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INFLUENCE OF PUNCH SHAPES ON FORCES AND PART QUALITY IN THE PUNCHING OF EXPLOSIVELY WELDED DP600, Al1100, AND DP600-Al1100 COMPOSITE PLATES

Summary

This study theoretically and experimentally investigates blanking/piercing operations of explosively welded commercial DP600 advanced steel sheets, Al1100 aluminium sheets, and DP600-Al1100 composite plates, in which punches with different tip shapes are used. The experimental studies included several methods, such as explosive welding, punching, tensile testing, and macro image analyses using digital, optical, and SEM microscopes. The theoretical studies comprised finite element modelling using 3D models. The explosive weld was successfully applied, and the obtained Fe-Al weld microstructure was evaluated. A total of five punches, which have different tip shapes – flat-ended (0°), angled (16°), concave (R1 and R2), and V-shaped (V16) tips – were used in the experiments. Blanking forces were obtained using a load cell mounted to the die, a data acquisition card, an amplifier, and computer software. The simulation and the experimental study results were in agreement and clearly showed the effects of the punch shear angle and shape on the forces required for blanking/piercing.

Key words: *sheet metal formability, steel, blanking force, edge quality, punch type and angle, DP600-Al1100 composite plate*

1. Introduction

Manufacturers want to use lightweight materials with superior properties of high strength, good formability, and good post-forming strength in all industrial areas. This desire is also felt by users. All these properties are exhibited by dual-phase (DP) steels, part of the advanced high strength steel (AHSS) family, which is produced from high strength low alloy (HSLA) steels by annealing at intercritical temperature and then by applying the quenching heat treatment. The microstructures of DP steels consist of martensite phases dispersed in the soft ferrite matrix. The term dual-phase originates from these two phases. These steels have ideal properties for many conditions compared to HSLA steels. These properties are continuous yield behaviour, low yield strength, high work hardening rate, uniform and total elongation, and low yield ratio [1].

Explosive welding is a solid-state welding technique. This method can join similar and dissimilar sheet metals such as copper-titanium, aluminium-titanium, copper-steel, aluminium-steel, titanium-steel nickel-aluminium, and the like. There are many studies in the literature about welding different sheet materials by using the process of explosive welding [1-12]. These researchers examined influences of explosive charge thickness, annealing process, strength, ductility, corrosion resistance, microstructure, and property relationship of the composites fabricated by different explosive welding techniques [1-12]. In addition, there are studies in which interlayer and multilayer composites are produced by explosive welding [7-9]. Studies in the literature have shown that the explosive welding process parameters affect characteristics of the weld bond zone and the fatigue life. In addition, heat treatment applied to sheets affects the microstructure and intermetallic compound growth in explosively welded materials [10-15].

Two plates are joined in the explosive welding process with high velocity. Therefore, the modelling and numerical simulation of this process could be seen as very complex. Various studies were carried out with the purpose of numerical modelling of the explosive welding process [16-18]. These studies were carried out using the smoothed particle hydrodynamics (SPH) and adaptive SPH models.

The use of high-strength alloys and their applications in a variety of industries has increased widely in the last decades. Many studies have been carried out on using and forming HSLA steels in this context. The application areas of high-strength alloys in industrial manufacturing are automotive, structural, aerospace, and energy applications [19]. It is known that strain rate and temperature affect mechanical properties and fracture behaviour of dual-phase steels in forming operations [20, 21]. Also, the formability of DP sheets and spring back behaviours were also investigated in many studies [22-24].

There are numerous studies in the literature on experimental and numerical investigations into the sheet metal blanking process. Most of these studies focused on burr height, blanking/piercing force, effects of clearance, sheet thickness, and punch angle in the blanking/piercing of various sheets materials [25-28]. Also, effects of the punch shear angle on the forces required for blanking DC01 sheets were also studied [29].

It is seen from the literature that there are not many studies on plastic behaviours of explosively welded sheets. Especially, studies on the blanking of explosively welded metal composite plates are inadequate. The explosive welding process has been applied to DP600-Al1100 composite plates for the first time in this study. In addition, blanking operations using a die on DP600, Al1100, and explosively welded aluminium-dual phase steel were investigated experimentally. A computer-aided model was also prepared to carry out the modelling and numerical simulation of the blanking of explosively welded sheets. The numerical simulations of the blanking process were done using the finite element analysis.

Furthermore, the material behaviour of welded steel and aluminium sheets was simulated, and the results were compared with the experimental results. The aim was to determine the material properties, and strain and stress distributions in the process of blanking these materials. Effects of punch shear angle and punch shape resulting in less force and better product quality in blanking/piercing operations of explosively welded DP600-Al1100 composites were examined in this study in detail.

2. Materials and methods

The chemical composition of the DP600 and Al1100 materials used in the study are given in Table 1 and Table 2, respectively. Sheet thicknesses are 1mm for steel and 1.4mm for Al1100. The dimensions of the explosively welded specimens were 100 x 100 mm. Although the sheet materials were supplied commercially, the explosive welding processes of the DP-Al sheet metals were done specifically for this study.

Table 1 Chemical composition of DP600 materials (wt.-%)

Material	C	Si	Mn	P	Cr	Ni	Mo	Cu	Ti	V
DP600	0.123	0.265	1.763	0.02	0.22	0.033	0.05	0.015	0.003	0.005
DP600x	0.123	0.262	1.6	0.02	0.22	0.034	0.05	0.014	0.003	0.006

Table 2 Chemical composition of Al1100 (wt.-%)

Material	P	Ca	Si	Ga	Mg	Fe	Al
Aluminium	0,01	0,05	0.6	0,02	0,09	0.55	98.66

An explosive welding process was carried out to fabricate the DP600-Al100 layered composite. MKE Barutsan Company, Turkey, supplied the explosive material. This material has an explosion velocity of 3,200 m/s and consists of 90% ammonium nitrate, min 4.5% fuel oil, and min 3.0% TNT.

