheets by mechanical fastening can create undesirable high tensionconcentrations.

Joining by forming, when applied in sheet joining, comprises a wide range of processes such as, self-piercing riveting, clinching and hemming [5]. Self-piercing riveting(iv) and clinching (v) avoid the applied forces to be concentrated at the points of fastening or riveting, since it does not require any pre-operation. However, most of the lap joints produced by these processes are not hermetic upon loading (due to the open nature of the joints) and, therefore, are not recommended to be used in working environments with moisture, water and other fluids. Moreover, some of the lap joints produced by forming can experience loosening during impact or material stress relaxation and can also be sensitive to fatigue failure in cyclic mechanical loadings.Hemming (vi) requires no additional filler materials and accessories and has the advantage of being an easy and economical way of producing lap joints in sheets that will permanently or semi-permanently attach to one another. However, the process is highly dependent on the behaviour of the material when bended, being necessary to possess good ductility and fracture toughnessand it is not yet adapted to thick sheets. It is also a not so well understood process like the previous referred, presenting defects and joint performances not yet deeply discussed in available literature.

2.3. Historicalreview

The ideal of the proposed process originated in a similar joining process recently investigated, also obtained by SBMF, used to join metal sheets perpendicular to each other [6].The joint was obtained in format of a mortise-and-tenon, but instead of fixing both components with localized heat or adhesive bonding, the fix was created by plastic deformation of the tenon inside the mortise, Fig. 2. By achieving success in joining aluminium sheets (i), later applications of its usability were investigated, like the joining of polymer sheets and also an hybrid joint between metal and polymer sheets (ii) [7].

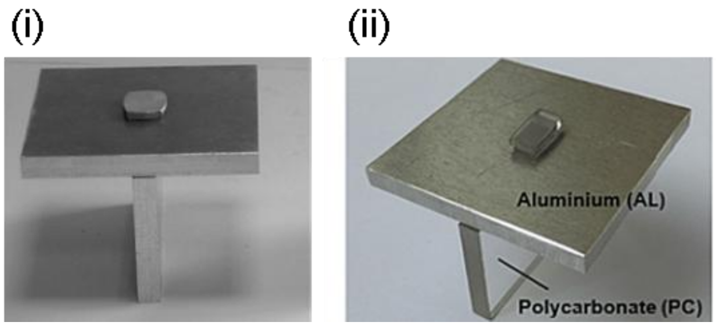


Fig. 2 – Joining sheets perpendicular to another by SBMF: **(i)** Aluminium-Aluminium joint [6]; **(ii)** Aluminium – Polycarbonate joint [7].

3. Theoreticaldevelopment

The new proposed joining my forming method begins with partial cutting on both sheets to be joined. Then, it involves three different operations by plastic deformation of the sheets: (i) localized bending of tabs on the region limited by the partial cutting made (ii) sheet bulk compression of the first tab and (iii) sheet bulk compression of the second and final tab, Fig 3, obtaining a mechanical interlocking between sheets without any protrusion. Both compressions are made in a direction perpendicular to the sheet thickness. While the first one requires an inferior die to restrict the material flow, the second and final compression is done with an identical constrain, but applied by the previously compressed tabinstead of the inferior die used in the first compression.

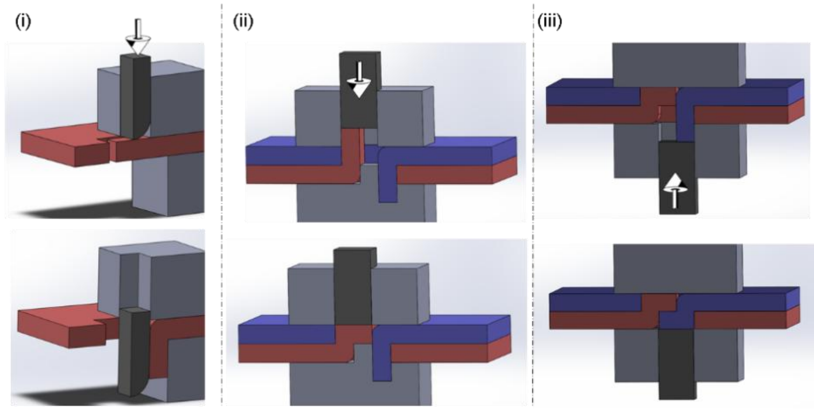


Fig. 3 – Schematic representation of the sequence of operations included in the proposed process: **(i)** bending of tabs; **(ii)** sheet bulk compression of the first tab; **(iii)** sheet bulk compression of the second tab.

3.1. Theoreticalmodelling

Fig. 4 presents a schematic cross section of new proposed lap joint at three different stages during the process (i) assembling of sheets obtained after cutting and bending of tabs, (ii) after compressing one of the bent tabs into the free hole of the joint and (iii) after compressing the two bent tabs into the free hole of the joint.

