

Article

An Experimental Study on Micro Clinching of Metal Foils with Cutting by Laser Shock Forming

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Abstract: This paper describes a novel technique for joining similar and dissimilar metal foils, namely micro clinching with cutting by laser shock forming. A series of experiments were conducted to study the deformation behavior of single layer material, during which many important process parameters were determined. The process window of the 1060 pure aluminum foils and annealed copper foils produced by micro clinching with cutting was analyzed. Moreover, similar material combination (annealed copper foils) and dissimilar material combination (1060 pure aluminum foils and 304 stainless steel foils) were successfully achieved. The effect of laser energy on the interlock and minimum thickness of upper foils was investigated. In addition, the mechanical strength of different material combinations joined by micro clinching with cutting was measured in single lap shearing tests. According to the achieved results, this novel technique is more suitable for material combinations where the upper foil is thicker than lower foil. With the increase of laser energy, the interlock increased while the minimum thickness of upper foil decreased gradually. The shear strength of 1060 pure aluminum foils and 304 stainless steel foils combination was three times as large as that of 1060 pure aluminum foils and annealed copper foils combination.

Keywords: micro joining; clinching with cutting; metal foils; laser shock forming; process parameters

1. Introduction

With the rapid development of the automobile industry, the lightweight design of the automobile has been a wide concern. In order to reduce the weight of the automobile body, lightweight materials such as aluminum alloy has been widely used, which has set a higher standard for the joining technology of similar and dissimilar metal plates [1]. In most cases, fusion welding, adhesive bonding and mechanical fastening are used to join metal sheets. Although fusion welding is widely used, the high temperatures required may reduce the quality, accuracy, and reliability of joined parts [2]. Moreover, it is difficult to weld dissimilar metal sheets, because the melting points of dissimilar materials are very different [3]. Adhesive bonding and mechanical fastening are available for joining dissimilar metal sheets [4]. However, adhesive bonding is time-consuming due to the curing process. In addition, adhesive bonding requires the cleaning and roughening of the surfaces to be bonded. The mechanical fastening technology needs pre-drilled holes on the surface of the metal plates, which may destroy the air tightness and water tightness of the joints [5]. To solve these problems, mechanical clinching (with or without cutting) and self-pierce riveting have been developed [6]. In mechanical clinching, metal sheets are joined by local cold forming between a punch and a die without the use of additional elements [7]. In self-pierce riveting, metal sheets are joined by forcing a rivet directly between two sheets without the use of a pre-drilled hole, thus saving much running time (which is

almost one second) [8]. The metal sheets are joined by plastic deformation in these two processes, during which the coating layer will not be destroyed and the heat affected zone will not be produced [9]. Furthermore, plastic joining processes without melting are attractive for joining dissimilar metal sheets [10]. Compared with the conventional joining technology, mechanical clinching and self-pierce riveting have additional advantages, such as process cleanliness, absence of surface pre-treatments and post-treatments, low cost per joint, ease, and robustness of the processes [11]. Besides, Varis [12] compared the joining costs of mechanical clinching and self-pierce riveting. The results showed that mechanical clinching without any additional joining elements has lower running costs than self-pierce riveting. An exhaustive literature research has been produced on mechanical clinching of metal sheets driven by the increasing interest from automotive industries. Lambiase and Di Ilio [13] proposed a numerical model which can accurately predict the fracture paths produced during the clinch joining of thin aluminum AA6086-T6 sheets. Jiang et al. [14] investigated the effect of pre-straining on the mechanical behavior and joint strength of the clinched aluminum-to-steel joint. Because of the advantages mentioned above, the employment of mechanical clinching has been extended to a wide range of materials. Lambiase and Di Ilio [15] verified the suitability of mechanical clinching for the production of hybrid metal-polymer joints and evaluated the influence of main process parameters (pre-heating conditions, forming pressure, and die geometry) on the joinability and mechanical behaviors of clinched connections. Lee et al. [16] developed a new mechanical clinching process, namely hole-clinching, which can join aluminum alloys to high-strength/low ductility materials including carbon fiber reinforced plastics. Lambiase [17] investigated the mechanical behavior of polymer-metal hybrid connections produced by clinching process using different types of tool.

However, there are two main problems while joining similar and dissimilar materials by mechanical clinching process. Firstly, the poor formability of materials limits the application scope of mechanical clinching. To this end, two possible solutions are available: increasing the material formability by pre-heating and improving the material flow by optimizing the geometry of the clinching tools [13]. Based on these two solutions, low-ductility materials can be joined by mechanical clinching. Lambiase [18] investigated mechanical clinching of heat-treatable aluminum alloy sheets (AA6082-T6) with low ductility and analyzed how to control the material flow during the clinching process by the employment of tool variation and different pre-heating schemes. Abe et al. [19] studied the suitability of mechanical clinching for joining ultra-high strength steel sheets with a low ductility and modified the diameter and depth of the die to control the metal flow. Secondly, the joint strength of clinched connections produced by mechanical clinching is lower than those obtained by the other joining methods. Mori et al. [20] reported that the static strength for the mechanical clinching was about half for the resistance spot welding. The joint strength is determined by the undercut and neck thickness, therefore the strength of mechanically clinched joints can be improved by maximizing the undercut and reducing the neck thinning. Lee et al. [1] proposed a design method of clinching tools with analytical models which can inversely calculate the required undercut and neck-thickness based on the desired joint strength.

The miniaturization of products is an important growing trend in precision mechanics and the electronic industry, which brings increased demands on joining processes in micro scale [21]. Nevertheless, the mature processing theory and technology for joining of macro scale metal plates cannot be directly transplanted into the field of micro scale joining owing to the size effects [22]. There are some limitations when mechanical clinching and self-pierce riveting are used in micro scale joining (where the thickness of metal foils is less than 100 microns). First of all, the fabrication of micro punch and micro rivet is very difficult and expensive. What is more, the extremely small clearance between micro punch and micro mold makes it difficult to control the alignment accuracy, which will reduce the service life of the tools and affect the quality of joints. Therefore, non-contact processes are very suitable for joining metal foils in micro scale. Daehn and Lippold [23] found that laser impact spot welding can be used to weld similar and dissimilar metal foils in the micro/nano scale. A further approach for joining metal foils is given by laser shock forming. With this non-contact process, undercuts of

micrometer-foils can be produced [2,24]. Afterwards, Veenas et al. [21,25] improved this technology and verified the feasibility of using a TEA-CO₂ laser to join aluminum foil (50 μm) and stainless steel (100 μm) which was pre-drilled with a hole having a diameter of 4 mm. They measured the pressure distribution in open and closed environments and analyzed the forming behavior during the joining process by laser induced shock waves to gain a better understanding of this process [26]. This is considered as a potential, but still immature, technology to join metal foils, however, the process is very complicated and influenced by many experimental variables. Since the use of different metal foils with different thicknesses would lead to differences in the performances of joining, a lot of further research is required.