The results of the tensile test performed on the materials were used to define the material properties using the finite element analysis software. The engineering stress-strain curves, obtained from the tensile tests, were used to calculate true stress-strain curves. The engineering and true stress-strain curves of the materials used (DP600, Al100 and explosively welded bimetal composite) are given in Fig. 1.

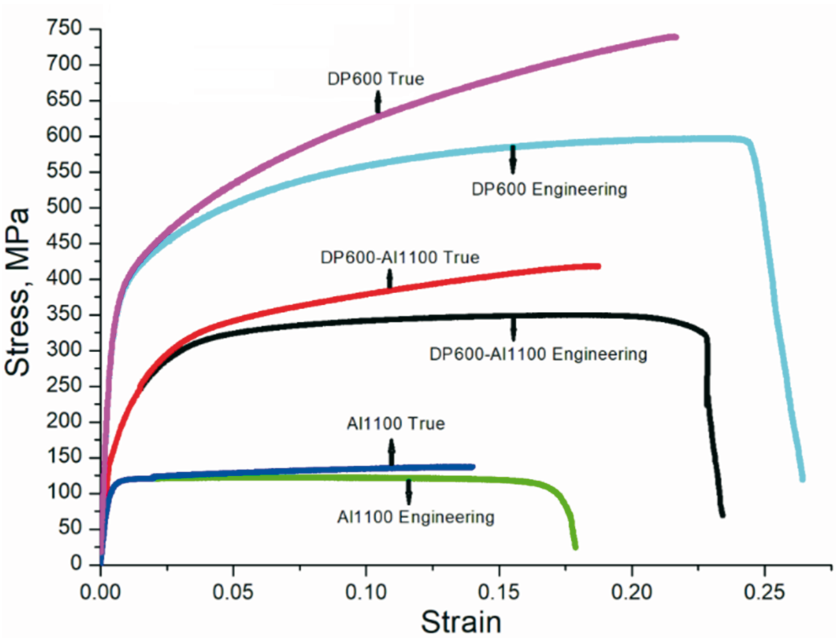

Fig. 1 Tensile test results for DP600, Al1100 and explosively welded DP600-Al1100

The punching process was carried out as follows: A modular die was used for the experimental process. A load cell was mounted on the upper side of the die to measure the loads during the experiments. The load cell had a measurement capacity of 240 kN on the vertical axis and a read capacity of 10,000 data per second. However, the amount of data was adjusted to 2,000 per second. This data value was quite enough to obtain suitable graphs. The data obtained from the load cell was transferred to a personal computer by using a data acquisition card, an amplifier, and software. The experimental setup is shown in Fig. 2.

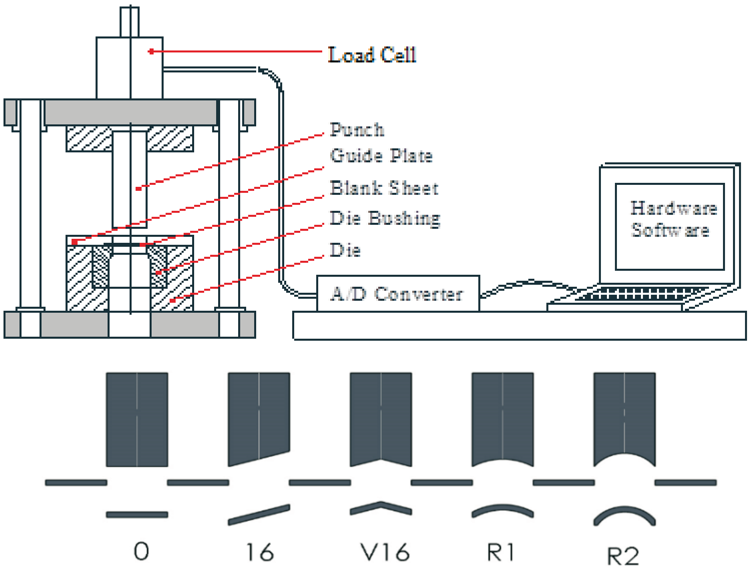

Fig. 2 Experimental setup and types of punches used in the study

The obtained and the amplified signals were relayed to a computer using an analogue-to-digital converter. The experimental setup was calibrated before the experiments, and the forces corresponding to the changes in the voltages generated by the load cell were determined. The punches used in the experiment were manufactured from high-speed steel of 20 mm in diameter. The punching experiments were carried out using five blanking punch shapes, namely 0°, 16°, R1, R2 and V16, as presented in Fig. 2. The punches used in the experiments were cut as flat ended (0°), concave (R1 and R2), and angled (16° and V16) by using wire electrical discharge machining (WEDM).

It has been indicated in the literature that the clearance value did not have a significant effect on the blanking force [28]. However, it does impact product quality; therefore, 0.4%t clearance value, which gives the best quality of the blanking surface, was used. Macro and micro images and analyses were carried out on the punched parts using stereo and scanning electron microscopy. Thus, the surface qualities on the blanking edge were also evaluated. The standard metallographic procedure (grinding with 220 to 1,200 papers and 1-micron diamond paste and cloth polishing) and etching with 2% Nital were applied to prepare an explosive weld part interface cross-section for the micro-examination.

3. Results and discussion

As seen in Fig. 3, the DP600-Al1100 steel demonstrates the microstructure after explosive welding which can be seen in the SEM images and EDS analysis as interface and base materials.