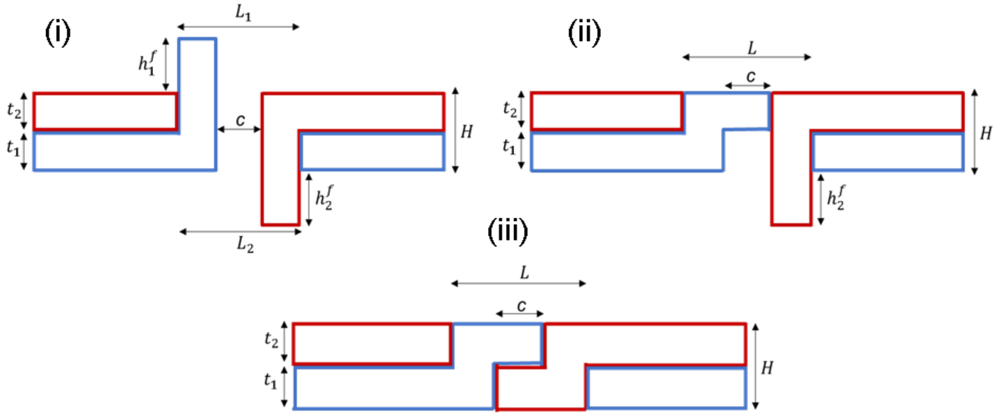


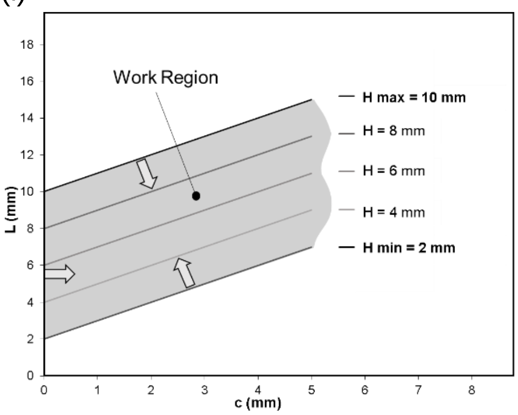
Fig. 4 – Schematic cross-section representation of the parameters considered in order to theoretically model the obtainable joint: **(i)**Assemble of tabs after bending; **(ii)** After compressing the first tab; **(iii)**After compressing the second tab.

As shown, it is assumed that the bent radius can be neglected and that each sheet thickness *t* remains constant in all stages. Plastic deformation of tabs is also assumed to be homogeneous and isotropic under plain strain conditions, admitting a width *W* of the deformed section also constant in all stages. Since it can be assured that the Volume of the deformed section remains constant, it is known that the protrusion height of the bent tabs before their respective compression h_1^f and h_2^f as to be equal to the horizontal clearance between bent tabs *c*. The cutting length *L* can be obtained as follows:

$$L = c + t_1 + t_2 = c + H \tag{1}$$

In equation (1), *H* represents the total thickness of the projected joint. Since this equation incorporates all the influent parameters considered to theoretically model the process, its handling is essential to project the mechanical interlocking region. It can also be plotted as shown in Fig. 5. In order to restrain its graphic representation (i), a spectre of sheet thicknesses was considered to simplify its understanding. A a maximum total joint thickness of 10 mm and a minimum of 2 mm was considered, with intermedium representations of total joint thicknesses by multiples of 2. The usability of sheets was restricted to individual whole number thicknesses between 1 mm and 5 mm (ii).

(i)



(ii)

H [mm]	Configurations of the proposed joints considered t_1, t_2 [mm]
2	1,1
4	1,3 2,2
6	1,5 2,4 3,3
8	3,5 4,4
10	5,5

Fig.5 - Representation of the configurations of the proposed joints considered: **(i)** Graphic representation of the work region by limiting the thickness of the total obtainable joint; **(ii)** All joint configurations considered in the proposed range of applicability

Nevertheless, it is predicted that clearance *c* cannot assume any positive value since that, with its large increase, the bent tab will have a higher height, potentializing the occurrence of plastic instability of the bent tab in the sheet bulk compression steps. In this case, it is predicted that plastic instability originates lapped material inside the mechanical interlocking. In order to avoid it, it is required to know the maximum height existent for which no lapped material occurs. The free height in sheet bulk compression stages can be related with the clearance as follows:

$$h_{1/2} = c + t_{2/1} \tag{2}$$

To know this geometrical limit, a numerical analysis was developed considering the theoretical modelling of the tab after the bending stage, Fig. 6 (i). This analysis regards only the first sheet bulk compression, differing from the numerical analysis related to the overall process, Subsection 3.2. However, the numerical modelling resources of both analysis are the same, supported by the in-house computer programme i-form, also described in Subsection 3.2. In order to find the maximum height of the tab before its compression, parameters like sheet thickness, friction and material were considered constant while variating the free height of the tab with gaps of 1 mm until lapped material is numerically visible. This analysis was made considering a joint composed by sheets with same thickness, being able to relate the maximum height with the respective sheet thickness. By doing this, a maximum clearance *c* is obtained regarding each sheet thickness *t,* being the maximum clearance of a joint limited by its thinner sheet.