The purpose of the current study was to experimentally verify the feasibility of a novel micro clinching with cutting process for joining similar and dissimilar metal foils. Many important process parameters were determined by studying the deformation behavior of single layer metal foil in the mold. The process window of the 1060 pure aluminum foils and annealed copper foils (Al/Cu) was given through a series of experiments. The effect of laser energy on the interlock and the minimum thickness of upper foils were studied. Moreover, the connection strength of different joints was measured by the single lap shearing tests.

2. Mechanism of Micro Clinching with Cutting by Laser Shock Forming

The basic schematic diagram of micro clinching with cutting by laser shock forming is shown in Figure 1. Metal foils can be joined using this specific joining device, which includes blank holder, confinement layer, ablative layer, soft punch, metal foils, mold sliders, spacer, mold substrate, and die anvil. When a high energy laser beam is focused onto the ablative layer through the transparent confinement layer, one part of the ablative layer is vaporized instantaneously into a high-temperature and high-pressure plasma after absorbing a large amount of laser energy. The plasma continues to absorb the laser energy, and the rapid deposition of laser energy ignites the plasma and changes into a laser supported detonation wave (LSD). Under the constraints of the confinement layer and blank holder, the induced shock wave can only propagate downwards and generate tremendous impact on the soft punch. As the soft punch is incompressible and hyper-elastic, the shock wave will load on the metal foils after propagating in the soft punch. Under the combined action of the impact load and the micro mold, the metal foils are subjected to a large shear stress at the fillet of the mold and a series of physical processes—such as elastic deformation, plastic deformation, and fracture—are completed. Subsequently, the lower foil is cut off and the material of the upper foil flows into the mold. A certain interlock is generated by the material flow, which can hook the upper and lower metal foils together [10]. Eventually, the metal foils under micro scale are clinched with cutting by laser shock forming.

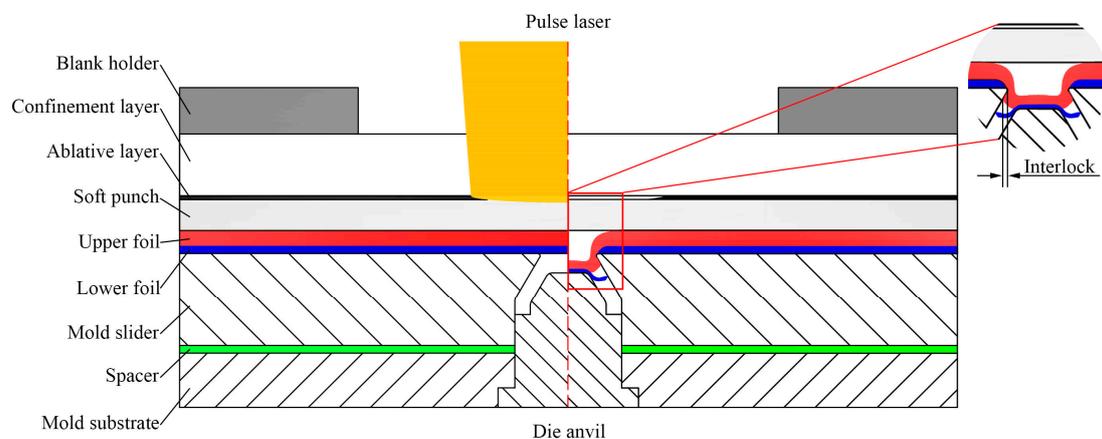


Figure 1. Schematic diagram of micro clinching with cutting by laser shock forming.

The necessary condition for the process of micro clinching with cutting by laser shock forming is the generation of interlock without fracture of upper foils [19]. The interlock between metal foils ensures the appropriate joining strength. However, the fracture of upper foils destroys the air tightness and water tightness of the joints and accelerates the corrosion of the joints.

3. Experimental Preparation

In this research, a Spitlight 2000 Nd-YAG laser (By InnoLas Corporation in München, Germany) with Gaussian distribution beam was employed, and its main parameters are listed in Table 1. A blank holder must be used to prevent the leakage of plasma, and the blank holder force used in the experiment was 12 N. Due to its high transmittance and mechanical strength, polymethyl methacrylate (PMMA) was used as the confinement layer, the thickness of which was 3 mm. The silica gel with the thickness of 100 μm was employed as soft punch, which ensured good surface quality of metal foils. A thin layer of black paint was used as the ablative layer, which was sprayed onto the surface of the silica gel.

Table 1. Main parameters of INNOLAS Spitlight 2000 Nd-YAG laser.

Pulse Energy	Energy Stability	Wave Length	Pulse Width	Spot Diameter
80~1800 mJ	< \pm 1%	1064 nm	8 ns	3 mm

The combined mold used in the experiments was made of SKH-51 high speed steel. This kind of high speed steel is suitable for processing the mold with high hardness, high stiffness, and good impact resistance. As shown in Figure 1, the combined mold consisted of two mold sliders, one spacer, one mold substrate, and one die anvil. In addition, two mold sliders can be disassembled to remove the connected metal foils from the mold completely. Each slider was positioned and fixed on the mold substrate with two dowels. The combined mold fabricated by the wire-cut electrical discharge machining (WEDM) is shown in Figure 2. The micrographs of the combined mold and metal foils in this paper were obtained by the KEYENCEVHX-1000C digital microscope (KEYENCE Corporation in Osaka, Japan). This digital microscope can also be used to measure the size of the interlock between the upper and lower metal foils from the cross sections of clinched joints. The die cavity of the mold was processed into a conical surface, the cone angle of which was 60°. In order to form a parallel chute, the top of the die anvil was also processed into a corresponding conical surface with a cone angle of 120°. The parallel chute can not only promote the flow of metal foils, but also eliminate the effect of air below materials, which is detrimental to the joining of metal foils. Furthermore, the depth of the mold (h) can be adjusted by changing the thickness of the spacer. As the depth of the mold (h) gradually increases, the width of the chute (w) on both sides of the mold also increases. Table 2 shows the main dimensions of the combined mold.

There were three kinds of metal foils used in the experiments: 1060 pure aluminum foils, pure copper foils annealed at 450 °C, and 304 stainless steel foils. Different kinds of metal foils with different thicknesses were combined together to verify the feasibility of joining similar and dissimilar materials by the micro clinching with cutting process. The upper foils were cut into square pieces of 10 \times 10 mm² and the lower foils are cut into square pieces of 15 \times 15 mm². The upper and lower foils were stacked on the combined mold. The combined mold was fixed on a three-dimensional mobile platform. By adjusting the distance between the metal foils and the focusing lens, the spot diameter was controlled so that it was larger than the mold diameter. In this experiment, a spot diameter of 3 mm was used. The detailed experimental parameters are listed as follows in Table 3, where “Ss” is the 304 stainless steel foils. For the combination of different materials, the “Al/Cu” indicates that the upper and lower foils are 1060 pure aluminum foils and annealed copper foils, respectively.