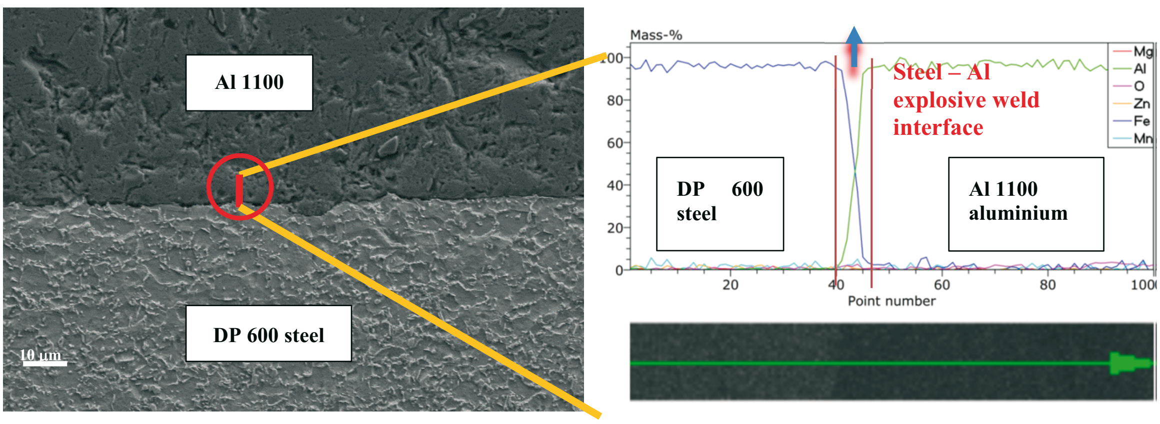

Fig. 3 Explosively welded metals and interface according to EDS analysis (chemical)

Etching with 2% Nital revealed the character of the composite steel and steel-Al interface. The DP600 steel contains a soft phase ferrite and a highly durable second phase martensite. This structure is the classical dual-phase steel microstructure. As a result of this structure and despite the high strength value, there is some martensite-ferrite orientation in the deformation direction of the biphasic steel piece at the interface due to the high energy produced by the explosive welding collision.

There is no change in the microstructure of the base material, as seen in Fig. 3, except for the interface. On the other hand, the interface of the composite structure produced by the DP steel - Al explosive welding joining is partially flat and wavy. This wavy interface is the high collision surface, which is due to the energy burst density. Researchers [1-7] reported that explosively welded joints could exhibit a flat, partially wavy, or often wavy interface between two metals. Intermetallic formation occurs at these interfaces depending on the properties, compositional abilities, and explosive weld parameters of two similar or dissimilar metals joined by an explosion [1-7]. In this study, as can be seen from the SEM-EDS analyses and images given in Fig. 1, it has been observed that an interface with an Fe-Al mixture at the interface and a region of about 2.9 μm thickness up to the wavelength level occurs in the areas where protrusions indent the steel part. Due to the high melting rate on the Al side, it gives a more flat appearance.

The experimental results obtained from the experiments using five different punch shapes have shown that the punch shape significantly affects the blanking force, as seen in Fig. 4. It was seen that the maximum blanking force value was obtained with a flat-ended punch (punch 0) for all the sheet materials used. Using V16, R1, R2 and 16, the blanking forces were reduced by approximately 50%, 54%, 64% and 70%, respectively, compared to the flat-ended (0) punch. Consequently, it is clear that the blanking force is much higher when using punch 0 and it sharply decreases with the use of the other punches.

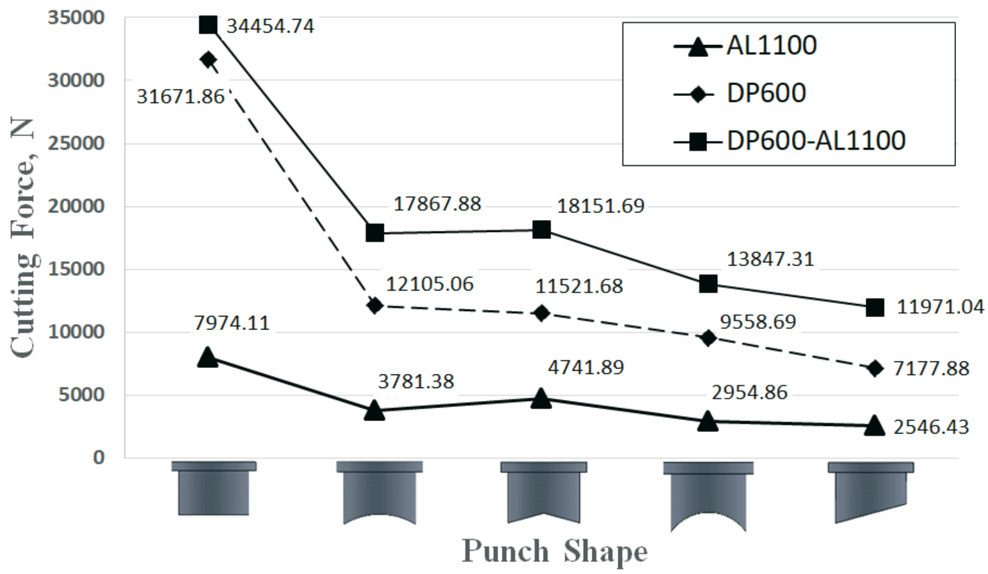

Fig. 4 Experimental results of blanking forces for different punch shapes

Furthermore, to better understand the forces that arise during the forming process, the comparative results for punch 0 for the DP600 sheets are given in Fig. 5.