Friction was modelled by a constant law (Prandtl), considering a friction coefficient *m*of 0.05, 0.1 and 0.2 while the material was modelled by its Ludwik-Hollomon equation (3), shown in Section 4. The existent lapped material was identified by its approximated horizontal distance*Δx*and quantified with the help of coefficient *K,* representing the percentage of lapping relative to the sheet thickness considered (*Δx* = *K* x *t*) . Resultsin proximity to the limit found in the case of a sheet thickness *t* = 5 and *m* = 0.1 mm are also shown in Fig. 6 (ii), (iii) and (iv). It was selected case (iii) as the maximum clearance allowablewith a correspondent maximum*K* of 0.2.

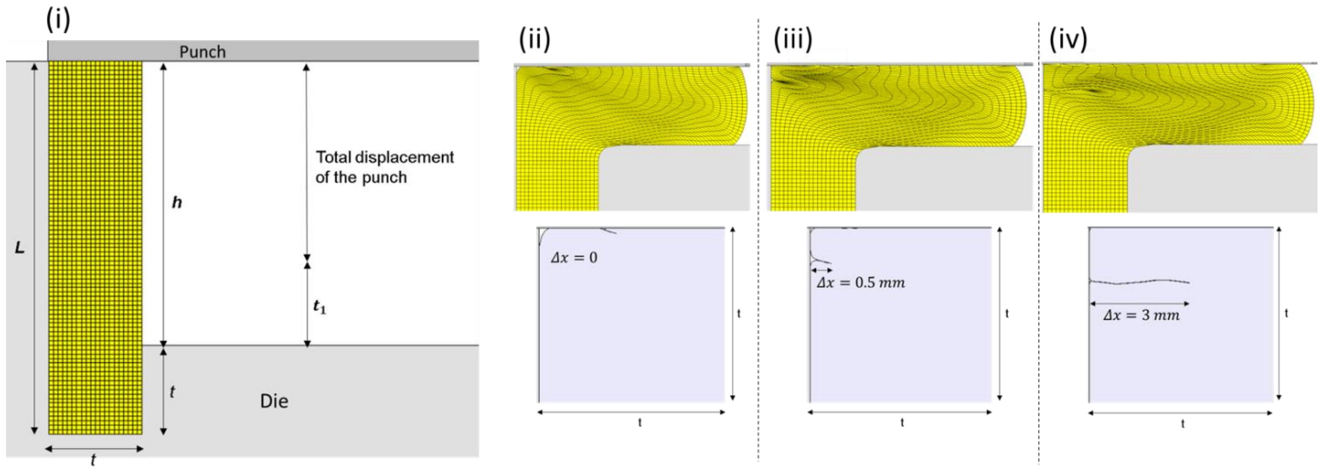


Fig.6– Numerical analysis executed in order to find the maximum value for *h* in which lapped material is acceptable: **(i)** Material mesh and die modelling in function of the geometrical parameters considered (initial step); **(ii)** Results for t = 5 mm, c = 9 mm – K = 0; **(iii)** Results for t = 5 mm, c = 10 mm – K = 0.1; (iv) Results for t = 5 mm, c = 11 mm – K = 0.6.

Results to all sheet thicknesses considered, assuming m = 0.1 and a maximum K = 0.2, are plotted in Fig. 7. In (i), all limits obtained for the configuration of joints considered are identified. As previously discussed, the limits identified for a certain thinnersheet, restrict the maximum clearance of the joint, independently of the thicker sheet thickness of the same joint. In (ii), a simplified representation of (i) is done to understand the dissimilar regions of workability presented. A total of 3 different regions is visable: region 1 represents the safe-work zone, region 3 represents the failure zone and region 2 intends to show an intermedium zone of applicability, where the process can be applicable but only regarding a special attention to its configuration.

