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An investigation of the shearing performance and sheared surface characterization of Ultra-Strength DP Steel-Al Explosive Welded Plate Composite

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Research Article

Keywords: Explosive welding, Cutting Force, Punch type and angle, Dual-phase steel, Aluminum

Posted Date: August 11th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1879408/v1

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Version of Record: A version of this preprint was published at The International Journal of Advanced Manufacturing Technology on March 16th, 2023. See the published version at https://doi.org/10.1007/s00170-023-11231-5.

Abstract

Piercing/blanking-cutting sheet metals with a punch are still the industry's most preferred process. This study previously aimed to fabricate the Ultra Strength DP1200 Steel-AA1100 sheet composite and then research punch shearing performance and surface characterization of this plate composite and original materials. Experimental studies include various applications such as metallography and micro image analysis, explosive welding of DP1200-Al dissimilar materials, punching operations, and tensile testing. Five different shaped punches were used in the Punching process. The force graphs corresponding to the procedure times were obtained thanks to the load-cell computer system. The resulted surface qualities of the cutting edges of the punched samples were evaluated by image analysis using digital and SEM microscopy. Shear analyzes were also performed using Finite element analysis to ensure consistency with experimental studies. As a result, the composite plate of DP1200 steel – 1100 aluminium sheet metals has been fabricated successfully by an explosive welding technic. Besides, the punching results showed good agreement between modelling and experimental punching forces. The highest cutting forces were observed when the punch "0" (flat-punch, 0°). The lowest cutting forces were obtained from the other used punch forms using punch R2, V16, R1, and 16, respectively. Moreover, the punched surfaces have been observed by comparing the force-time graphs. In addition, this study is a pioneer in the literature on its concepts, such as explosive weld materials and their punch process.

1- Introduction

A more challenging situation is when two very different materials must be joined [1]. However, composite materials fabricated from two different metals by welding are important in industrial applications, especially corrosion resistance, wear resistance, high mechanical properties, etc. New materials like that with superior properties trigger current developments in material technologies. Therefore, researchers are developing new plate composite materials for many other reasons. Steel materials except stainless steel can require combined with different metals to use common sense of composite to gain corrosion resistance. They can be isolated by welding particularly explosive with materials such as Al, Ti, and stainless steel [2]–[4] can improve low corrosion resistance. As with other solid-state welds, explosive welding allows the direct joining of similar and dissimilar metal combinations that cannot be joined by other techniques [5]. In addition, explosive welding can show superiority in joining large surfaces due to its high energy density and ability to distribute it over large areas. To date, researchers have investigated similar metals (low carbon steel, steel-to-steel [5], Al-Al, stainless steel-to-steel [4], different metals such as steel and Al [6]–[8], steel and Ti, Ni film and Al alloys [9], Fe and Cu, Al, Cu and Mg, Cu, Ti and steel, Al, Al-Mg and Cu [10]. They can provide composite plates useful in many fields, especially chemistry and nuclear reactors, by combining metal pairs such as Al-steel and triple detonation welding [4], [6].

Dual-phase steels, their microstructures consisting of martensite phases dispersed in a soft ferrite matrix, have left their mark for about 40 years and continue to be the automotive industry's basic body-in-white, technological, and economical material. [11]–[13]These steels have properties that can be expressed as ideal for many conditions compared to the HSLA steels from which they are produced [14], [15]. These are

continuous yielding behaviour, low yield strength, high cure rate, smooth and total elongation, low yield rate, etc.

The industry desperately needs more reliable information about force and industrial friction processes. Because these phenomena are not generally well understood and cause many inconveniences such as high and unpredictable machining forces, tool life, poor precision, and surface condition of workpieces. [16]–[19]. Punching is one of the most frequently used processes in sheet metal, especially punch-piercing forming. These situations are also valid for piercings of dual-phase and all AHSS steels [20]and their plate composites. Many studies on sheet metal cutting experimental and theoretical investigation are in the literature. Most of these studies have focused on burr height, shear/punching force, gap effects, and punch angle for cutting different sheet materials [19]–[23]. On DP steel, there are several studies. One of them, Wu et al. [23], Analyzed the characterization of shared edges for the DP600, DP780, and DP980 [30]; they highlighted the importance of predicting and avoiding this, highlighting the impact of punch wear on product quality and cost efficiency, which is one of the key challenges in cutting AHSS sheet metal. Metal punching processes are widely used in mass production due to their simplicity, high efficiency, and low cost. The quality of the product obtained by punching; Punch-die tool geometries develop depending on various process conditions such as sheet material properties, punching conditions and parameters, punching and die material properties and tool wear [16], [17], [24].

DP-Al metal plate composite can offer economical and technological advantages for many fields as one of the best combinations with its superior strength ductility relationship and corrosion expansion [8], [25]. On the other hand, cutting and punching operations are basic manufacturing techniques that provide financial and technological benefits to the sheet metal industry [26]. Indeed, during punch cutting of sheet metals and sheet composites, the deformation properties of the cut materials have a significant impact. The cutting forces required for strong and thick materials may increase in this context. The cutting surface quality may also be affected significantly depending on the cutting tool life and cutting stress. In other words, increased cutting forces require higher performance of the press machine and cause more wear on the punch and die [15], [16]. Although it is used differently to reduce the required force, optimizing the punch cutting angle is the most important. Another approach is to use shaped tip punches [27]. Both approaches were used in this study.

A more challenging situation is when two very different materials must be joined [1], [4]. This article examines the punching process, which is mainly needed for sheet and flat materials and performs different metal welding applications of this joint class. DP-Al sheet metal composite can be considered one of the best combinations with economic and technological advantages. On the other hand, cutting and piercing these materials is an essential manufacturing technique for economic and technological gain. A significant challenge when using punching/piercing sheet metals and sheet composites is providing the necessary shear force for high strength and thick stock. Increased cutting forces lead to higher performance requirements expected from the press machine and cause more wear on the punch and die. At this point, punch tip types are essential [27]. Because of all these, this study aims to pierce the piercing processes by using different punch tips in the economic and technological secondary production

stages and joining them with industrially important ultra-high-strength steel-Al explosion welding. In addition, the quality of the cutting surface, the resulting region, and other phenomena were examined in detail. In the literature, after the DP steel-Al explosive-welded joints of Acarer and Demir [7], the combination of explosion welding and Al-DP steel wasn't studied.

Moreover, DP1200-Al explosive welding hasn't also been studied. Moreover, the piercing process of the composite plate material produced by Steel-Al explosive welding, and using different punches, has never been studied. Therefore, this study provides significant new contributions to the literature by including innovations in many aspects. Besides, a computer-aided model was prepared to realize modelling and numerical simulation of the cutting of explosively welded sheets. Analyzes/simulations were carried out using FEM analysis. These 3D models were used in the analysis to ensure consistency with experimental studies and to see the performance of the software in the simulation of punching operations. Furthermore, the welded steel and Aluminum sheets' material behaviour was simulated, and the results were compared with the experimental results. By the way, it is aimed to figure out the material characterizations.

2- Material And Method

The sheet materials used in this study are commercial DP1200 and AA1100 grades. The chemical compositions of these sheet materials are given in Tables 1 and 2. In addition, the thicknesses of these sheet materials (DP1200 and AA100) were 1mm and 1.4 mm, respectively. Fig. 1 shows the SEM images with EDS analysis of the interface of explosive welded samples of the DP 1200-AA 1100 sheets. DP sheet steel is a significant commercial and engineering material,

With the DP1200-Al 1100, explosive welding was performed to fabricate the laminated sheet composite. Explosive material for this process was supplied from MKE Barutsan Company, Turkey. This material is a mixture of 90% ammonium nitrate, at least 4.5% fuel oil, and at least 3.0% TNT, reaching an explosion velocity of 3200 m/s.