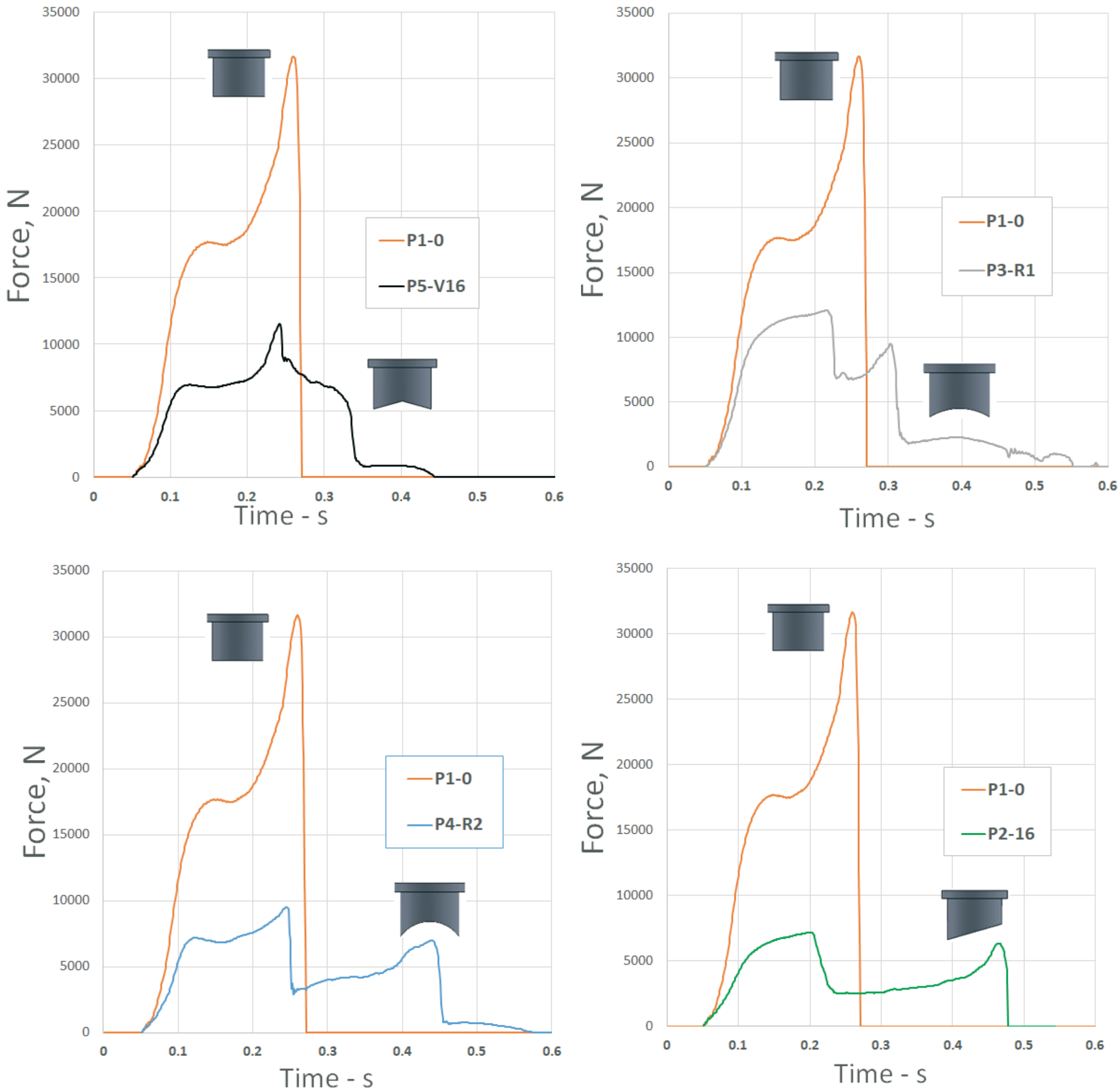

Fig. 5 Comparative force-time graphs obtained from blanking experiments on DP600 sheets

According to the force changes that occurred during the punching operations, it is seen that blanking/piercing operations occur simultaneously in one shot along the blanking line when using punch 0. In other punches (R1, V16, R2 and 16), the process is not instantaneous and takes a certain time since the blanking area changes according to the punch tip shape. This change in the blanking area also affects the thickness changes and the quality of the blanking surface.

The finite element analyses were also done for the blanking/piercing operations using the same punch and sample geometries as in the experiments. 3D models were used for die, punch, and specimens in the analyses to ensure consistency with the experimental studies. The images of the analyses were obtained using 3D models of the blanking of the DP600 sheet material by flat (0), concave (R1) and angled (16) punches, see Fig. 6.