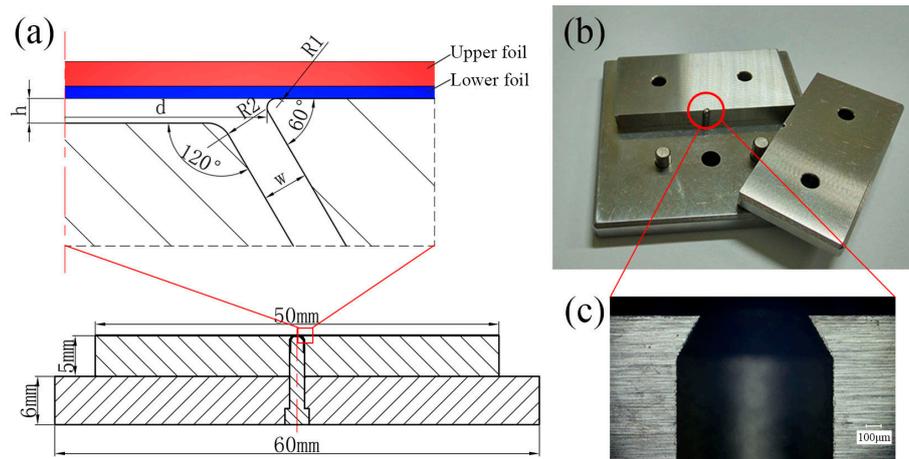


Figure 2. The combined mold: (a) the main dimensions (h -the depth of the mold, d -mold diameter, w -the width of the chute); (b) real product photo; (c) local magnification of the mold slider.

Table 2. Main dimensions of the combined mold.

Parameters	Value
Diameter (mm)	1.3
Depth (μm)	40, 50, 60, 70, 80, 90, 100
Corresponding width (μm)	128, 133, 138, 143, 148, 153, 158
Fillet radius (μm)	$R1 = 30/R2 = 80$
Chute angle	60°

Table 3. The detailed experimental parameters.

Parameters	Value
Blank holder force (N)	12
Confinement layer thickness (mm)	3
Ablative layer thickness (μm)	10
Soft punch thickness (μm)	100
The number of laser pulses	1, 2, 3, 4, 5
1060 pure aluminum foils thickness (μm)	20, 30, 40, 50, 60, 80, 100
Annealed copper foils thickness (μm)	20, 30, 40, 50, 60, 80, 100
304 stainless steel foils thickness (μm)	10, 20, 30
Material combinations (upper foils/lower foils)	Cu/Cu; Cu/Ss; Al/Cu; Al/Ss

In this experiment, single lap shearing tests were carried out to measure the mechanical strength of the clinched joints under different material combinations. For each processing condition, three samples were tested. Figure 3 shows the dimensions of the test sample used in the single lap shearing tests. The tests were conducted at room temperature by using a controlled electronic universal testing machine (Instron Type UTM 4104 made in Shenzhen, China) at a constant speed of 2 mm/min until the complete separation of the metal foils. The load force and displacement were recorded during lap shearing tests.

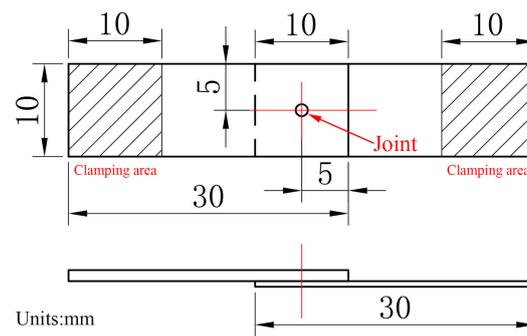


Figure 3. Schematic of single lap shearing test sample.

4. Results and Discussion

Micro clinching with cutting by laser shock forming is a very complicated process which involves many process parameters such as the number of laser pulses, the depth of the combined mold, laser energy, and the combination of different materials with different thicknesses. In order to study the influence of various process parameters on different material combinations, the deformation behavior of single layer metal foil under different experimental conditions was studied first. During this study, some important process parameters were determined. Subsequently, the experiments of different material combinations were carried out according to the laws derived from the study of single layer metal foil.

4.1. Determination of Process Parameters Based on the Study of Single Layer Material Deformation

4.1.1. Determination of the Number of Laser Pulses

The study of the deformation behavior of single layer metal foil under different laser energy and the different number of laser pulses is essential for better understanding the micro clinching with cutting process. The deformation behavior of single layer 1060 pure aluminum foil with the thickness of 100 μm produced under different laser energy is shown in Figure 4, where the depth of the mold is 70 μm and the number of laser pulse is one pulse. It can be seen that with the gradual increase of laser energy, more and more materials flowed into the die cavity and the thinning phenomenon of the 1060 pure aluminum foil became more obvious because it was subjected to larger shear stress at the two corners of the mold. As shown in Figure 4c, when the laser energy is increased to 1690 mJ, a part of 1060 pure aluminum foil began to flow into the chute. However, due to the short action time of single laser pulse, the material flow was insufficient. Only a small interlock was formed between the material and the combined mold, which was not enough to join similar and dissimilar materials together. Meanwhile, a section of straight wall was produced above the small interlock after intense shearing, which is disadvantageous to the joining of similar and dissimilar materials. In short, under the single laser pulse, the large interlock cannot simply be formed by an increase of laser energy.

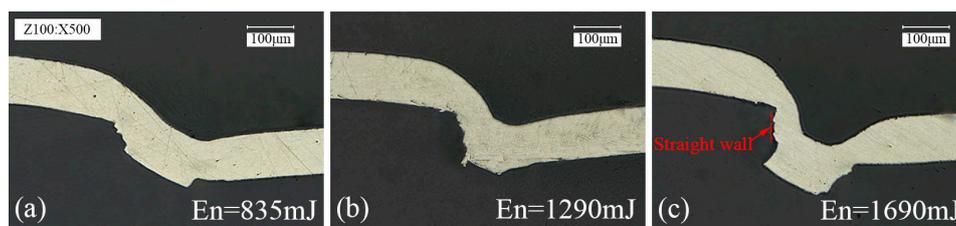


Figure 4. Cross sections of single layer 1060 pure aluminum foil (100 μm in thickness) produced under different laser energy E_n ($h = 70 \mu\text{m}$, 1 pulse): (a) $E_n = 835 \text{ mJ}$; (b) $E_n = 1290 \text{ mJ}$; (c) $E_n = 1690 \text{ mJ}$.