A tensile test was applied to both base materials and composite plate samples produced by explosive welding. Tensile tests were carried out on a Zwick/Roell 600 kN machine within the scope of ISO 6892-1 standard and 2 mm/min tensile velocity. The engineering stress-strain curves obtained from the tests were used to calculate the actual stress-strain curves. Tensile test results presented in Table 3. were used to describe material properties in the numerical modelling process described later in the topic.

Piercing process and this test system; A modular mould was used for the experimental procedure. During the experiments, a load cell was connected to the upper part of the mould to measure the loads instantaneously over time. The load cell capacitance was 240 kN. Although this load cell can read 10000 data per second, the data for this study is set to 2000 per second. The results were transferred from the die to the computer using a load cell, data card, amplifier, and computer software. Also, this experimental system is schematically shown in Figure 4.

Punches 20mm in diameter and made of high-speed steel were used. Punching experiments were carried out using five cutting punch shapes, namely 0°, 16°, R1, R2, and V16, presented in Fig. 5. The punches used in the experiments were cut by using a wire EDM as flat-ended (0°), concave formed (R1 and R2), and angled (16° and V16). Furthermore, the piercing processes were also simulated using numerical modelling in the Simufact software. Thus, it aimed to determine the material characterizations and strain-stress distributions in cutting these materials.

The samples were prepared for microstructural examination following the standard metallographic method and fine grinding, polishing, and etching in 2% Nital (2% HNO3 + 98% Methanol) solution. Microstructural characterizations and piercing cut surface examinations were performed using a scanning electron microscope (SEM, Carl Zeiss Ultra Plus) equipped with an energy dispersive spectrometer (EDS) and digital microscopy.

Numerical analyzes were performed using Simufact Forming software. 2D-3D models were used in the analysis to ensure consistency with the experimental studies and to see the performance of the software in the simulation of punching operations. As it is known, if the simulation programs are consistent, it can save time and money without many experiments and applications. Their usability was also investigated in this study.

3- Experimental And Numerical Results And Discussion

3.1 Microstructure and tensile test

As seen in Fig. 1, Ultra high strength DP1200 steel contains a very high-volume fraction of the tough phase, martensite. This value contains about 75% martensite and 25% soft phase ferrite. Also, as seen in this figure, an explosive blasting joint with a wavy interface is provided. Since the Al sheet used is a well-known, unalloyed, single-phase structure, it has not been further characterized as microstructural. According to this figure and the EDS result, it can be said that the formation of intermetallics (Al-Fe) at the interface was limited [29], [30].

Intermetallic formation at explosive welding of dissimilar metals is a well-known phenomenon. However, this is observed in limited areas of an interface (Fig. 1). Another phenomenon in explosive and pulse welding, the joining interface offers three morphologies: wavy, flat, and fused layers. These morphologies are a very interesting and complex topic [4], [7], [30], [31]. The interfacial formation, for technical purposes, these morphologies depend on the speed and angle of impact [5], [31]. The interface developed is related to two important events during bonding: sparsity wave interaction and mechanical friction. The first factor that comes to mind is the material's spread of pressure and tension waves due to the impact and shock caused by the explosion and their interaction. Secondly, it is responsible for the acceleration of the flyer plate to the base plate and sliding due to jet formation and its interaction with both the wing and base plates [5]. These phenomena can cause several changes in metallurgical properties, such as deformation at the interface, especially melting of the low melting metal, and if possible, the formation of stoichiometric intermetallics (partial or general) between two metals [7], [32]

The tensile test results obtained in this study are given in Table 3. As can be seen from these results, unalloyed did not show a significant yield strength / tensile strength ratio, while DP 1200 sheet steel showed approximately 0.84 and DP1200-AA1100 plate composite showed about 0.675. In this way, while the yield strength/tensile strength ratio improved with composite production, there was no significant decrease in the elongation value. In addition, the strength of the composite decreased due to the field effect of Al. These results are approximately expected results according to composite rules about combining materials [7], [13]

3.2. Piercing process of the samples

3.2.1. The Piercing process of the base materials

Fig 4 shows cutting force vs time graphs of the DP1200 punching experiment. In addition, Fig 5 compares punching forces in punching operations using 5 different punch tips. As seen in these Fig., the shearing force was the maximum value of 45452.2 N when punch "0" was used. The shearing forces were obtained as 19949, 17118.9, 16535.5, and 11237.8 N when the punches R1, V16, R2, and 16 were used, respectively. Consequently, it is evident that the cutting force is very high in using the "0" punch type and sharply decreases when the other punches are used. On the other hand, as seen in Fig. 5., when experiments were conducted with theoretical studies using FEM analysis, it was found that the results were compatible. The shearing force obtained from FEA Program is 45725N, and the experiment result is 45452N for the punch "0". Similarly, the results were obtained as 20089N and 19949N for R1, 15959N, 16535N for R2, 11002N, and 11237N for punch 16, 17245N, 17118N for punch V16, respectively. This situation was associated with the higher cutting and stripping forces when using the flat punch because of the more significant blanking area.

In addition, Firstly, Fig. 4. shows that the force vs time graph of the piercing process using a P0 straight punch is interpreted as follows;

1. Elastic stage: Elastic deformation is when the force rises when the punch encounters the sheet and continues until the plastic deformation begins.
2. Elastoplastic stage: The stage of plastic deformation. In this stage, the force increases until the crack occurs
3. Punch penetration: When the crack occurs, the force decreases sharply, and at this stage, a slight force appears, which is the force that the punch penetrates the sheet

Secondly, Fig. 4. shows also that the piercing operation performed using the P2-16 punch is interpreted to define the cutting process in the force vs time graph, and the following result emerges. Unlike piercing with a P-0 punch, it has been observed that there are four different stages in piercing with this angled punch:

1. In this elastic deformation stage, the force rises when the punch encounters the sheet and continues until the plastic deformation begins.

2. In this plastic deformation stage, the force increases until the first crack occur at point (A).
3. After the occurrence of the first crack, a decrease in the force can be observed in this area because it has become a shear force and continues with the same value until it approaches point (B), so the force rises again until the occurrence of the second crack.
4. When the second crack occurs, the force decreases sharply, and at this stage, a slight force appears, which is the force that the punch penetrates the sheet.

In related literature, similar works were performed in this study manner. For example, Hambali and Guerin [32] reported that during the punching-blanking process, the part is exposed to complex conditions such as deformation, work hardening, and crack initiation and propagation. It is possible to understand the different stages of the cutting process, which ends with the complete separation of the sheet metal of such operations, by defining the force-time graphs. Still, they can be challenging to model. They also show force vs time graphics as described in this study, but there are some differences. This way, accurate knowledge of the failure process is essential for selecting an appropriate damage model. A precise understanding of the failure process is critical to choosing a proper damage model. In the case of sheet shearing by shearing operations, numerous authors have studied the different physical mechanisms that lead to eventual breakage and proposed their models. Dos Santos and Organ [33] performed a viscoplastic study of the rectangular bar blanking operation. They analyzed the deformation of a pattern engraved on the surface of the cut area. As a result, he studied the different physical mechanisms that lead to many eventual ruptures in the case of cutting sheet metal by shearing operations and proposed his models.

During the blanking process, shearing and stripping forces occur between the die, punch, and sheet material. When the movement of the punch is at right angles to the die, the force required in a blanking operation can be determined as follows;

$$F = L_t \cdot S_s \quad (1)$$

Where F is the force required for blanking, L is the total cutting length (perimeter), t is the sheet thickness, and Ss is the material's shear strength.

The compressive stress in the punch is calculated as follows;

$$S_p = F / A_p \quad (2)$$

Where Ap is the cross-sectional area of the punch.

Stripping force is needed to free the blank from the die or the strip from the punch and increase the total blanking force. Stripping force is calculated as follows;

$$L_{st} = k. A_s \quad (3)$$

L_{st} is the stripping force, k is a stripping constant, and as is the cut surface area [34].