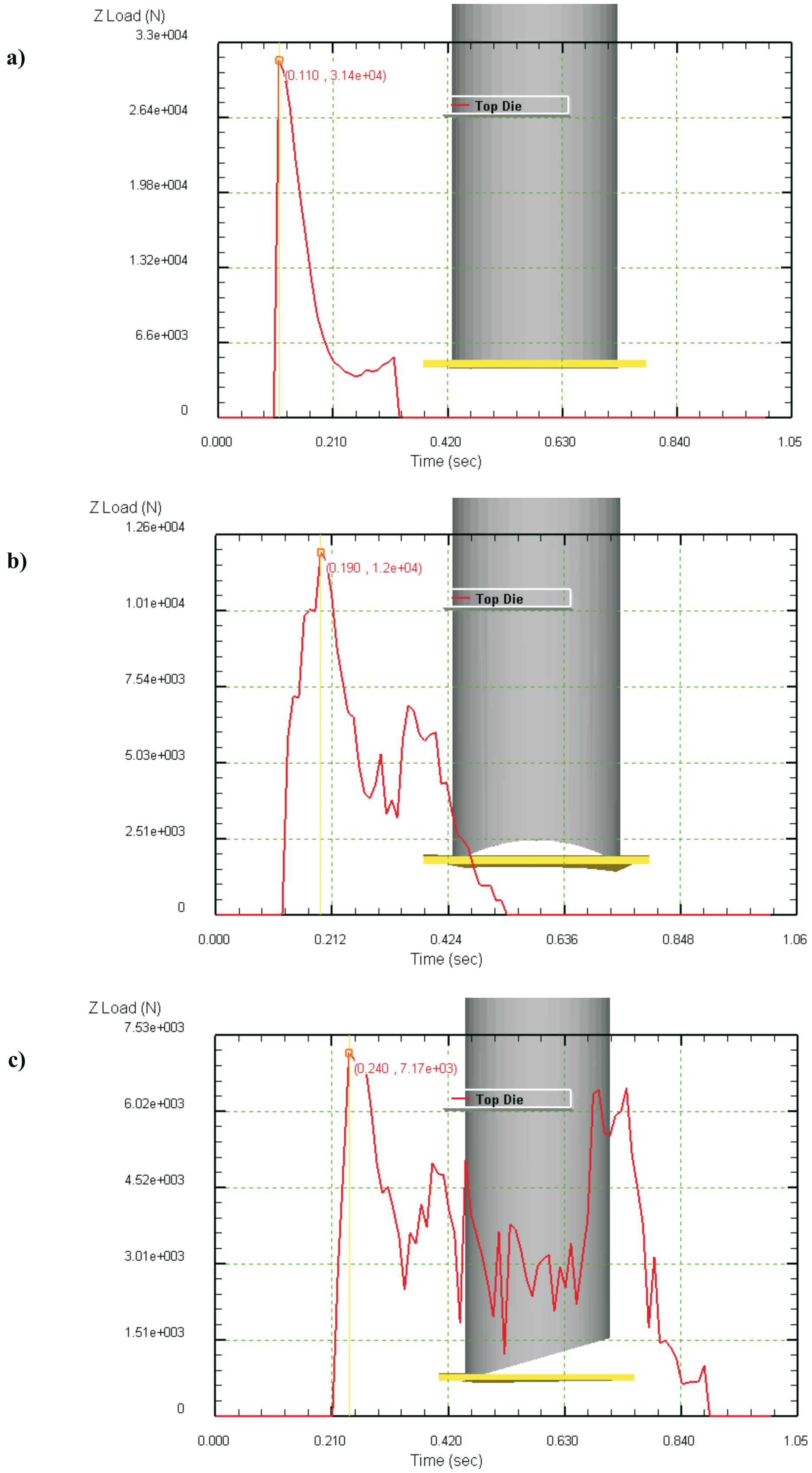

Fig. 6 Analyses obtained using 3D models of blanking of DP600 sheet material
a) flat punch (0), b) concave punch (R1), c) angled punch (16)

The theoretical studies conducted by using the FEM have shown that the results are very similar to the experimental ones. The maximum blanking force obtained from the finite element analysis is 31.4 kN for punch 0, and the experimental result is 31.6 kN for the same punch. Similarly, the maximum blanking forces obtained were 11.9 and 12.1 kN for punch R1, 9.8 and 9.5 kN for punch R2, 7.16 and 7.17 kN for punch 16, and 11.6 and 11.5 kN for punch V16. The first given values refer to the analysis results, and the second values are the experimental results. The results obtained from the analyses and experiments with the used punches are given in Fig. 7.

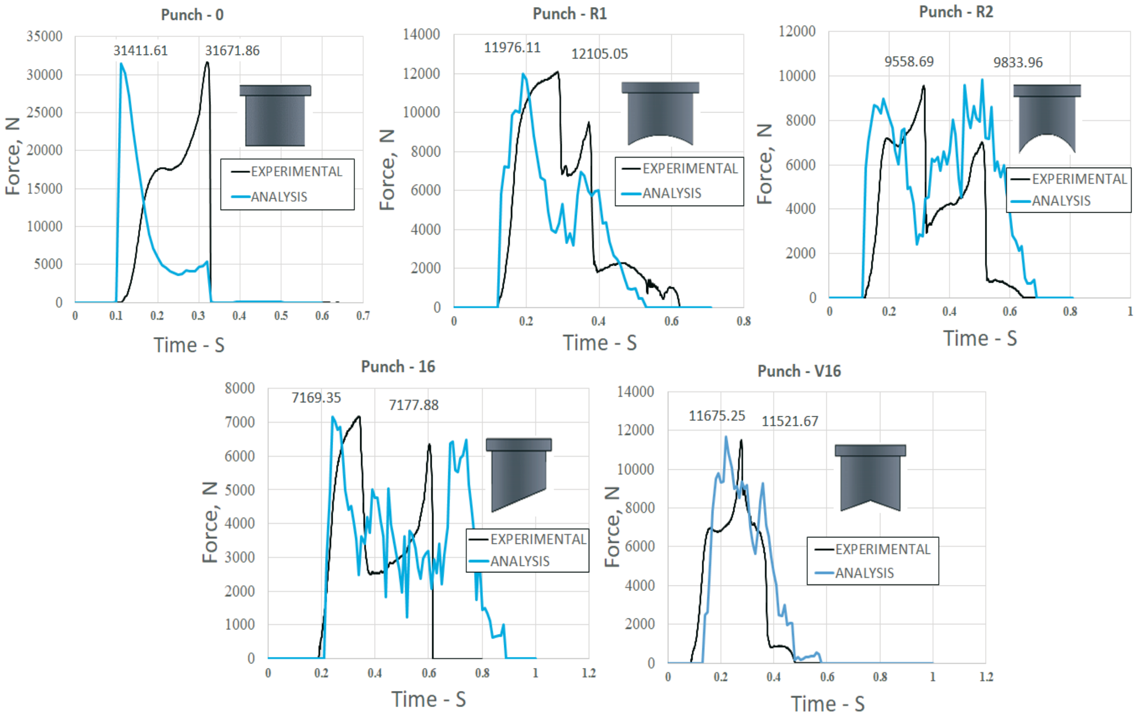

Fig. 7 Comparative force-time graphs obtained from analyses and experiments on different punch shapes

The comparisons of the blanking forces obtained from the analyses and experiments on the DP600, AL1100, and DP600-Al1100 explosively welded sheet materials are given in Fig. 8, Fig. 9, and Fig. 10, respectively, for all the punches used.