Veenaas et al. [26] produced a large interlock between the aluminum foil (50 μm) and stainless steel (100 μm) by using 200 laser pulses. Therefore, the use of moderate energy and multiple laser pulses may be able to solve the problems above. The use of moderate energy can ensure that the material is subjected to an appropriate shear stress, which can avoid the generation of straight wall. The employment of multiple laser pulses is equivalent to increasing the action time of the single laser pulse, which can increase the material flow to form a large interlock. The deformation behavior of single layer 1060 pure aluminum foil with the thickness of 100 μm produced under different numbers of laser pulses is shown in Figure 5, where the depth of the mold is 70 μm and the laser energy is 1290 mJ. Compared with the deformation of 1060 pure aluminum foil in Figure 4, with the increase of the number of laser pulses, the increase of material flow is more significant. After being impacted by three laser pulses (see Figure 5c) a large interlock was produced between the material and the mold without the formation of straight wall. According to the analysis above, the applicability of moderate laser energy and multiple laser pulses to the joining of materials was fully illustrated. Nonetheless, the employment of multiple laser pulses is not unlimited. First of all, the production efficiency of the micro clinching with cutting process will be greatly reduced by the overuse of laser pulses. Besides, after impacted by four or five laser pulses, PMMA will break and the ablative layer near the focus will be completely vaporized, as shown in Figure 6. In this case, the surface quality of the metal foils cannot be guaranteed. Therefore, the number of laser pulses was determined to be three pulses, which was used in subsequent experiments.

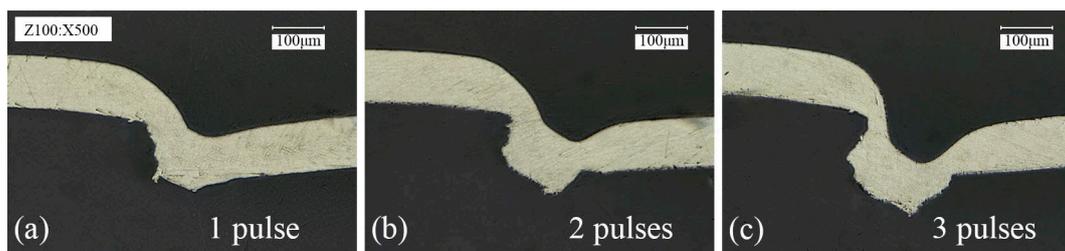


Figure 5. Cross sections of single layer 1060 pure aluminum foil (100 μm in thickness) produced under different number of laser pulses ($h = 70 \mu\text{m}$, $En = 1290 \text{ mJ}$): (a) 1 pulse; (b) 2 pulses; (c) 3 pulses.

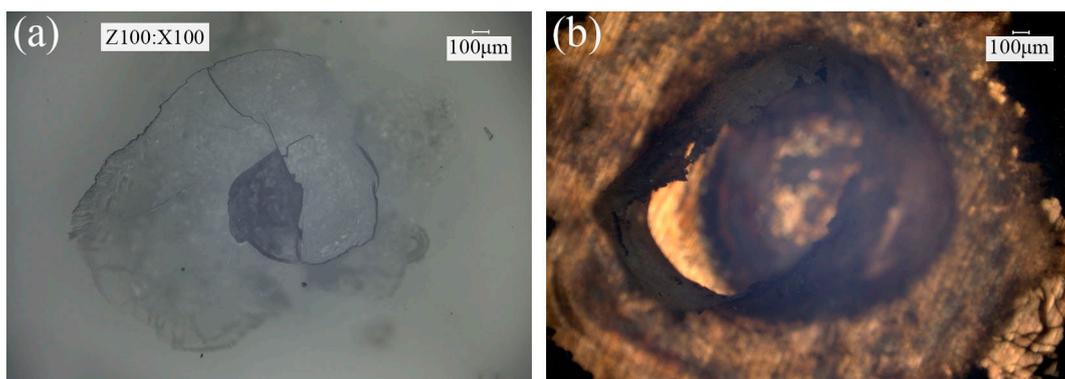


Figure 6. Surface morphology of polymethyl methacrylate (PMMA) and soft punch after impacted by 4 laser pulses, $En = 1550 \text{ mJ}$: (a) cracks appear on the surface of PMMA; (b) ablative layer is completely vaporized and the soft punch is ablated.

4.1.2. The Matching Relationship between the Total Thickness of Materials and Die Depth

The total thickness of materials and the die depth are two important parameters in the process of micro clinching with cutting. It was important for this experimental research to study the matching relationship between the two process parameters. Firstly, the matching relationship between the

thickness of single layer 1060 pure aluminum foil and the die depth was investigated. The deformation behaviors of single layer 1060 pure aluminum foil differ when produced under differing mold depths, as can be observed in Figure 7, where the foil thickness is 100 μm , laser energy is 1290 mJ, and the number of laser pulses is 3 pulses. As shown in Figure 7b, a large interlock between 1060 pure aluminum foil and the mold was formed, which is the prerequisite for joining similar and dissimilar materials. In the small die depth, the material flow was limited and the interlock could not be formed as shown in Figure 7a. When clinching dies with shallow die depth were used, the die cavity volume was relatively small and high hydrostatic stress developed [27]. Such a stress condition is beneficial to the improvement of the material formability; however, the material flow was highly restricted in radial direction [8,18]. In the large die depth, a bowl-shape deformation of the 1060 pure aluminum foil was formed due to a larger die cavity as shown in Figure 7c. If the other parameters remained unchanged and the laser energy continued to increase, the fracture was observed on the 1060 pure aluminum foil because of the excessive shearing. Therefore, the large interlock cannot be formed in a large die depth either.

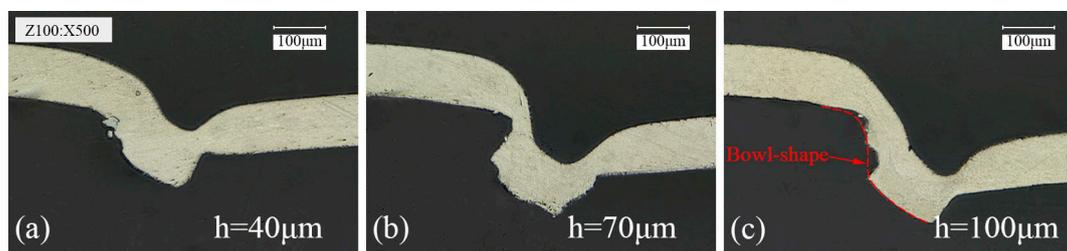


Figure 7. Cross sections of single layer 1060 pure aluminum foil (100 μm in thickness) produced under different die depth h ($E_n = 1290$ mJ, 3 pulses): (a) $h = 40$ μm ; (b) $h = 70$ μm ; (c) $h = 100$ μm .

On the basis of the above research, the matching relationship between the total thickness of two layers of metal foils and die depth was identified. After additional experiments, the matching relationship between the total thickness of the materials and die depth was determined and is illustrated in Figure 8. It can be seen that with the increase of the total thickness of materials, the corresponding die depth which could form a large interlock increased. In addition, the change of the die depth had less influence on the joining of thicker materials. As can be inferred from Figure 8, when the total thickness of the material was in the range of 60–100 μm , the optimum die depth was about two-thirds of the total thickness. Subsequent experiments followed this matching relationship.