When examining the forces changes that occurred during the punching operations (Fig.4.), it can be said that while using the punch "0", blanking/piercing operations co-occur in one shot along the shearing line. Therefore, cutting and stripping forces are also high. Using other punches (R1, V16, R2, and 16) is not instantaneous and takes time. The cutting and stripping forces also decrease depending on the decreasing cutting area. The significance of these results is that the cutting/deformation relationship can be seen. The change in the cutting area also affects the thickness changes and the quality of the cutting surface.

All experiments and FEM analyses conducted using five different punch shapes and AA1100 sheet material have shown that the shearing force is significantly affected by the punch form, as given in Fig. 6. As experimental results, the shearing force was the maximum value when the punch "0" was used. The shearing force was obtained as 7879.5 N for the Al-1100 sheet material. However, it was found that punch V16 comes in second place instead of punch R1, and the shearing force was 4741.8 N. The shearing forces were measured as 3781.3 N, 2954.8 N and 2546.4 N for the punches R1, R2, and 16, respectively.

It was found that when comparing the shearing force of the punch "0" with the rest of the punches, the shearing force decreases markedly. Changing the punch shapes reduced the cutting forces by 39%, 53%, 63%, and 68% using V16, R1, R2, and 16 punches, respectively, compared to flat-ended (0) one (Fig. 6). When these results are compared with the results of the DP1200 shown in Fig. 4 and 5, it is seen that the rate of decrease in the force is lower than expected. This situation can be explained by the low strength of the Al sheet and the reduction in the piercing resistance.

When the experimental results and analysis results are compared, it is seen that the required shearing forces for cutting the Al-1100 sheet material are very close. The shearing force obtained from Deform Program is 7.4 KN, and the experiment result is 7.8 KN for the punch "0". Both results are 3.7 KN for punch R1. The other results were obtained as 2.9 KN and 2.7 KN for the punch R2, 2.6 KN and 2.5 KN for punch 16, and 4.69 KN and 4.7 KN for the punch V16.

3.3. Piercing/Punching of the DP1200 – AA1100explosive welded plate composite by Experimental and FEM

Piercing/punching tests and analyzes were carried out on DP1200 – AA1100explosive welded sheet materials experimentally and theoretically. The maximum shearing force was 47541 N with the punch "0". While the shearing forces were obtained at 20485 N, 21644 N, 18088 N, and 13374 N for punches R1, V16, R2, and 16, respectively, as seen in Fig. 7. and 8. Like base materials, plate composite punching force is reduced by changing the punch shapes. Reducing portions in the cutting forces were 54.5%, 57%, 62% and 72% by using V16, R1, R2, and 16 punches, respectively, compared to flat-ended (0) one (Fig. 8). It is also seen that the required shearing forces obtained from experimental studies and analyses for cutting off the DP1200-AA1100 explosive welded sheet material are very close. The shearing force obtained from Deform Program is 48435N, while the practical result is 47541N for punch 0. The other

results were 21274 N and 20485N for the punch R1, 18088N and 18706N for the punch R2, 22204N and 21644N for the punch V16, 13673 N and 13374N for punch 16.

3.2. Experimental and FEM studies of Piercing of the DP1200 – AA1100pairs (welded by explosive and unwelded)

DP1200-AA1100 sheet specimens with and without welding were also tried to shear by piercing to see the welding process's effect on the shear force. It is known that both components' hardness increases after the explosive welding process. Hardness is increased with increasing explosive ratio, and the highest hardness values are obtained near the bonding interface [1, 8, 9]. Therefore, the cutting force of the materials combined with explosive welding was somewhat higher than the not welded (Fig. 9). However, the force increase was minimal. That may be interpreted as reducing the thickness of the shearing area due to the deformation mentioned above.

Besides, it was determined that there was slippage on the contact surfaces when cutting unwelded sheet materials together. No slippage was observed when cutting explosively welded sheet materials (Fig. 10).

On the other hand, in the cutting with punch 16, the cutting surfaces of the falling apart and the blank are not smooth. It was observed from the measurements that these cutting surfaces are angular. Deformation of the falling part and blank when using punch – 16 are shown in Fig. 10. When the interface of explosively welded DP1200-AA1100 bimetal was also investigated as macrostructure, it was observed that the composite components did not separate from each other during punching in which shear forces reached up to 47 kN. Therefore, it can be said that the punch process can be used for layered composite produced by explosive welding.

The experimental results of shearing processes of the DP1200, AA1100, and DP1200-AA1100 explosively welded specimens. It is convenient to use the punch "0" in blanking and piercing processes. The R1, R2, and V16 punches can be used just for piercing processes. Using these punches for the blanking processes leads to uncontrolled part sizes because the side form of the falling part is not flat. It was also determined that punch 16 is unsuitable for blanking and piercing processes since it allows lateral travel of the cut part along the cutting edge. Therefore, the cutting surfaces of both sides are obtained as angular edges. For this reason, it is unsuitable to be used in manufacturing processes, not only the blank but also falling apart.

3. 3. Pierced-punched-Sheared surface and areas examination

The cutting-punch-piercing surface images of DP1200 obtained in this study are given in Fig. 11. It has been achieved to define the rollover, shear, fracture, and burr regions generally expressed in the literature in these photographs [33], [35]. In addition, in this study, SEM images of the cutting cross surface of the DP1200-AA1100plate composite samples are given in Fig. 12. The measurement analysis of the micro images taken from the mid of the samples is shown in Fig.13, with the measured state of the cutting surface regions. It has been achieved to define the rollover, shear, fracture, and burr regions, generally

expressed in the literature in these photographs [19], [23], [36]. Correctly, in the case of two different materials combined with this explosion in these images, it is observed that these regions almost formed in both parts.

Punch 16 was used, and the falling part and blank cutting surfaces were not smooth. It was observed from the measurements that these cutting surfaces are angular. Deformation of the falling part and blank when using punch 16 are shown in Fig. 10. When the interface of explosively welded DP1200-AA1100 bimetal was also investigated as macrostructure (Fig. 11), it was observed that the composite components did not separate from each other during punching in which shear forces reached up to 47 kN Therefore, it can be said that the punch process can be used for layered composite produced by explosive welding.

share surface quality is one of the most important factors that provide flexibility and stretchability during expansion and flanging in the punching process. Therefore, it is an essential criterion in the quality approach of the cutting process [37]–[39]. This study determined that four different regions can be analyzed according to the literature's surface texture and cutting surface. As mentioned before, these areas are; burr, cutting, tipping and breaking areas are primarily expressed. It is desirable to have a large cutting area and smaller burrs for a good quality cutting surface. In addition, in the surface roughness criteria, the fracture and tipping areas are desired to be minor, while the cutting area is more significant. As shown in Fig.s 11, 12 and 13, the punch type has a distinct effect on the cutting surface. In this study, the cutting speed was kept constant. It is accepted that the cutting speed also affects the region and areas here.

In some studies, it has been mentioned that the cutting surface properties are affected by the clearance. When the clearance is too low, the second finishing area is formed due to the contact of the fractured surfaces [15], [32], [33]. In 2D numerical studies, it has been observed that the broken surfaces touch each other. Surface cutting is slower in punches with inclined geometry because the shear angle and crack propagation move perpendicular to the punch surface according to the inclination angle[42]. In this case, the deformation increases and the rollover size increases due to slow sliding. That can be understood from the top view of the rollover regions formed due to stapling with different staples [43].