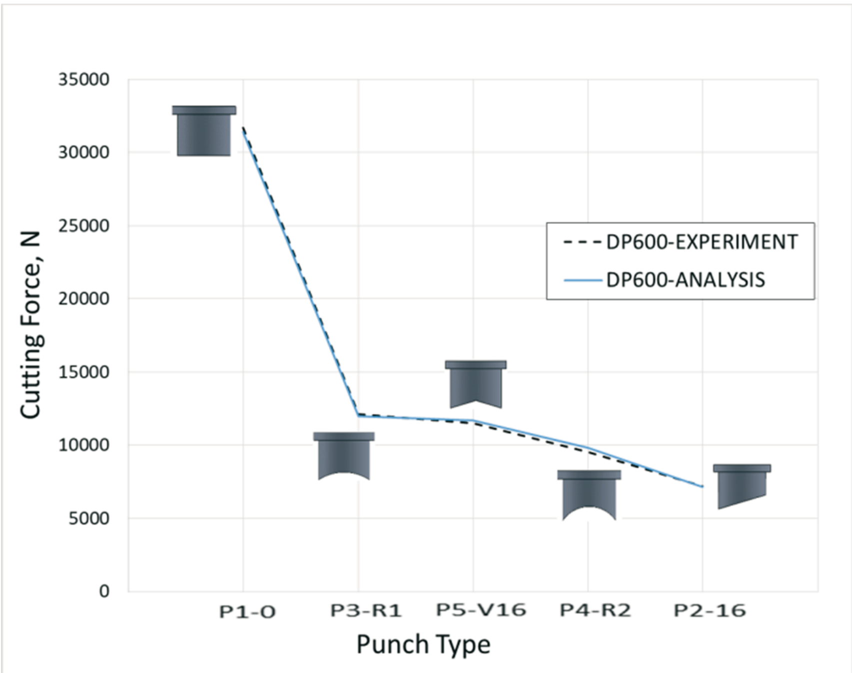

Fig. 8 Comparison of blanking forces obtained from experiments and analyses of the blanking of DP600 sheet material

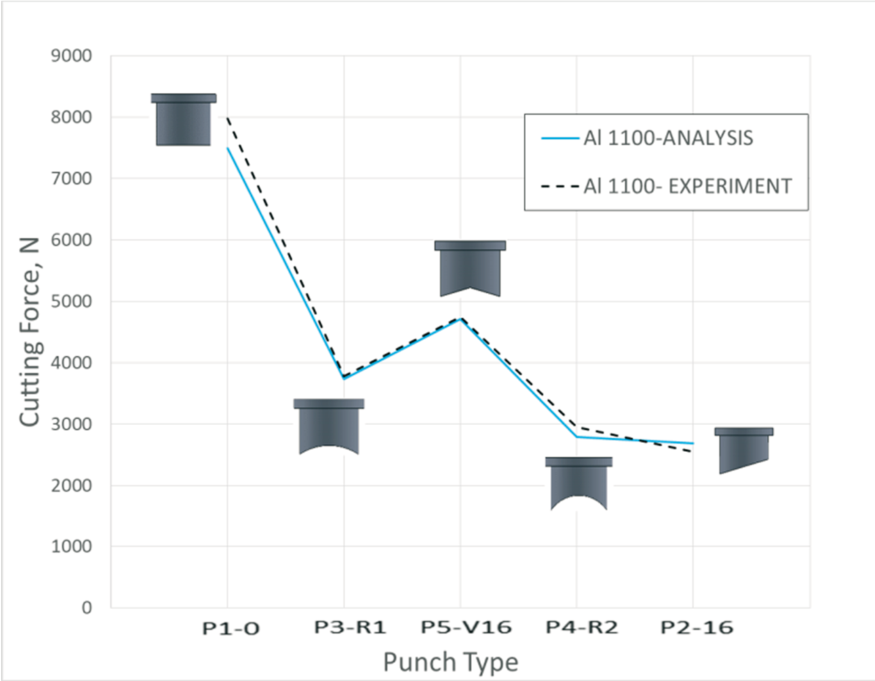

Fig. 9 Comparison of blanking forces obtained from experiments and analyses of the blanking of Al-1100 sheet material