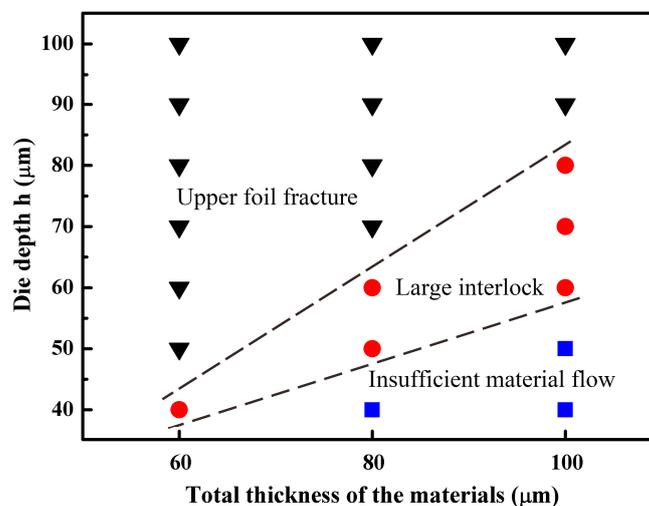


Figure 8. Matching relationship between the total thickness of materials and die depth.

4.2. Feasibility of Micro Clinching with Cutting Process for Joining Similar and Dissimilar Materials

4.2.1. Defects in Micro Clinching with Cutting

In the conventional mechanical clinching, the main failure modes of clinched joints are button separation, neck fracture, or a combination of both mechanisms [1]. The separation of the upper sheet and the lower sheet results from the small interlock between the two sheets. Additionally, the neck fracture is caused by the excessive neck thinning [28]. According to Lambiase [18], the punch-side sheet undergoes severe thinning (even to fracture) during the offsetting phase because of highly localized strain produced around the punch corner. Therefore, if the mechanical clinching tools are not designed properly, a crack may develop at the upper sheet.

In contrast, the main failure modes of micro clinching with cutting by laser shock forming differ from the conventional mechanical clinching. To obtain optimum joining conditions of the metal foils, a series of experiments were conducted. As shown in Figure 9, the defects for the process of micro clinching with cutting have been categorized as follows: (1) no interlock between the upper foil and the lower foil; (2) neck fracture; and (3) bottom fracture of the upper foils. The corresponding experimental conditions are listed on the right side of the cross-sectional shapes. For the combination of the annealed copper foils and the 304 stainless steel foils (Cu/Ss), the 'Thickness (μm): 60/30' indicates that the thickness of annealed copper foils was 60 μm and the thickness of 304 stainless steel foils was 30 μm . In the 'no interlock between the upper foils and the lower foil' case, the laser energy was too small to join the metal foils, and the joined foils were easily separated. When the upper foil thickness was less than two-thirds of the total thickness and the laser energy was extremely large, the upper foil and lower foil suffered an excessive neck thinning during the offsetting phase. Cracks appeared and developed at the upper foil because the neck thickness was relatively small. Under the continuous effect of the shear stress, the neck fracture finally occurred at the upper foil. The bottom fracture could be attributed to the large proportion of the upper foil thickness in the total thickness and the large laser energy. Since the upper foil was relatively thick, cracks did not appear at the upper foil throughout the offsetting phase. During the upsetting phase, the shear stress around the fillet of the die anvil was larger than that around the fillet of the mold slider. Therefore, the bottom thickness (the thickness of upper foil around the fillet of die anvil) became thinner than the neck thickness. The interlock between the upper foil and the lower foil was developed during the flow pressing phase. With the formation of the interlock, the lower foil was cut off and the material of the upper foil flowed into the chute. Cracks appeared and developed at the upper foil around the fillet of the die anvil, while the bottom thickness suffered a further thinning effect. Finally, the bottom fracture occurred at the upper foil.

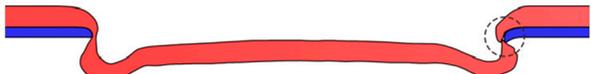
Defects	Cross-Sectional Shapes of the Metal Foils	Experimental Conditions
No interlock		Materials: Cu/Ss Thickness (μm): 60/30 $E_n = 1800 \text{ mJ}$; $h = 70 \mu\text{m}$; Laser pulses: 3 pulses
Neck Fracture		Materials: Al/Ss Thickness (μm): 60/30 $E_n = 1290 \text{ mJ}$; $h = 70 \mu\text{m}$; Laser pulses: 3 pulses
Bottom fracture		Materials: Al/Cu Thickness (μm): 80/20 $E_n = 1550 \text{ mJ}$; $h = 70 \mu\text{m}$; Laser pulses: 3 pulses

Figure 9. Defects in micro clinching with cutting.

4.2.2. Process Window of 1060 Pure Aluminum Foils and Annealed Copper Foils

The joinability for the 1060 pure aluminum foils and annealed copper foils combination of different thickness by micro clinching with cutting process is shown in Figure 10. As the total thickness of different combinations changed, the die depth and the laser energy was adjusted correspondingly. The matching relationship between the total thickness and the die depth must abide by the above research. Three laser pulses were used in this experiment, which remained unchanged throughout the study. Seen from the process window of 1060 pure aluminum foils and annealed copper foils, the upper foil was at least 30 μm thicker than the lower foil in the no defect area. Therefore, it can be inferred that the micro clinching with cutting process is more suitable for the material combinations where the upper foil is thicker than the lower foil. In the no interlock and the upper foil fracture region, when the proportion of upper foil thickness in the total thickness was less than two-thirds, no interlock could be formed, regardless of the laser energy. What is more, when the total thickness of metal foils was more than 140 μm , the maximum laser energy was not enough to form the interlock. The upper foil fracture was probably caused by the small proportion of upper foil thickness relative to the total thickness, and the small total thickness.

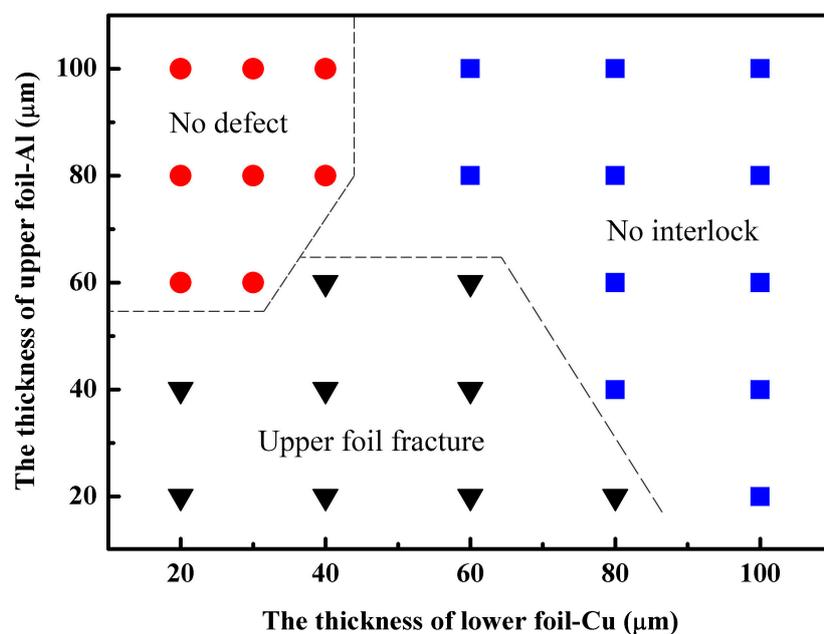


Figure 10. Process window of 1060 pure aluminum foils and annealed copper foils (Al/Cu).