Another important subject where cutting processes are combined is punching and hole boring in automotive body production applications. The quality and undamaged performance of these processes are very important indicators in terms of the quality of the subsequent parts and service performance. Hole boring test is one of the most important processes to understand the cutting surface quality and production and service conditions in sheet materials. In this context, the ductility and formability of plate and sheet metals must also meet the requirements of automotive and other applications. Typically, the hole expansion ratio (HER) is a good indicator of the sheared edge ductility of sheet materials, emphasizing the importance of surface quality and pain caused by hole formation used in hole formation and downstream processing. In this context, room temperature punch-cutting is the most cost-effective way to create profile cuts compared to other methods. Therefore, understanding the punching process

and its effect on subsequent cutting behavior is beneficial for the validity of punch cutting [44], [45]. It is performed as a cutting process that divides the samples into two parts by cutting the profile hole and forms the first hole surfaces with the areas affected by the cutting edge shearing (SAZ) in the remaining space. (SAZ) in the remaining space. Wu et al. [[46] It is performed as a cutting process that divides the samples into two parts by cutting the profile hole and forms the first hole surfaces with the areas affected by the cutting edge shearing (SAZ) in the remaining space. Wu et al. [[46] showed that plastic deformation and effects caused by punch cutting have a high degree of strain localization in the first hole-edge region. This results in a deformation gradient where the stress decreases as you move away from the cutting edge. The effect of this shear stop for subsequent deformation processes is very obvious. In this study, the development and final conditions of the surface quality as susceptibility to the next production processes were evaluated in detail and it was shown that these results could be considered as an important criterion when starting the next processes. In this context, the cutting edge properties of the plate composite flat product produced by both dual-phase steel and burst welding and the cutting forces resulting from the process are given in great detail.

4- Conclusion

This study examined the effects of various punch types (V16, R1, R2, "0", 16) on cutting forces and part quality in the blanking/piercing process experimentally and theoretically. DP1200, AA1100, and DP1200-AA1100 explosive welded plate composite materials were used in the experiments. While AA1100 and DP1200 sheet materials were supplied commercially, DP1200-AA1100 plate composite was produced by explosive welding, which is very effective and available for manufacturing the metal composite, particularly in combining different metals like steel and Al like this study's samples. As a result, the following conclusions can be drawn:

1. DP1200 quality steel and AA1100 quality aluminium sheet metals could be joined and fabricated by explosive welding.
2. The lowest cutting forces were obtained from the experiments when using the punch 16 (16° angled punch). However, using this punch is not suitable for manufacturing processes since the cutting surfaces of the blank and falling part have angular edges.
3. The highest cutting forces were observed using the punch "0" (flat-ended punch, 0°). When this punch was used, the blank and the falling parts were obtained in appropriate form and dimensional accuracy. It was confirmed that punch 0 could be used in blanking and piercing operations.
4. Between the other used punch forms (except punch "0" and punch 16), the lowest cutting forces were obtained using punch R2, V16, and R1, respectively. These punches can be used for piercing processes to decrease cutting force.
5. Only punch "0" can be used in blanking processes to achieve desired part form and dimensional accuracy. However, punches named "0", V16, R1, and R2 can be used for piercing processes.
6. It was observed that the materials slipped on each other, and the part forms were not smooth during the cutting of DP1200-AA1100 sheets cut by stacking without welding. No slipping was observed

between the sheet materials when cutting the explosively welded DP1200-AA1100 sheets. It has been determined that it is feasible to cut sheet materials after the explosive welding process.

7. The cutting forces that occurred during the cutting of the explosively welded DP1200-AA1100 sheets were higher than the DP1200-AA1100 sheets cut by stacking without welding. It is confirmed that the hardness of both components increases near the bonding interface after the explosive welding process.
8. During punching, despite high shearing forces, there is no separation in explosively welded DP1200-AA1100 bimetal from each other.

Declarations

Acknowledgement

The authors would like to thank ME Barutsan Company for assisting in procuring explosives and performing explosive welding to supply steel materials. The authors would also like to thank and Karabuk University Scientific Research Coordination Unit for their financial support of this study with the project number KBÜBAP-22-DS-059

Funding

This work was supported by Karabuk University’s Scientific Porcect Unit with [KBÜBAP-22-DS-059] coded Project

Competing Interests

The authors have no relevant financial or non-financial interests to disclose

Author Contributions

All authors contributed to the study's conception and design. Material preparation, data collection and analysis were performed by Khalil Belras Ali, Bilge Demir, Hakan Gürün, Mustafa Acarer. The first draft of the manuscript was written by Khalil Belras Ali, Bilge Demir, Hakan Gürün, and Mustafa Acarer, and all authors commented on previous versions. All authors read and approved the final manuscript.

References

1. Md. A. Karim and Y.-D. Park, "A Review on Welding of Dissimilar Metals in Car Body Manufacturing," *Journal of Welding and Joining*, vol. 38, no. 1, pp. 8–23, Feb. 2020, doi: 10.5781/JWJ.2020.38.1.1.
2. J. Kaur, V. Mangla, J. Singh, S. Kumar, and N. Srivastava, "Cladding of Stainless Steel (SS304) on Aluminium Alloy (AA1100) by Explosive Welding," *Materials Today: Proceedings*, vol. 5, no. 9, pp. 19136–19139, Jan. 2018, doi: 10.1016/J.MATPR.2018.06.267.

3. K. Raghukandan, "Analysis of the explosive cladding of cu-low carbon steel plates," *Journal of Materials Processing Technology*, vol. 139, no. 1-3 SPEC, pp. 573–577, Aug. 2003, doi: 10.1016/S0924-0136(03)00539-9.
4. F. Findik, "Recent developments in explosive welding," *Materials & Design*, vol. 32, no. 3, pp. 1081–1093, Mar. 2011, doi: 10.1016/J.MATDES.2010.10.017.
5. M. Acarer, B. Gülenç, and F. Findik, "Investigation of explosive welding parameters and their effects on microhardness and shear strength," *Materials and Design*, vol. 24, no. 8, pp. 659–664, 2003, doi: 10.1016/S0261-3069(03)00066-9.
6. G. H. S. F. L. Carvalho, I. Galvão, R. Mendes, R. M. Leal, and A. Loureiro, "Explosive welding of aluminium to stainless steel," *Journal of Materials Processing Technology*, vol. 262, pp. 340–349, Dec. 2018, doi: 10.1016/J.JMATPROTEC.2018.06.042.
7. M. Acarer and B. Demir, "An investigation of mechanical and metallurgical properties of explosive welded aluminum–dual phase steel," *Materials Letters*, vol. 62, no. 25, pp. 4158–4160, Sep. 2008, doi: 10.1016/J.MATLET.2008.05.060.
8. K. B. Ali, B. Demir, H. Gürün, and M. Acarer, "Influence of Punch Shapes on Forces and Part Quality in the Punching of Explosively Welded DP600, AA1100, and DP600-AA1100 Composite Plates," *Transactions of FAMENA*, vol. 46, no. 2, pp. 58–68, 2022, Accessed: Jul. 13, 2022. [Online]. Available: https://hrcak.srce.hr/en/clanak/406191
9. I. A. Bataev *et al.*, "Explosively welded multilayer Ni–Al composites," *Materials and Design*, vol. 88, pp. 1082–1087, Dec. 2015, doi: 10.1016/J.MATDES.2015.09.103.
10. M. Acarer, B. Demir, B. Dikici, and E. Salur, "Microstructure, mechanical properties, and corrosion resistance of an explosively welded Mg–Al composite," *Journal of Magnesium and Alloys*, 2021, doi: 10.1016/j.jma.2021.08.009.
11. B. Demir and M. Erdoğan, "The hardenability of austenite with different alloy content and dispersion in dual-phase steels," *Journal of Materials Processing Technology*, vol. 208, no. 1–3, pp. 75–84, Nov. 2008, doi: 10.1016/J.JMATPROTEC.2007.12.094.
12. B. Demir and M. Erdogan, "Tensile Properties Of The Hardenable Dual Phase Steel With Different Martensite Dispersion," *JESTECH*, vol. 15, no. 1, pp. 13–19, 2012.
13. M. D. Taylor, E. de Moor, J. G. Speer, and D. K. Matlock, "Effects of Constituent Hardness on Formability of Dual Phase Steels," *steel research international*, p. 2100281, 2021, doi: 10.1002/SRIN.202100281.
14. S. H. Choi, E. Y. Kim, W. Woo, S. H. Han, and J. H. Kwak, "The effect of crystallographic orientationon the micromechanical deformation and failure behaviors of DP980 steel during uniaxial tension," *International Journal of Plasticity*, vol. 45, pp. 85–102, 2013, doi: 10.1016/j.ijplas.2012.11.013.
15. Y. Li, R. Song, L. Jiang, and Z. Zhao, "Strength response of 1200 MPa grade martensite-ferrite dual-phase steel under high strain rates," *Scripta Materialia*, vol. 164, pp. 21–24, Apr. 2019, doi: 10.1016/J.SCRIPTAMAT.2019.01.031.