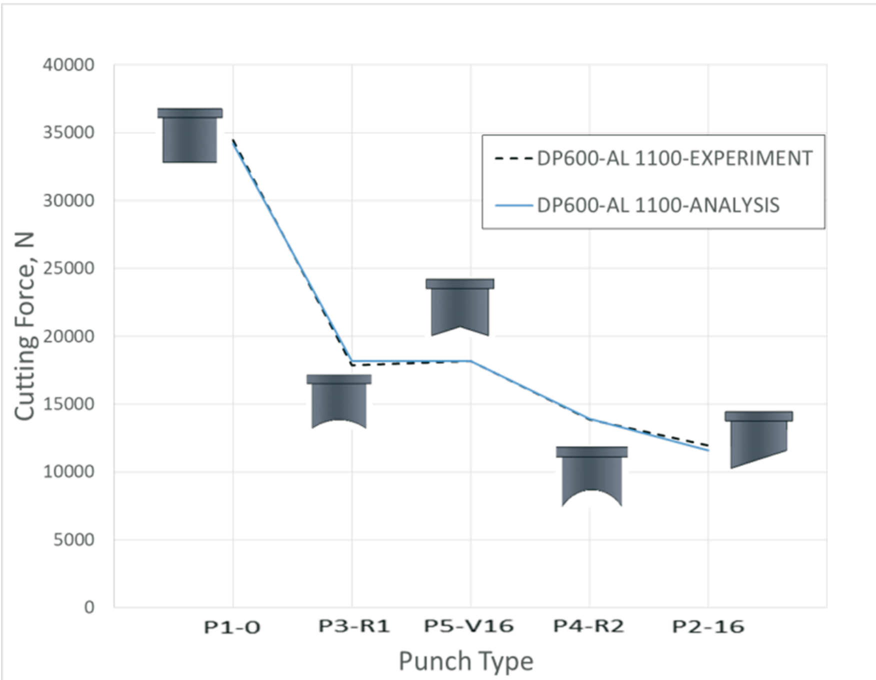

Fig. 10 Comparison of blanking forces obtained from experiments and analyses of the blanking of DP600-Al1100 explosively welded sheet material

To see the effect of the welding process on the blanking force, welded and non-welded DP600-Al1100 sheet specimens were also cut. It is known that hardness of both components increases after the explosive welding process. Hardness increases when the explosive ratio is increased and the highest hardness values are obtained for these materials near the bonding interface [1, 11, 13]. Therefore, the obtained blanking force of the materials joined with explosive welding was somewhat higher than that of the non-welded specimens (Fig. 11).

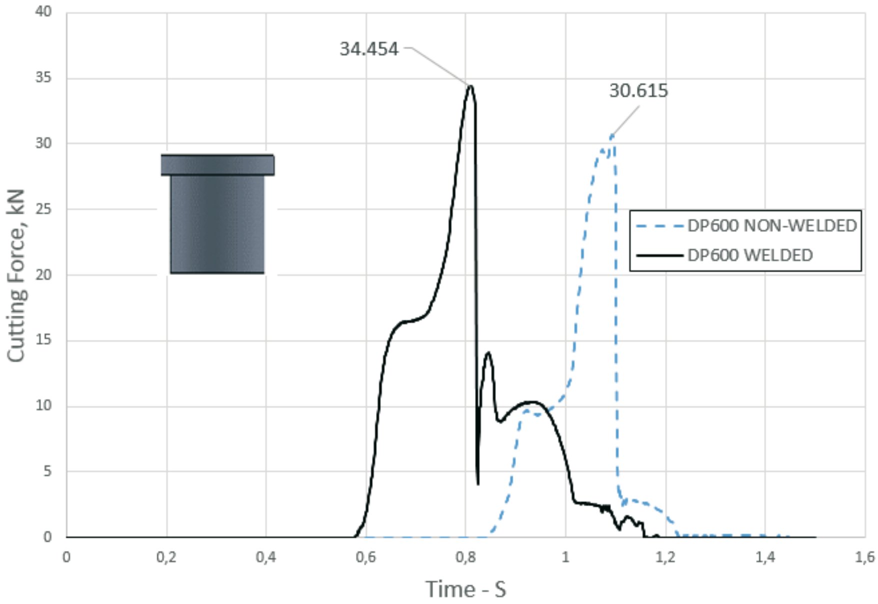

Fig. 11 Comparison of welded and non-welded DP600-Al1100 sheet specimens

The interface of the explosively welded DP600-Al1100 bimetal was also investigated as macrostructure. It was determined that there were slippages on the contact surfaces during the blanking of the non-welded sheet materials. However, the composite components have not separated one from another during punching, and no slippage was observed between the materials in the case of blanking of explosively welded sheet materials (Fig. 12). Therefore, it can be said that the punching processes can be applied to a layered composite produced by explosive welding.

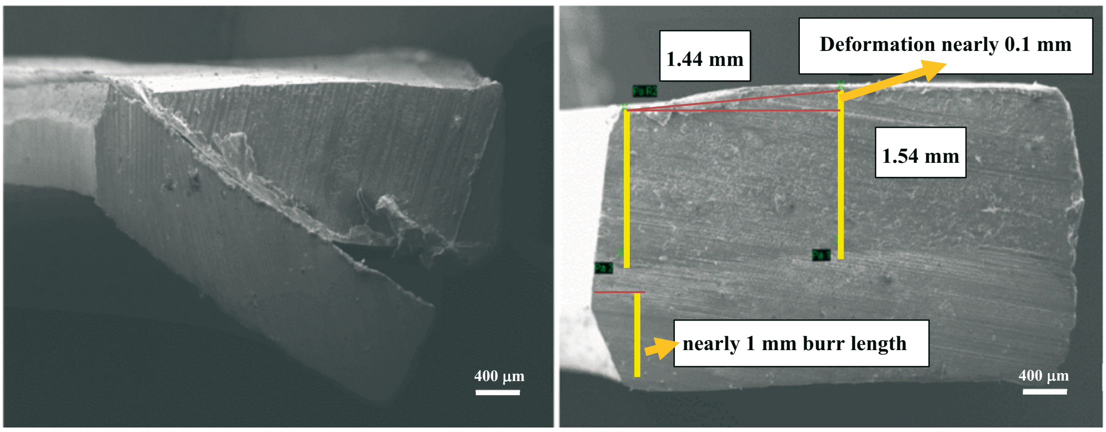

Fig. 12 Blanking of welded and non-welded sheet materials

The experimental results show that the side profile shapes of the falling parts were flat where punch 0 was used. However, the side profile shapes of the falling parts for the other used punches were not flat. Therefore, it is very difficult to achieve the dimensional accuracy for the falling parts in the blanking processes where other punches are used and not punch 0. The obtained side profile shapes of the blanks were planar in all punch shapes that were used. The side profile shape of the falling part and the blank after the blanking process in which punch R2 was used are shown in Fig. 13.