4.2.3. Joining of Similar and Dissimilar Metal Foils

The cross sections of the clinched joints with different material combinations are shown in Figure 11, where all the thickness of upper and lower foils is 80 μm and 20 μm , respectively. According to the above research, three laser pulses and 70 μm in die depth were employed in this section. As can be seen, in different material combinations, the deformation behavior of metal foils and the optimal laser energy were different. The interlock formed in the combination of Al/Cu and Al/Ss was larger than that in the combination of Cu/Cu. As shown in Figure 11a,b, the lower foils were not completely cut because of the good plasticity of annealed copper foils. However, the 304 stainless steel foil was completely cut due to its relatively poor plasticity as shown in Figure 11c. The surface morphology of clinched joint is shown in Figure 12.

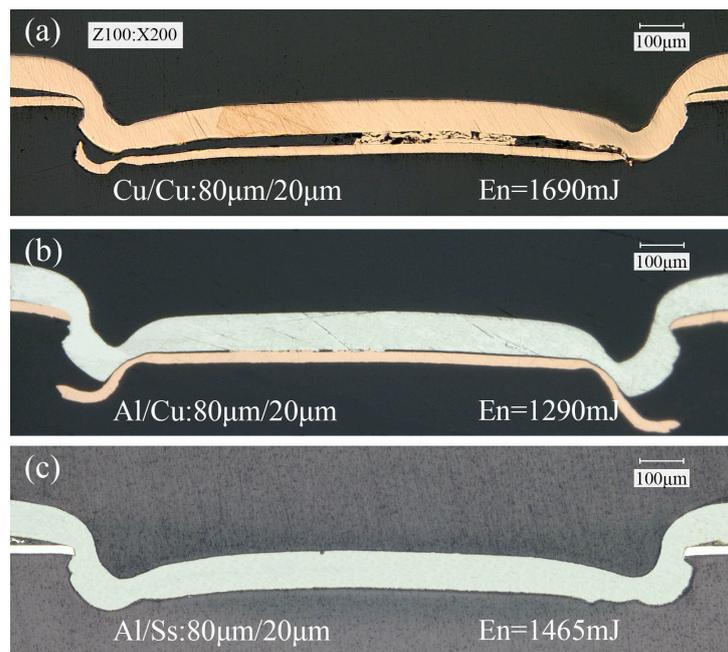


Figure 11. Cross sections of clinched joints with different material combinations. (a) Cu/Cu; (b) Al/Cu; and (c) Al/Ss.

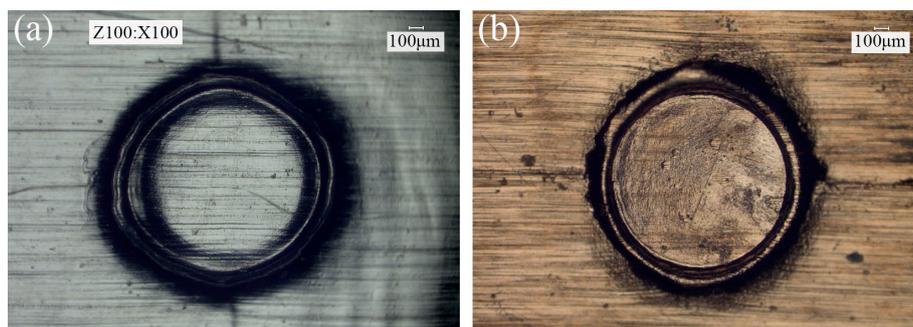


Figure 12. Surface morphology of the joint (Al/Cu: 80/20 µm; $E_n = 1290$ mJ; 3 laser pulses; $h = 70$ µm): (a) upper surface of the joint; (b) bottom surface of the joint.

Table 4 shows the joining results of similar and dissimilar materials under different laser energy. The applicable ranges of laser energy for the above three material combinations were different. Comparing the combinations of Al/Cu with Al/Ss, the higher the tensile strength of the lower foil, the larger the laser energy needed to join materials. Due to the large proportion of the upper foil thickness relative to the total thickness, the bottom fracture appeared on the upper foil first under the excessive laser energy. With the laser energy continuing to increase, the neck fracture on the upper foil subsequently appeared, and two layers of materials were completely cut at last.

Table 4. Joining results of similar and dissimilar materials under different laser energy.

Laser Energy (mJ)	1110	1200	1290	1380	1465	1550	1620	1690	1745	1800
Cu/Cu	■	■	■	■	■	■	●	●	●	▼
Al/Cu	■	●	●	●	▼	▼	▼	×	×	×
Al/Ss	■	■	■	●	●	●	▼	▼	▼	×

(1) ■: insufficient material flow; (2) ●: joint with large interlock; (3) ▼: joint with bottom fracture of upper foil; (4) ×: joint with bottom and neck fracture of upper foil.

4.3. Effect of Laser Energy on the Interlock and Minimum Thickness of Upper Foil

The interlock and the minimum thickness of upper foil were the main quality criteria of the clinched joints. It is very important to study the variation tendency of the interlock and minimum thickness of upper foil under different laser energy. As shown in Table 4, the optimal laser energy for joining the 1060 pure aluminum foils and annealed copper foils (Al/Cu) was in the range of 1200–1380 mJ. Additional tests were performed to study the influence of laser energy on the interlock and minimum thickness of upper foil. Nominal thickness of the upper and lower foils that were used in the experiments were 80 μm and 20 μm , respectively. Three laser pulses and 70 μm in die depth were used in this experiment. Figure 13 depicts the cross sections of clinched joints as well as the values of the interlock and the minimum thickness of the upper foils. When the laser energy was less than 1200 mJ, the interlock could not be produced due to the insufficient material flow. With the increase of laser energy, the interlock between the metal foils increased while the minimum thickness of upper foil decreased gradually. On the one hand, the increase of laser energy produces a higher material flow, which contributed to the formation of a large interlock. On the other hand, large laser energy was usually accompanied by a large shearing stress, which led to a huge thinning effect on the upper foil. When the laser energy was higher than 1380 mJ, the bottom fracture appeared on the upper foil due to the excessive shearing.