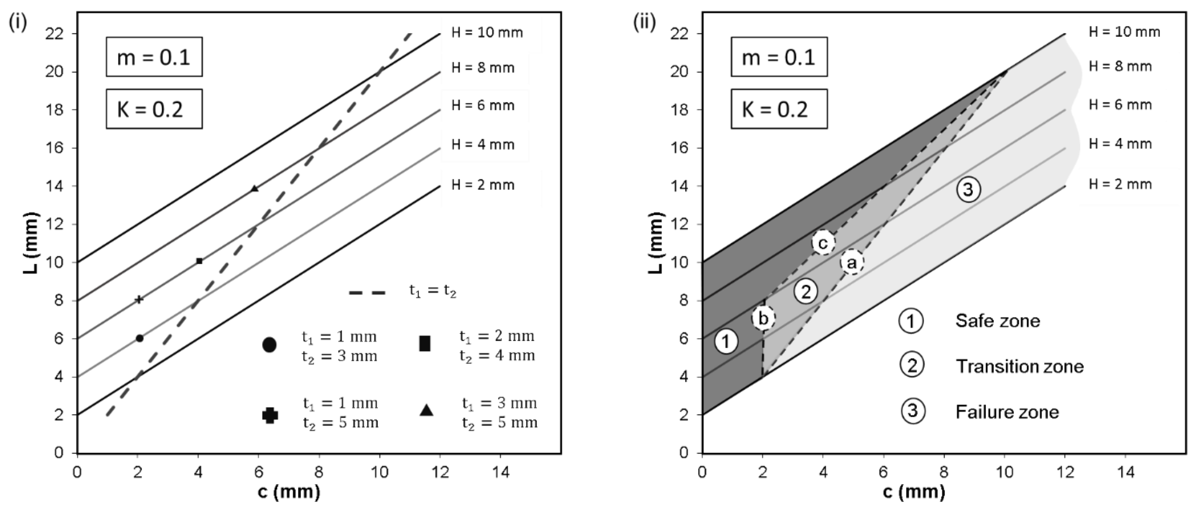


Fig.7– Final graphical representation of the process applicability for K = 0.2, m = 0.1: **(i)** Representation of the limits identified for the joint configurations considered; **(ii)** Subdivision of the final graph in different zones of applicability considered.

3.2. NumericalModelling

As referred earlier, the numerical development of the new joining process was supported by finite element analysis with the in-house computer program i-form. The computer program incorporates the irreducible finite element formulation with concepts from the Theory of Plasticity, accounting the contact with friction between rigid and deformable objects [8]. It allows the user to inspect the detailed material flows existent in processes based on plastic deformation, being able to predict and optimize it. The software is also very useful in order to extrapolate data comparable with the same one but extracted by experimental work. If satisfactory consistency of results is ensured by both approaches, the process can be validated with high assertiveness.

The numerical simulation of the forming operations performed on the tabs (bending and sheet-bulk compression) made use of two-dimensional plane strain deformation models. The cross-section of the sheets was discretized by means of quadrilateral elements and the tools were modelled as rigid objects with their geometries discretized by means of linear contact-friction elements. Fig. 8 shows the initial finite element meshes before the bending of tabs (i) and before the first sheet-bulk compression (ii), exemplified for only one of the modelled works. The computer is equipped with used the operating system Windows 10 with an i7-5700HQ (2.70GHz) processor.

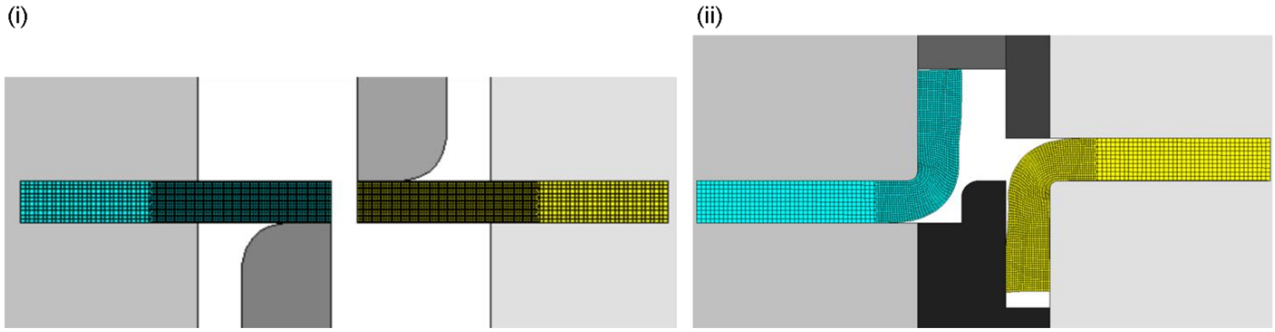


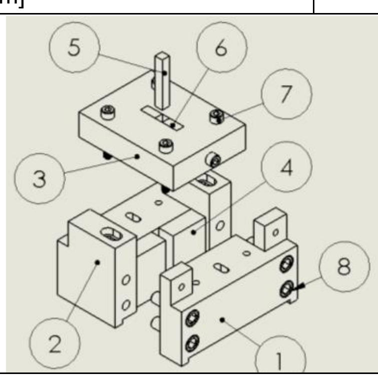
Fig.8– Finite element model of the process (initial steps): **(i)** bending phase; **(ii)** first sheet-bulk compression phase