16. S. Y. Luo, "Studies on the wear conditions and the sheared edges in punching," *Wear*, vol. 208, no. 1–2, pp. 81–90, Jul. 1997, doi: 10.1016/s0043-1648(96)07439-x.
17. N. Hatanaka, K. Yamaguchi, N. Takakura, and T. Iizuka, "Simulation of sheared edge formation process in blanking of sheet metals," *J Mater Process Technol*, vol. 140, no. 1–3, pp. 628–634, Sep. 2003, doi: 10.1016/s0924-0136(03)00803-3.
18. M. Murakawa *et al.*, "Precision piercing and blanking of ultrahigh-strength steel sheets," *Procedia Engineering*, vol. 81, pp. 1114–1120, 2014, doi: 10.1016/j.proeng.2014.10.219.
19. Z. Tekiner, M. Nalbant, and H. Gürün, "An experimental study for the effect of different clearances on burr, smooth-sheared and blanking force on aluminium sheet metal," *Mater Des*, vol. 27, no. 10, pp. 1134–1138, 2006, doi: 10.1016/j.matdes.2005.03.013.
20. X. Wu, H. Bahmanpour, and K. Schmid, "Characterization of mechanically sheared edges of dual phase steels," *J Mater Process Technol*, vol. 212, no. 6, pp. 1209–1224, Jun. 2012, doi: 10.1016/j.jmatprotec.2012.01.006.
21. R. Hambli, "Design of experiment based analysis for sheet metal blanking processes optimization," *Int J Adv Manuf Technol*, vol. 19, no. 6, pp. 403–410, 2002, doi: 10.1007/s001700200041.
22. J. A. Soares, M. L. Gipiela, S. F. Lajarin, and P. V. P. Marcondes, "Study of the punch–die clearance influence on the sheared edge quality of thick sheets," *Int J Adv Manuf Technol*, vol. 65, no. 1–4, pp. 451–457, Mar. 2013, doi: 10.1007/s00170-012-4184-2.
23. C. Husson, J. P. M. Correia, L. Daridon, and S. Ahzi, "Finite elements simulations of thin copper sheets blanking: study of blanking parameters on sheared edge quality," *J Mater Process Technol*, vol. 199, no. 1–3, pp. 74–83, Apr. 2008, doi: 10.1016/j.jmatprotec.2007.08.034.
24. X. Wu, H. Bahmanpour, and K. Schmid, "Characterization of mechanically sheared edges of dual phase steels," *Journal of Materials Processing Tech.*, vol. 6, no. 212, pp. 1209–1224, Jun. 2012, doi: 10.1016/J.JMATPROTEC.2012.01.006.
25. J. Samei, L. Zhou, J. Kang, and D. S. Wilkinson, "Microstructural analysis of ductility and fracture in fine-grained and ultrafine-grained vanadium-added DP1300 steels," *International Journal of Plasticity*, 2018, doi: 10.1016/j.ijplas.2017.12.009.
26. E. Gustafsson, M. Oldenburg, and A. Jansson, "Experimental study on the effects of clearance and clamping in steel sheet metal shearing," *J Mater Process Technol*, vol. 229, pp. 172–180, Mar. 2016, doi: 10.1016/j.jmatprotec.2015.09.004.
27. "EXPERIMENTAL EXAMINATION OF EFFECTS OF PUNCH ANGLE AND CLEARANCE ON SHEARING FORCE AND ESTIMATION OF SHEARING FORCE USING FUZZY LOGIC", doi: 10.21278/TOF.40302.
28. N. A. Jaafar, A. B. Abdullah, and Z. Samad, "Effect of punching die angular clearance on punched hole quality of S275 mild steel sheet metal," *The International Journal of Advanced Manufacturing Technology 2018 101:5*, vol. 101, no. 5, pp. 1553–1563, Nov. 2018, doi: 10.1007/S00170-018-3040-4.
29. P. Chen *et al.*, "Investigation on the explosive welding of 1100 aluminum alloy and AZ31 magnesium alloy," *Journal of Materials Engineering and Performance*, vol. 25, no. 7, pp. 2635–2641, Jul. 2016, doi: 10.1007/s11665-016-2088-2.

30. K. Raghukandan, K. Hokamoto, and P. Manikandan, "Optimization of process parameters in explosive cladding of mild steel and aluminum," *Metals & Materials International*, vol. 10, no. 2, pp. 193–197, 2004, doi: 10.1007/bf03027325.
31. B. Gulenc, "Investigation of interface properties and weldability of aluminum and copper plates by explosive welding method," *Materials & Design*, vol. 29, no. 1, pp. 275–278, 2008, doi: 10.1016/j.matdes.2006.11.001.
32. I. A. Bataev *et al.*, "High cooling rates and metastable phases at the interfaces of explosively welded materials," *Acta Materialia*, vol. 135, pp. 277–289, Aug. 2017, doi: 10.1016/j.actamat.2017.06.038.
33. W. dos Santos and A. J. Organ, "Deformation in the ductile fracture processes examined by the visioplasticity method," *International Journal of Machine Tool Design and Research*, vol. 13, no. 4, pp. 217–232, Dec. 1973, doi: 10.1016/0020-7357(73)90001-2.
34. F. Gutknecht, F. Steinbach, T. Hammer, T. Clausmeyer, W. Volk, and A. E. Tekkaya, "Analysis of shear cutting of dual phase steel by application of an advanced damage model," *Procedia Structural Integrity*, vol. 2, pp. 1700–1707, Jan. 2016, doi: 10.1016/J.PROSTR.2016.06.215.
35. R. Hambli and F. Guerin, "Application of a neural network for optimum clearance prediction in sheet metal blanking processes," *Finite Elements in Analysis and Design*, vol. 39, no. 11, pp. 1039–1052, Aug. 2003, doi: 10.1016/S0168-874X(02)00155-5.
36. D. Brokken, W. A. M. Brekelmans, and F. P. T. Baaijens, "Numerical modelling of the metal blanking process," *Journal of Materials Processing Technology*, vol. 83, no. 1–3, pp. 192–199, Nov. 1998, doi: 10.1016/S0924-0136(98)00062-4.
37. P. W. Myint, S. Hagihara, T. Tanaka, S. Taketomi, and Y. Tadano, "Application of Finite Element Method to Analyze the Influences of Process Parameters on the Cut Surface in Fine Blanking Processes by Using Clearance-Dependent Critical Fracture Criteria," *Journal of Manufacturing and Materials Processing 2018, Vol. 2, Page 26*, vol. 2, no. 2, p. 26, Apr. 2018, doi: 10.3390/JMMP2020026.
38. S. Thipprakmas, M. Jin, K. Tomokazu, Y. Katsuhiro, and M. Murakawa, "Prediction of Fineblanked surface characteristics using the finite element method (FEM)," *Journal of Materials Processing Technology*, vol. 198, no. 1–3, pp. 391–398, Mar. 2008, doi: 10.1016/j.jmatprotec.2007.07.027.
39. S. Y. Luo, "Effect of the geometry and the surface treatment of punching tools on the tool life and wear conditions in the piercing of thick steel plate," *J Mater Process Technol*, vol. 88, no. 1, pp. 122–133, Apr. 1999, doi: 10.1016/s0924-0136(98)00375-6.
40. J. Mucha, "An experimental analysis of effects of various material tool's wear on burr during generator sheets blanking," *The International Journal of Advanced Manufacturing Technology 2010 50:5*, vol. 50, no. 5, pp. 495–507, Feb. 2010, doi: 10.1007/S00170-010-2554-1.
41. C. Pu *et al.*, "A Comprehensive Study of Hole Punching Force for AHSS," *SAE Technical Papers*, vol. 2018-April, Apr. 2018, doi: 10.4271/2018-01-0802.
42. B. S. Levy and C. J. van Tyne, "Review of the shearing process for sheet steels and its effect on sheared-edge stretching," *Journal of Materials Engineering and Performance*, vol. 21, no. 7, pp.