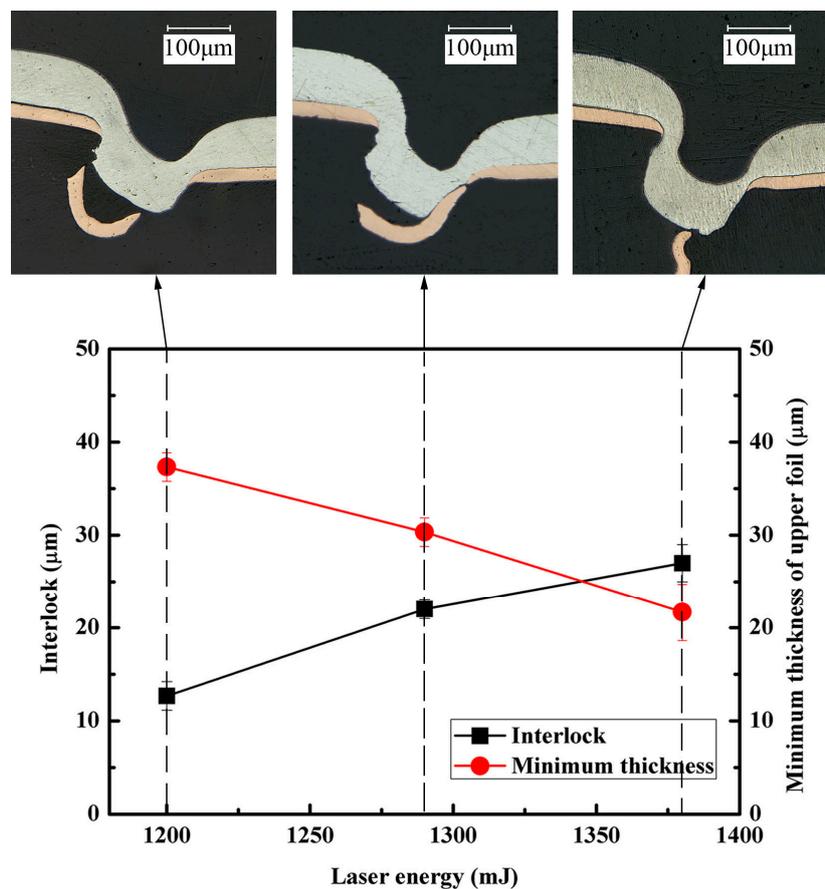


Figure 13. Effect of laser energy on the interlock and minimum thickness of upper foils.

4.4. Single Lap Shearing Test

For each processing condition, three samples were tested. Figure 14 depicts the load-displacement curves and the failure modes of two different material combinations. Figure 15 shows the shear strength of all the performed tests. The two different material combinations were Al/Cu and Al/Ss.

Except for the different materials used in the experiments, the rest of experimental conditions were identical. Thickness of all the upper foils and all the lower foils were 80 μm and 20 μm , respectively. Three laser pulses and 70 μm in die depth were employed in this experiment. In order to form a large interlock in both material combinations, 1380 mJ of laser energy was used in the experiments. However, under identical experiment conditions, the interlock sizes and the neck thickness of the different material combinations were different. According to the load-displacement curves, it can be seen that the maximum load force of Al/Ss combination was about 13.12 N, which is three times larger than that of the Al/Cu combination. Al/Ss combination with higher shear strength may be due to higher tensile strength of the lower foil or larger interlock and neck thickness of the upper foil. In order to verify this speculation, a lot of work needs to be done in the future.

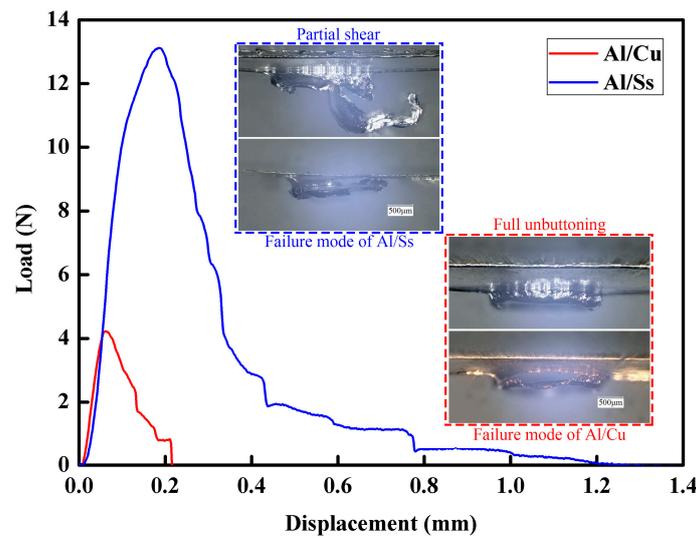


Figure 14. Load-displacement curves measured from single lap shearing tests.

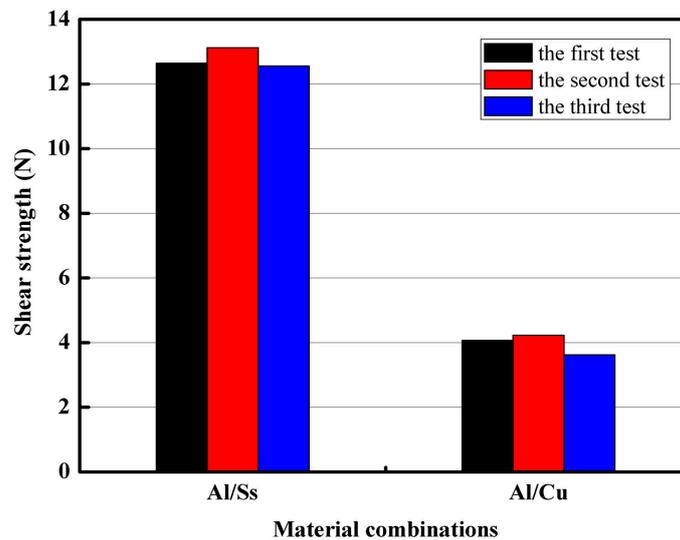


Figure 15. Shear strength of all the performed tests of different material combinations.

In the conventional mechanical clinching, the main failure modes on clinched joints can be categorized into full shear, partial shear, and unbuttoning with crack as well as the full unbuttoning. The failure mode of the clinched joints depends on the size of interlock and α -angle [27]. Moreover, these four failure modes occurred on samples joined by three different dies. In contrast, all the samples

were joined by the same die in this experiment. Additionally, only two different failure modes can be observed in the experiments. Due to suffering a larger shear force, the protrusion of upper foil in the Al/Ss combination was partially sheared. On the other hand, the failure mode of the Al/Cu combination was mainly in the form of full unbuttoning.