4. Experimental development

The experimental procedure begins with the localized partial cutting in the sheets. This operation was made using electro discharge wire cutting, using a 0.3 mm diameter wire. However, some volume is lost when regarding the initial sheet volume, reducing the volume of the tab. These volume losses, although considered in the numerical procedure presented earlier, originate a gap in the direction of the width, compromising the plane strain assumption made in the theoretical modelling of the process. The existence of some volume loss does not compromise the process, but it may originate some divergencies when comparing experimental and numerical results and it is expected that the mechanical interlocking will not be totally filled. Hypothetically, the volume loss in this step of the process could be avoided when using a piercing operation known as lancing, since it could pierce the sheet partially and also bend the tabs in one single tool stroke. However, by lack of knowledge about the applicability of this process to a certain range of sheet thicknesses and material, as well as tool geometry, it was disregarded due to potential difficulties in its correct usage.

The experimental tests were performed for different sheet thicknesses, cutting lengths and clearances between the bent tabs. Table 2 provides geometric details about the obtained joints and shows a schematic representation of the laboratory tool that was utilized in the experiments. This representation only shows the components of the tool present in all operations, knowing that some of them vary with the corresponding operation. For example, when bending tabs, a wipping die tool must be used, while when compressing, a total parallelepipedal tool is used instead. The part used to constrain the material flow during the first sheet compression is also presented in Table 2 (last photography shown) and it is only used during this operation. From all the parts belonging to the tool displayed, only the acting punch, the guiding blocks (adjacent to the punch) and the part used to constrain the material flow in the first sheet compression are geometrically changeable based on the joint parameters (*L, c,* t_1 and t_2).

Table 1–Experimental work plan with auxiliary figures of the used tool.

Geometrical parameters	Work Case 1	Work Case 2	Work Case 3
t_1 x t_2 [mm]	5 x 5	2.5 x 2.5	5 x 2.5
c [mm]	5	2.5	2.5
L [mm]	15	7.5	10
			

As shown is Table 2, specifically in work cases 2 and 3, sheet thicknesses used to obtain the proposed joint were not previously considered in the applicability graphic plot exhibited in Fig. 7, t = 2.5 mm that originates H = 5 and 7.5 mm. By doing so, the limits identified may not be the same, since is it known that these are highly dependent on the sheet and joint thicknesses considered for its application. This will be discussed in the next section of the research work.

All the experiments were performed in aluminium EN AW 5754 H111 sheets with 5 mm thickness in the 'as-supplied' condition. The stress-strain curve of the material was determined by means of tensile tests regarding 0, 45, and 90 degrees with respect to the rolling direction and stack compression tests by pilling up three discs with 10 mm diameter that were also cut out from the supplied sheets [9]. The average stress-strain curve resulting from the entire set of tests was approximated by the following Ludwik–Hollomon's equation.

$$\sigma = 325\ \varepsilon^{0.18}(\text{MPa}) \tag{3}$$

After physically obtaining the joint, a set of destructive tests are realized. These consist in shear tests for determining the maximum load that the new proposed lap joints can withstand without detachment or failure, as well as understandingthe consequential failure mode by visual inspection to find out the critical section of the joint when subjected to shear loadings.

5. ResultsandDiscussion

Results from the experimental procedure regarding the proposed new process are shown in Fig. 9, where it can be seen three different obtainable joints (i), (ii) and (iii). It can be seen that protrusion was totally avoided, ensuring that all the deformed material flow could be compressed inside the existent clearance between sheets. However, as predicted, some material is missing in the localized joint, concluding that the low material loss existent after the electro discharge wire cutting is influent enough to be noticed visually. It can also be verified that, in both sheet bulk compression, the material flow went through the small gap originated by electro discharge wire cutting in the width direction (iv), therefore impugning the plane strain assumption.