1205–1213, Jul. 2012, doi: 10.1007/S11665-011-9997-X.

43. O. Cavusoglu and H. Gürün, "The Relationship of Burr Height and Blanking Force with Clearance in the Blanking Process of AA5754 Aluminium Alloy," *Transactions of FAMENA*, vol. 41, no. 1, pp. 55–62, Apr. 2017, doi: 10.21278/TOF.41105.
44. J. H. Kim, E. J. Seo, M. H. Kwon, S. Kang, and B. C. de Cooman, "Effect of quenching temperature on stretch flangeability of a medium Mn steel processed by quenching and partitioning," *Materials Science and Engineering: A*, vol. 729, pp. 276–284, Jun. 2018, doi: 10.1016/J.MSEA.2018.05.083.
45. S. Chatterjee and H. K. D. H. Bhadeshia, "Stretch-flangeability of strong multiphase steels," *Materials Science and Technology*, vol. 23, no. 5, pp. 606–609, May 2007, doi: 10.1179/174328407X179511.
46. Y. Wu, J. Uusitalo, and A. J. DeArdo, "Investigation of effects of processing on stretch-flangeability of the ultra-high strength, vanadium-bearing dual-phase steels," *Materials Science and Engineering: A*, vol. 797, p. 140094, Oct. 2020, doi: 10.1016/J.MSEA.2020.140094.

Tables

Table 1

Chemical compositions of the DP1200steel sheet (wt.-%)

Material	C	Si	Mn	P	Cr	Ni	Mo	Cu	Ti
DP1200	0.125	0.182	1.513	0.018	0.023	0.023	0.05	0.012	0.04

Table 2

Chemical compositions of the AA1100 aluminum sheet (wt.-%)

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

Table 3

Tensile test results of all samples

Group number	Materials	Proof Yield Stress (%0,2) MPa	UTS MPa	True stress MPa	Engineering strain (%)	True strain (%)
1	DP1200	1145	1375	1310	5	4
2	Al 1100	117	119	135	17.5	15
3	DP1200-AA1100 plate composite	450	667	6	5.7	4.6

Figures

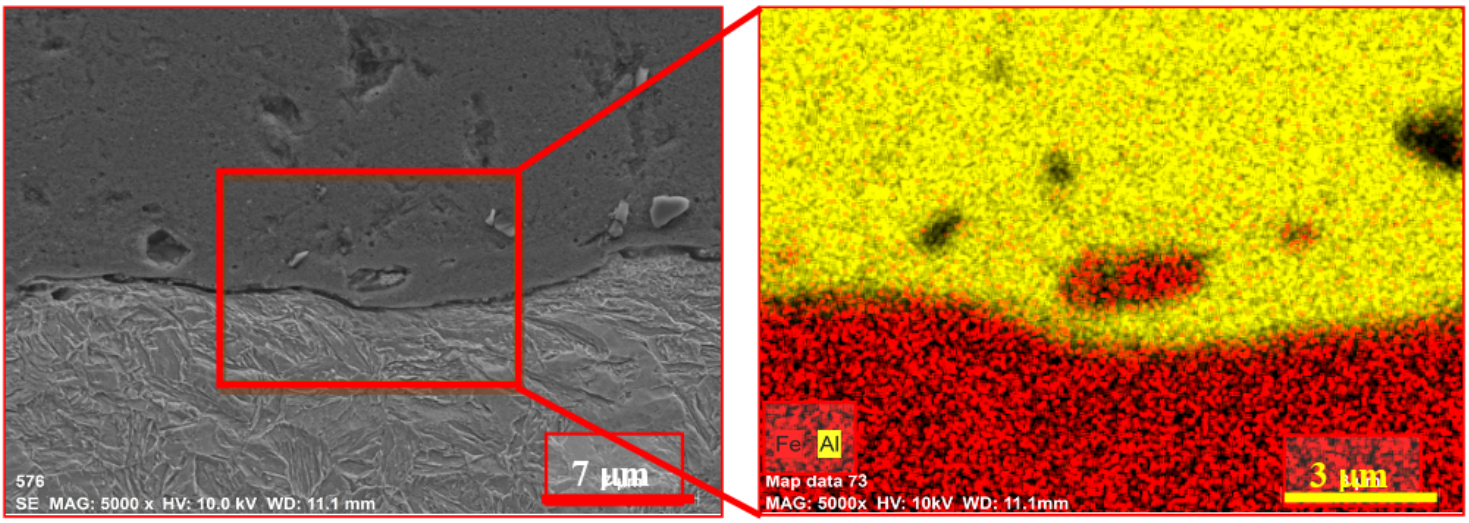


Figure 1

The SEM images EDS-map analysis of interface of explosive welded samples of the DP 1200-AA1100sheets