Fig. 13 Side profile of the falling part and the blank

On the other hand, when blanking using punch 16, the blanking surfaces of the obtained falling part and the blank did not have the desired shape. Depending on the punch form, it has been observed that the edges of the blanks and falling parts were in an angular form in the blanking operations made with all non-flat punch forms. This is an undesirable situation in manufacturing and is caused by the shearing of the blank with an angular punch edge. These deformations occurred on the cut surface of the falling parts and blank edges, adversely affecting the strength and dimensional stability of the parts. The deformations that occurred on the cut edges of the falling part and the blank after the blanking process in which punch 16 was used are shown in Fig. 14.

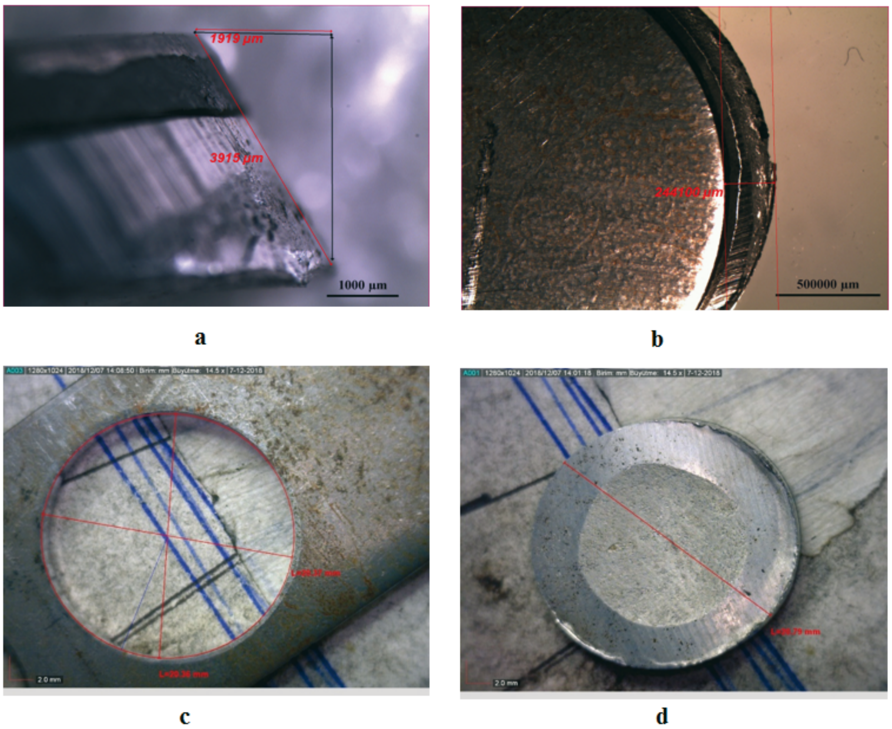

Fig. 14 Deformations on part and blank after blanking process using punch 16
a) Blanking surface of part, b) Blanking surface of blank
c) Upper side of part, d) Lower side of part

Based on the experimental results of the blanking processes of the DP600, Al1100, and DP600-Al1100 explosively welded specimens it can be said that it is convenient to use punch 0 in blanking processes. The concave (R1 and R2) and V-shaped (V16) punches can be used just for blanking processes. Using these punches for blanking processes leads to uncontrolled part sizes because the side form of the falling part is not flat. It was also determined that using punch 16 is not suitable for blanking processes since it allows lateral travel of the cut part along the cutting edge. Therefore, the blanking surfaces of both sides are obtained as angular. For this reason, it is not suitable to use not only the blank but also the falling part in manufacturing processes.

4. Conclusions

This study experimentally and theoretically examined the influence of various punch types (V16, R1, R2, 0, 16) on blanking forces and part quality in the blanking/piercing process. DP600 and Al1100 sheet metals and DP600-Al1100 explosively welded plate composite materials were used in the experiments. Al1100 and DP600 sheet materials were supplied commercially. The DP600-Al1100 plate composite was produced by explosive welding, which is a very effective and useful manufacturing process for the production of metal composites, particularly for joining different metals such as steel and Al, like in this study. Based on the results of the study, the following conclusions can be drawn:

1. DP600 quality steel and 1100 quality aluminium sheet metals can be joined and fabricated by using the explosive welding method.
2. The lowest blanking forces were obtained when punch 16 (16° angled punch) was used in the experiments. However, using this punch is not suitable for manufacturing processes since the blanking surfaces of the blank and falling part have angular edges.
3. The highest blanking forces were achieved when punch 0 (flat-ended punch, 0°) was used. The blank and the falling parts were obtained as appropriate and with dimensional accuracy. It was confirmed that punch 0 could be used in blanking and piercing operations.
4. The maximum blanking forces were reduced significantly when punches R2, V16, and R1 were used. These punches can be used for blanking processes to decrease the required force.
5. Only punch 0 can be used in the piercing processes in which the desired part shape and dimensional accuracy are achieved. However, punches 0, V16, R1, and R2 can be used for blanking processes.
6. It was observed that the materials slipped on each other, and the part shapes were not smooth during the blanking of DP600-Al1100 sheets cut by stacking without welding. No slippage was observed between the sheet materials during the explosively welded DP600-Al1100 sheets. It has been determined that blanking the sheet materials after the explosive welding process is feasible.
7. The blanking forces in the blanking of the explosively welded DP600-Al1100 sheets were higher than the forces obtained during the blanking of the DP600-Al1100 sheets by stacking without welding. It is confirmed that after the explosive welding process hardness of both components increases near the bonding interface zone.
8. No separation was observed upon completion of the blanking process in the explosively welded DP600-Al 1100 bimetal despite high blanking forces.

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