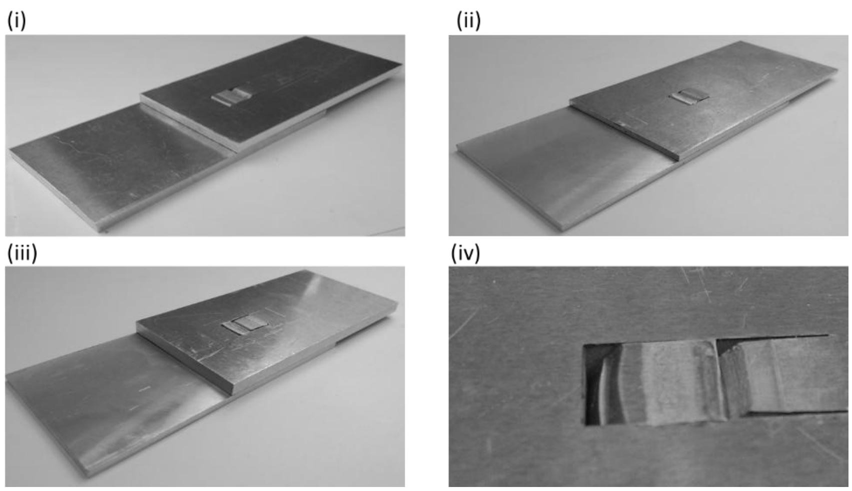


Fig. 9 – Results obtained by the proposed experimental procedure: **(i)** Work Case 1; **(ii)** Work Case 2; **(iii)** Work Case 3; **(iv)** Demonstration of the lack of complete filling in the interlock region (Work Case 1)

As discussed in the previous section, the graphic plot presented earlier to expose the applicability of the process could suffer some changes when introduced different sheet thicknesses than the ones considered in Section 3.In order to check if the limits considering the joints produced by experimental work, a numerical simulation identical to the one explained in Section 3 in order to find the geometrical limits in which lapped material is visualized when compressing the sheets. It was verified that, by considering two new plots where H = [5 ; 7.5] mm, same material, a friction coefficient m of 0.1 and a maximum K of 0.2 , the graphic plot does not suffer any change at all, concluding that these new limits are presented in the same way as the ones exposed in Section 3.

In order to discuss the different stages of the process, experimental and numerical results are exhibited by the corresponding chronological order. However, due to an increased similarity of graphic evolution in each operation for every work case, only one is exposed with a detailed description associated to points of interest visible in its graphic plots.In the bending operation, the obtained results are shown in Fig. 10. An almost perfect correlation between numerical and experimental work is watchable, only slightly diverging in the final steps of the operation. The graphic plot obtained was as predicted in most wipping die bending operations with a one-step acting punch, where the existing loading reaches a peak caused by the maximum area of contact between the sheet and the fillet of the punch. After it, the load decreases gradually to zero, finalizing the bending phase.

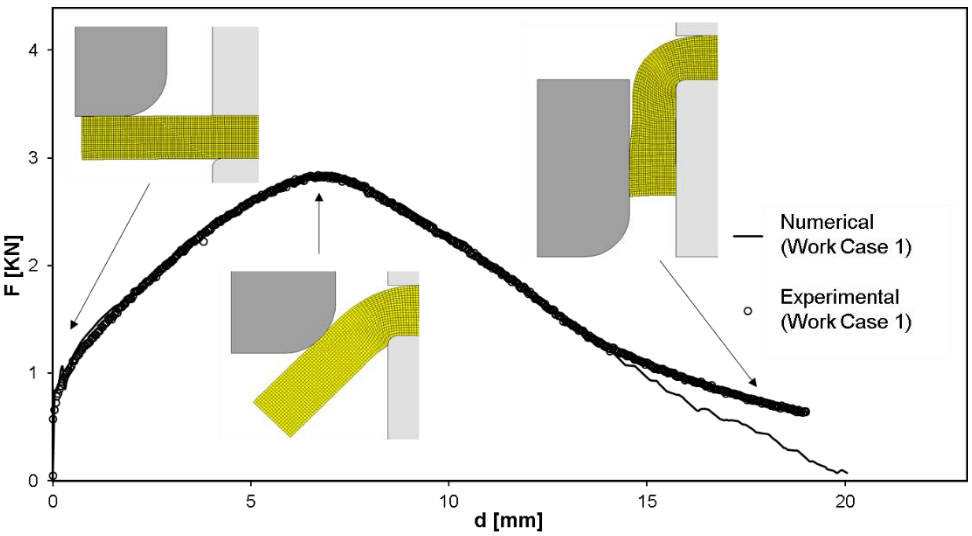


Fig. 10 -Experimental and finite element predicted evolution of the force with displacement in the bending phase (Work Case 1)

For the first sheet-bulk compression, the corresponding results are exposed in Fig. 11. Comparing to the one shown earlier, this graphic plot appears to be more complex in terms of changes in the evolution of the loads with the displacement of the acting punch. Still, both approaches appear to be really similar to each other. To understand all the sudden changes observed, a description of the graphic plot by three different phases is proposed. **PhaseI** represents the beginning of the compression stage. However, with the existence of a small horizontal clearance between the to be deformed sheet and the inferior die, the material presents a tendency to slide through the punch, maintaining a relatively constant load since almost no material compression is yet happening. **Phase II** begins exactly when the deformed material touches the inferior die. A small rise in the existent load is noticed. However, the deformed material continues to slide through the contact surface of the punch, resulting again in an almost constant load.**Phase III** begins when the deformed material can no longer slide through the punch, which is when it touches the superior-right die. After this contact, the material is being totally compressed, resulting in a large increase of the applied load since the contact area between the material and the punch is also increasing.