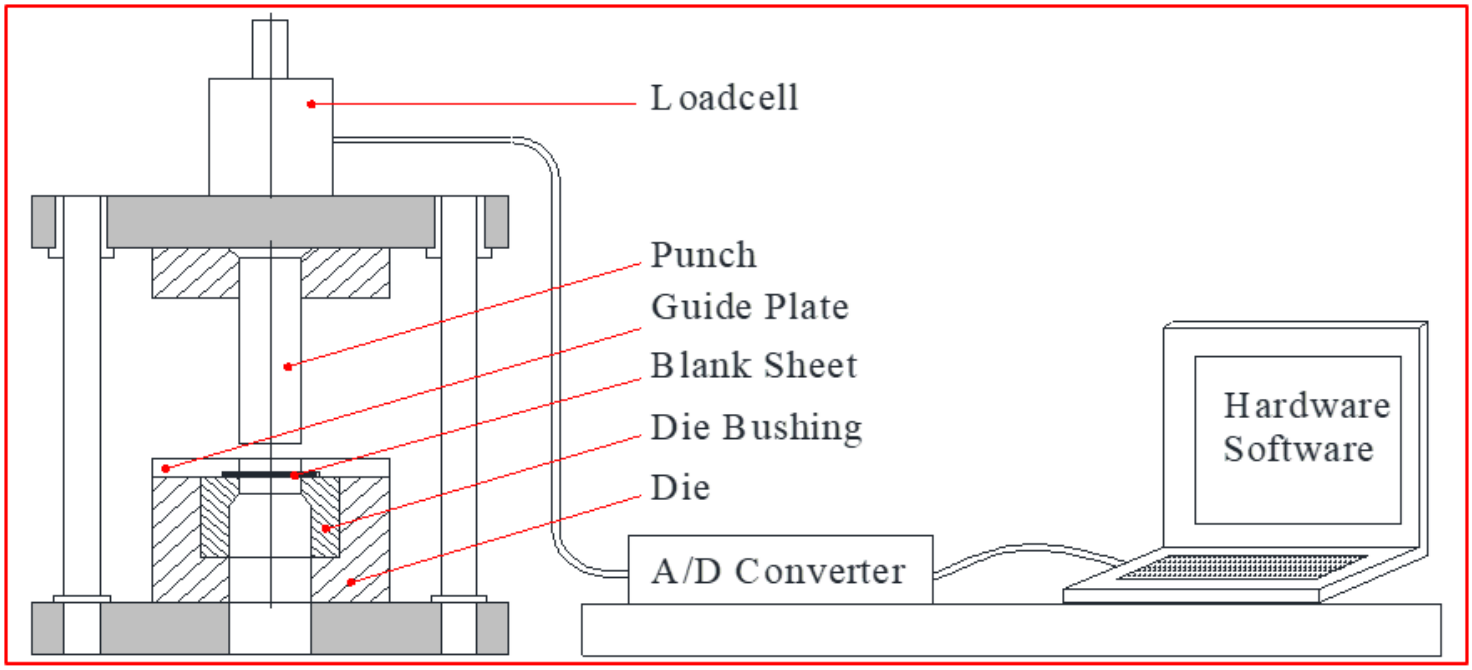


Figure 2

The experimental setup

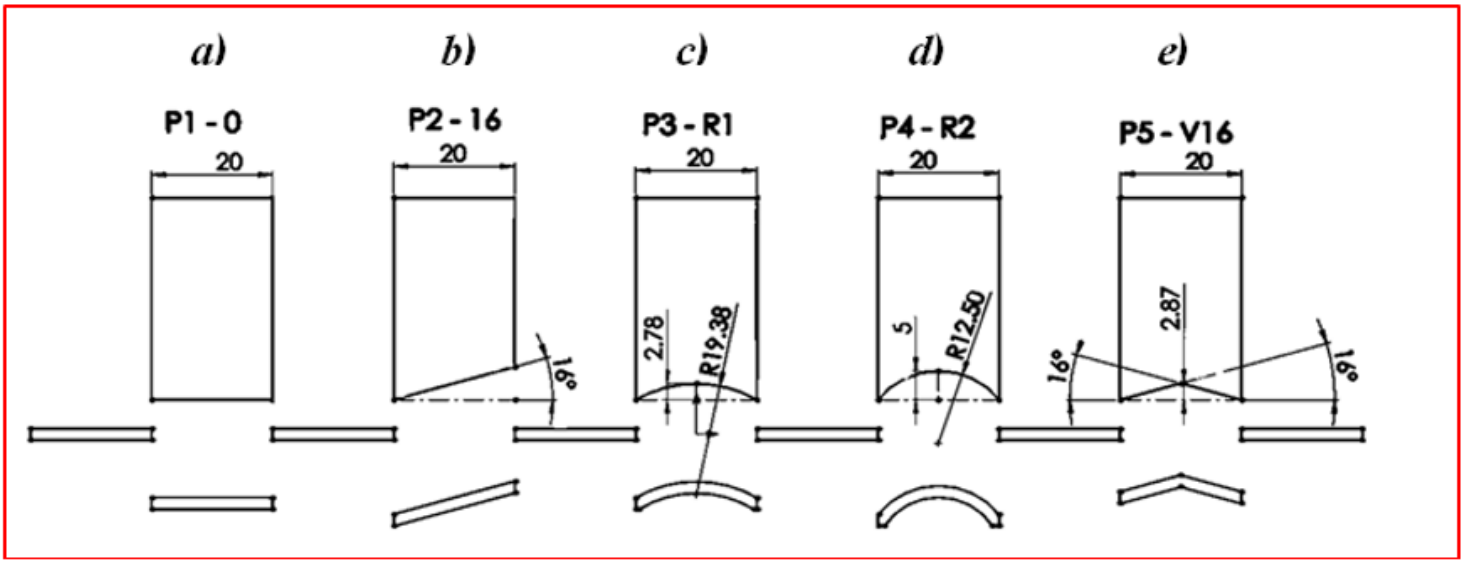


Figure 3

Used Punch types in cutting/punching (Five different Punch) a) P1 - 0, b) P-16 (angle:16^{o}), c)P-R1 (radius:19.4), d) P4 – R2 (radius: 12.5), e) P5 – V16 (angle-two side: 16^{o})

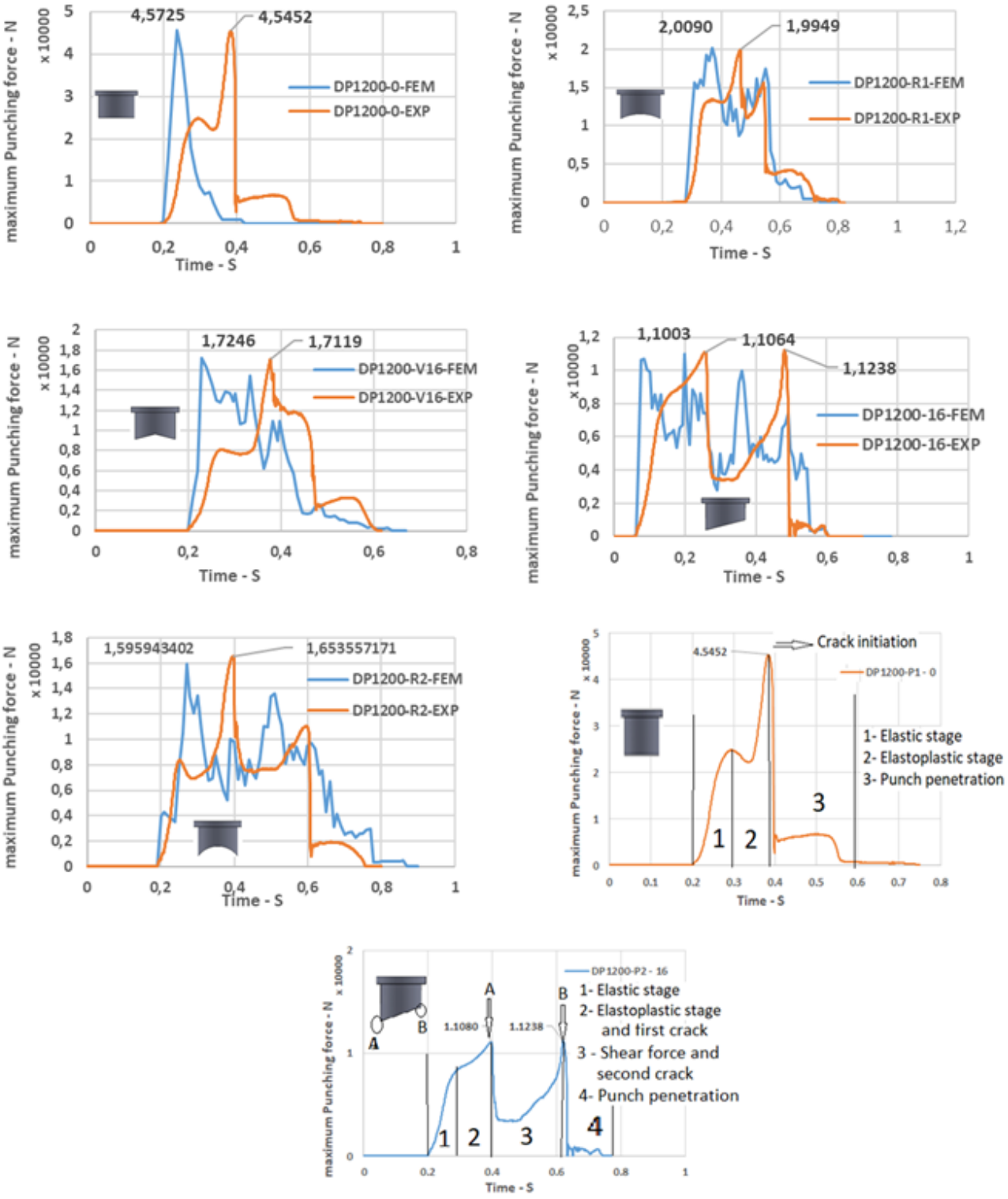

maximum Punching force - N
x 10000
Time - S
4,5725
4,5452
DP1200-0-FEM
DP1200-0-EXP
2,0090
1,9949
DP1200-R1-FEM
DP1200-R1-EXP
1,7246
1,7119
DP1200-V16-FEM
DP1200-V16-EXP
1,1003
1,1064
1,1238
DP1200-16-FEM
DP1200-16-EXP
1,595943402
1,653557171
DP1200-R2-FEM
DP1200-R2-EXP
Crack initiation
4.5452
DP1200-P1 - 0
1- Elastic stage
2- Elastoplastic stage
3- Punch penetration
DP1200-P2 - 16
1.1080
1.1238
1- Elastic stage
2- Elastoplastic stage
and first crack
3 - Shear force and
second crack
4- Punch penetration