5. Conclusions

In this paper, a novel micro clinching with cutting by laser shock forming technology is described. Many important process parameters were determined by studying the deformation behavior of single layer 1060 pure aluminum foil under different experimental conditions. The feasibility of this novel technology was verified by joining similar and dissimilar materials in micro scale. The effect of laser energy on the interlock and minimum thickness of upper foil was investigated. In addition, the mechanical strength of different material combinations joined by micro clinching with cutting process was measured. The main results are summarized as follows:

- (1) Under the single laser pulse, the large interlock could not simply be formed by the increase of laser energy. The use of moderate energy and multiple laser pulses can solve this problem. After a series of experiments, the number of laser pulses was determined to be three pulses.
- (2) There is a certain matching relationship between the total thickness of the materials to be connected and the die depth. With the increase of the total thickness of materials, the corresponding die depth that can form a large interlock increases. In addition, the change of the die depth has less influence on the joining of thicker materials. When the total thickness of the materials was in the range of 60–100 μm , the optimum die depth was about two-thirds of the total thickness.
- (3) The similar and dissimilar materials could be joined by the micro clinching with cutting process. Seen from the process window of 1060 pure aluminum foils and annealed copper foils, micro clinching with cutting process is more suitable for the material combinations where the upper foil is thicker than the lower foil.
- (4) The optimal laser energy for joining the 1060 pure aluminum foils and annealed copper foils (Al/Cu) was in the range of 1200–380 mJ. With the increase of laser energy, the interlock between the metal foils increased while the minimum thickness of the upper foil gradually decreased.
- (5) According to the load-displacement curves, it was observed that the maximum load force of Al/Ss combination is about 13.12 N, which is three times larger than that of the Al/Cu combination. The Al/Ss combination with higher shear strength may be due to higher tensile strength of the lower foil or larger interlock and neck thickness of the upper foil. Furthermore, different material combinations had different failure modes.

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References

1. Lee, C.J.; Kim, J.Y. Design of mechanical clinching tools for joining of aluminum alloy sheets. *Mater. Des.* **2010**, *31*, 1854–1861. [[CrossRef](#)]
2. Mori, K.I.; Bay, N. Joining by plastic deformation. *CIRP Ann.-Manuf. Technol.* **2013**, *62*, 673–694. [[CrossRef](#)]
3. Abe, Y.; Kato, T. Joinability of aluminum alloy and mild steel sheets by self piercing rivet. *J. Mater. Process. Technol.* **2006**, *177*, 417–421. [[CrossRef](#)]

4. Mori, K.; Abe, Y. Self-pierce riveting of multiple steel and aluminum alloy sheets. *J. Mater. Process. Technol.* **2014**, *214*, 2002–2008. [[CrossRef](#)]
5. Varis, J.P.; Lepistö, J. A simple testing-based procedure and simulation of the clinching process using finite element analysis for establishing clinching parameters. *Thin-Walled Struct.* **2003**, *41*, 691–709. [[CrossRef](#)]
6. Klocke, F. *Joining by Forming; Manufacturing Processes 4*; Springer: Berlin/Heidelberg, Germany, 2013; pp. 457–469.
7. Oudjene, M.; Ben-Ayed, L. On the parametrical study of clinch joining of metallic sheets using the Taguchi method. *Eng. Struct.* **2008**, *30*, 1782–1788. [[CrossRef](#)]
8. Lambiase, F.; Ilio, A.D. Finite element analysis of material flow in mechanical clinching with extensible dies. *J. Mater. Eng. Perform.* **2013**, *22*, 1629–1636. [[CrossRef](#)]
9. Busse, S.; Merklein, M. Development of a mechanical joining process for automotive body-in-white production. *Int. J. Mater. Form.* **2010**, *3*, 1059–1062. [[CrossRef](#)]
10. Abe, Y.; Mori, K. Joining of high strength steel and aluminum alloy sheets by mechanical clinching with dies for control of metal flow. *J. Mater. Process. Technol.* **2012**, *212*, 884–889. [[CrossRef](#)]
11. Lambiase, F.; Ilio, A.D. Joining aluminum alloys with reduced ductility by mechanical clinching. *Int. J. Adv. Manuf. Technol.* **2014**, *77*, 1295–1304. [[CrossRef](#)]
12. Varis, J. Economics of clinched joint compared to riveted joint and example of applying calculations to a volume product. *J. Mater. Process. Technol.* **2006**, *172*, 130–138. [[CrossRef](#)]
13. Lambiase, F.; Ilio, A.D. Damage analysis in mechanical clinching: Experimental and numerical study. *J. Mater. Process. Technol.* **2016**, *230*, 109–120. [[CrossRef](#)]
14. Jiang, T.; Liu, Z.X. Effect of aluminum pre-straining on strength of clinched galvanized SAE1004 steel-to-AA6111-T4 aluminum. *J. Mater. Process. Technol.* **2015**, *215*, 193–204. [[CrossRef](#)]
15. Lambiase, F.; Ilio, A.D. Mechanical clinching of metal–polymer joints. *J. Mater. Process. Technol.* **2014**, *215*, 12–19. [[CrossRef](#)]
16. Lee, C.J.; Lee, J.M. Design of hole-clinching process for joining of dissimilar materials—Al6061-T4 alloy with DP780 steel, hot-pressed 22MnB5 steel, and carbon fiber reinforced plastic. *J. Mater. Process. Technol.* **2014**, *214*, 2169–2178. [[CrossRef](#)]
17. Lambiase, F. Mechanical behaviour of polymer-metal hybrid joints produced by clinching using different tools. *Mater. Des.* **2015**, *87*, 606–618. [[CrossRef](#)]
18. Lambiase, F. Clinch joining of heat-treatable aluminum AA6082-T6 alloy under warm conditions. *J. Mater. Process. Technol.* **2015**, *225*, 421–432. [[CrossRef](#)]
19. Abe, Y.; Kato, T. Mechanical clinching of ultra-high strength steel sheets and strength of joints. *J. Mater. Process. Technol.* **2014**, *214*, 2112–2118. [[CrossRef](#)]
20. Mori, K.; Abe, Y. Mechanism of superiority of fatigue strength for aluminium alloy sheets joined by mechanical clinching and self-pierce riveting. *J. Mater. Process. Technol.* **2012**, *212*, 1900–1905. [[CrossRef](#)]
21. Veenaas, S.; Wielage, H. Joining by laser shock forming: Realization and acting pressures. *Prod. Eng.* **2013**, *8*, 283–290. [[CrossRef](#)]
22. Zhang, K.F.; Kun, L. Classification of size effects and similarity evaluating method in micro forming. *J. Mater. Process. Technol.* **2009**, *209*, 4949–4953. [[CrossRef](#)]
23. Daehn, G.S.; Lippold, J.C. Low Temperature Spot Impact Welding Driven Without Contact. U.S. Patent PCT/US09/36299, 11 September 2009.
24. Wielage, H.; Vollertsen, F. Undercuts by laser shock forming. *AIP Conf. Proc.* **2011**, *1353*, 1309–1312.
25. Veenaas, S.; Vollertsen, F. High Speed Joining by Laser Shock Forming. *Adv. Mater. Res.* **2014**, 966–967, 597–606. [[CrossRef](#)]
26. Veenaas, S.; Vollertsen, F. Forming behavior during joining by laser induced shock waves. *Key Eng. Mater.* **2015**, 651–653, 1451–1456. [[CrossRef](#)]
27. Lambiase, F.; Ilio, A.D. An experimental study on clinched joints realized with different dies. *Thin-Walled Struct.* **2014**, *85*, 71–80. [[CrossRef](#)]
28. Mucha, J. The analysis of lock forming mechanism in the clinching joint. *Mater. Des.* **2011**, *32*, 4943–4954. [[CrossRef](#)]