The major divergency observed in numerical and experimental plots is visible in the ending of the operation. This tends to happen since the numerical solution is obtained by assuming plane strain conditions, so that, in the late stages of this operation, the difficultness of the material flow to enter certain unfilled regions grows exponentially, requiring large loadings with the objective to oblige it to fill the clearance section. In the experimental cases, the material flow can simply enter the small gaps existent in the direction of the width without increasing the corresponding loads as much as in the numerical case.

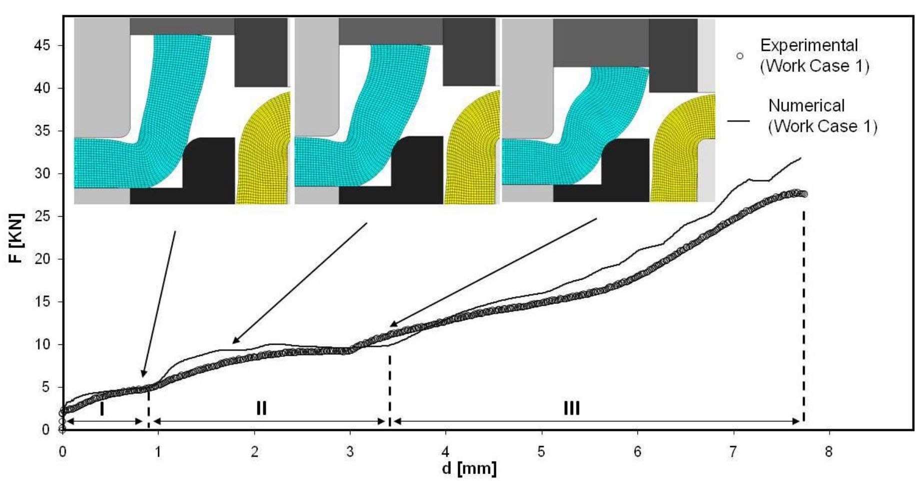


Fig.11 - Experimental and finite element predicted evolution of the force with displacement in the first sheet-bulk compression phase (Work Case 1)

The results obtained for the second sheet-bulk compression are exhibited in Fig 12. It can be seen a graphic plot almost identical to the one presented in Fig. 11 for the first sheet-bulk compression. This evidence shows that the usage of the deformed material in the first sheet-bulk compression as a die for the final sheet-bulk compression of the other sheet acts exactly in the same way as the inferior die used in the first compression. The characterization done for the previous operation is also applicable to this final operation of the process proposed, with some small differences again in the ending of the operation, where the difficultness of the material flow to enter certain unfilled regions is even harder than in the previous operation, resulting in even bigger loads.

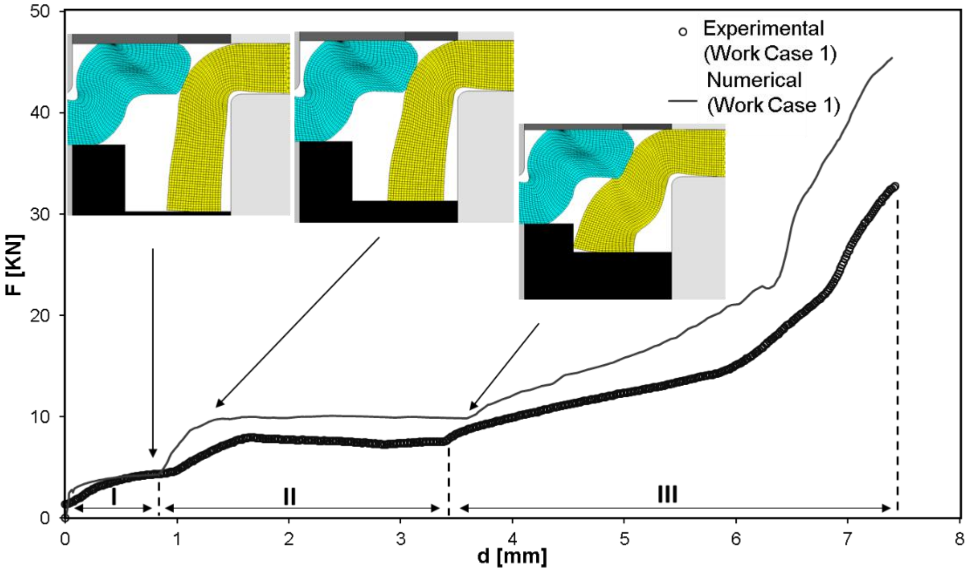


Fig. 12 -Experimental and finite element predicted evolution of the force with displacement in the second sheet-bulk compression phase (Work Case 1)

With the objective of visualizing the inside of the mechanical joint obtained, a cross-section cut was performed, as well as a numerical simulation without volume losses, Fig. 13. As predicted, results show a high similarity between experimental (i) and numerical (ii) results concerning the respective volume losses. A totally filled section (iii) would be the desirable case, but it cannot be accomplished while using a cutting method in the first stage of the process. However, the corresponding forging loads in such case could be even bigger, due to the equally bigger difficultness of the deformed material to fill all the mechanical interlocking region.

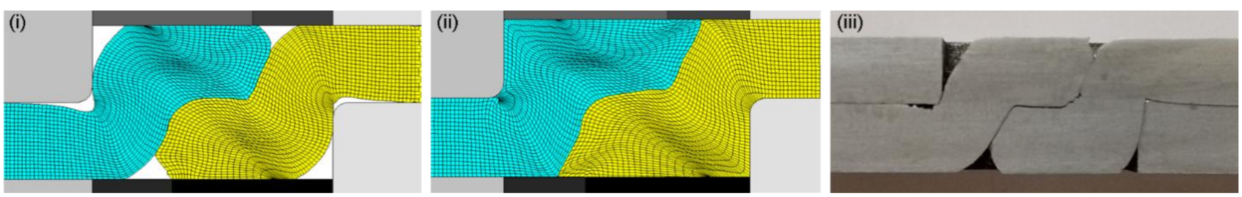


Fig. 13–Different cross section views of the mechanical interlocking obtained for Work Case 1: **(i)** Experimental result obtained; **(ii)** Numerical result with volume loss; **(iii).** Numerical result without any volume loss.

The results obtained in the destructive shear test performed on the joint are shown in Fig 14. By analysing its representative graphical plot (i), a maximum load of 10.7 KN can be seen, showing some promising results regarding the mechanical resistance of the joint. The separation of the two sheets happened by total fracture in one of the deformed sheets in the bent region.

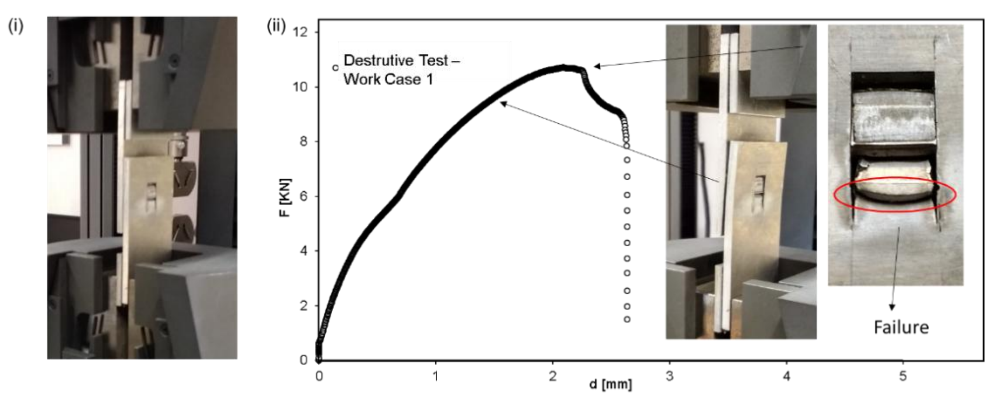


Fig. 14 –Destructive shear test results for one of the obtainable joints (Work case 1): **(i)** Setup of the destructive test;**(ii)** Experimental evolution of the force with displacement during the test.

6. Conclusions

The new joining by forming process proposed obtained by SBMF is proved to work and it can be considered as an alternative to other sheet joining processes due to its simplicity and resultant joint strength. From an applicability point of view, bending defects were avoided and the occurrence of lapped material in sheet-bulk compression could be predicted. The destructive test experimented on the joint presented satisfactory results, although evidencing the dependency of a correctly executed bending phase, since the failure in the joint is noticeable in one of the bent regions of the sheets. The workability of the new proposed process in non-metallic materials could be investigated, as well as the correct joining with dissimilar materials. A detailed experimental study similar to the numerical work described in Section 3 regarding the geometrical joint limits for which lapped material occurs when compressing the sheets is also desirable in order to fully understand the total workability of the proposed process. A detailed study of the piercing operation known as lancing could also be considered as an alternative to both partial cutting and bending phases, since the correct use of this operation foresights a considerable evolution in the productivity of the proposed process.

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