Figure 4

Comparative force-time graphs obtained from FEM analyses and experiments using different punch shapes on DP1200 sheet

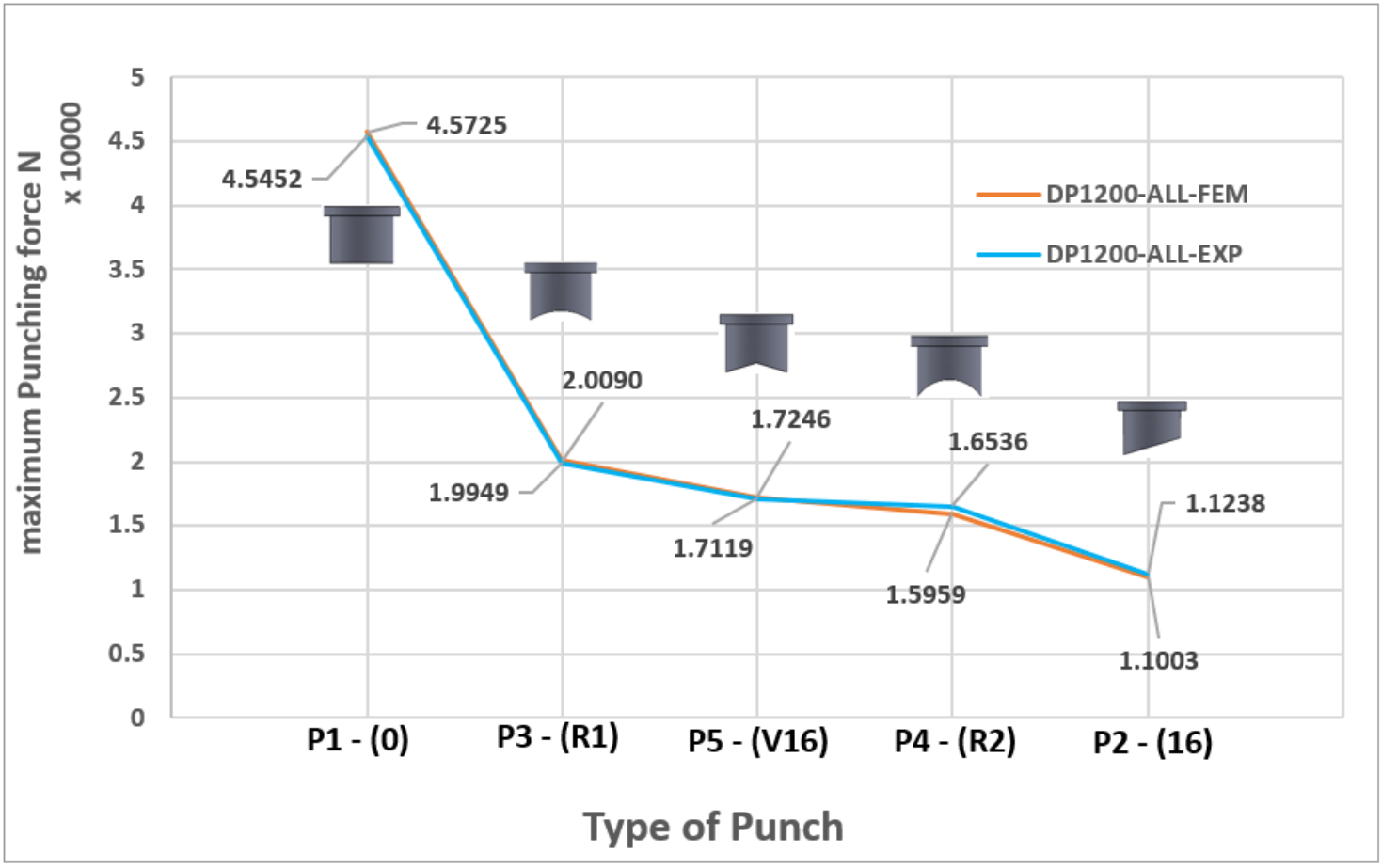


Figure 5

Comparison of the shearing forces obtained from experiments and FEM analyses for DP1200 sheet material

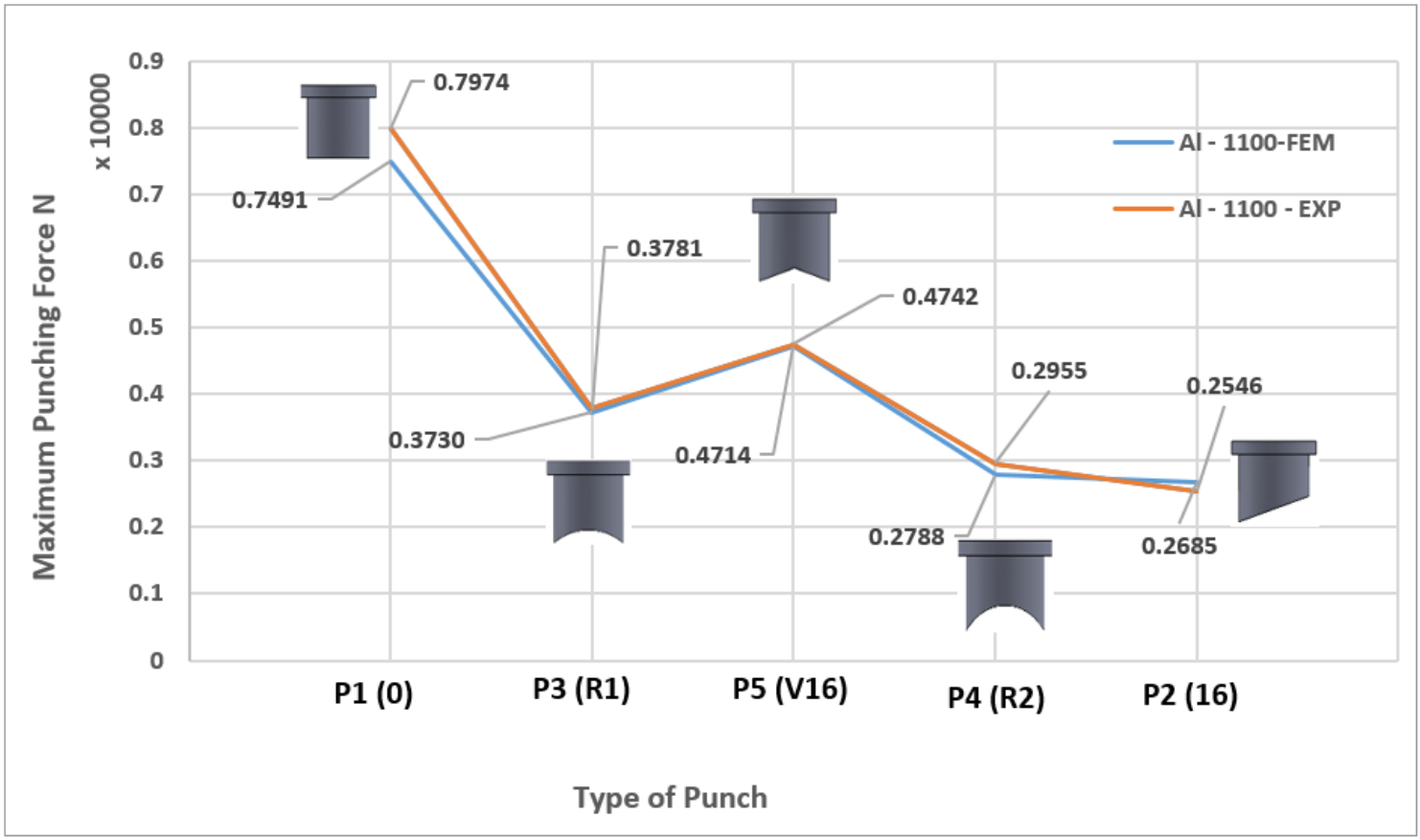


Figure 6

Comparison of the shearing forces obtained from experiments and analysis for Al-1100 sheet material

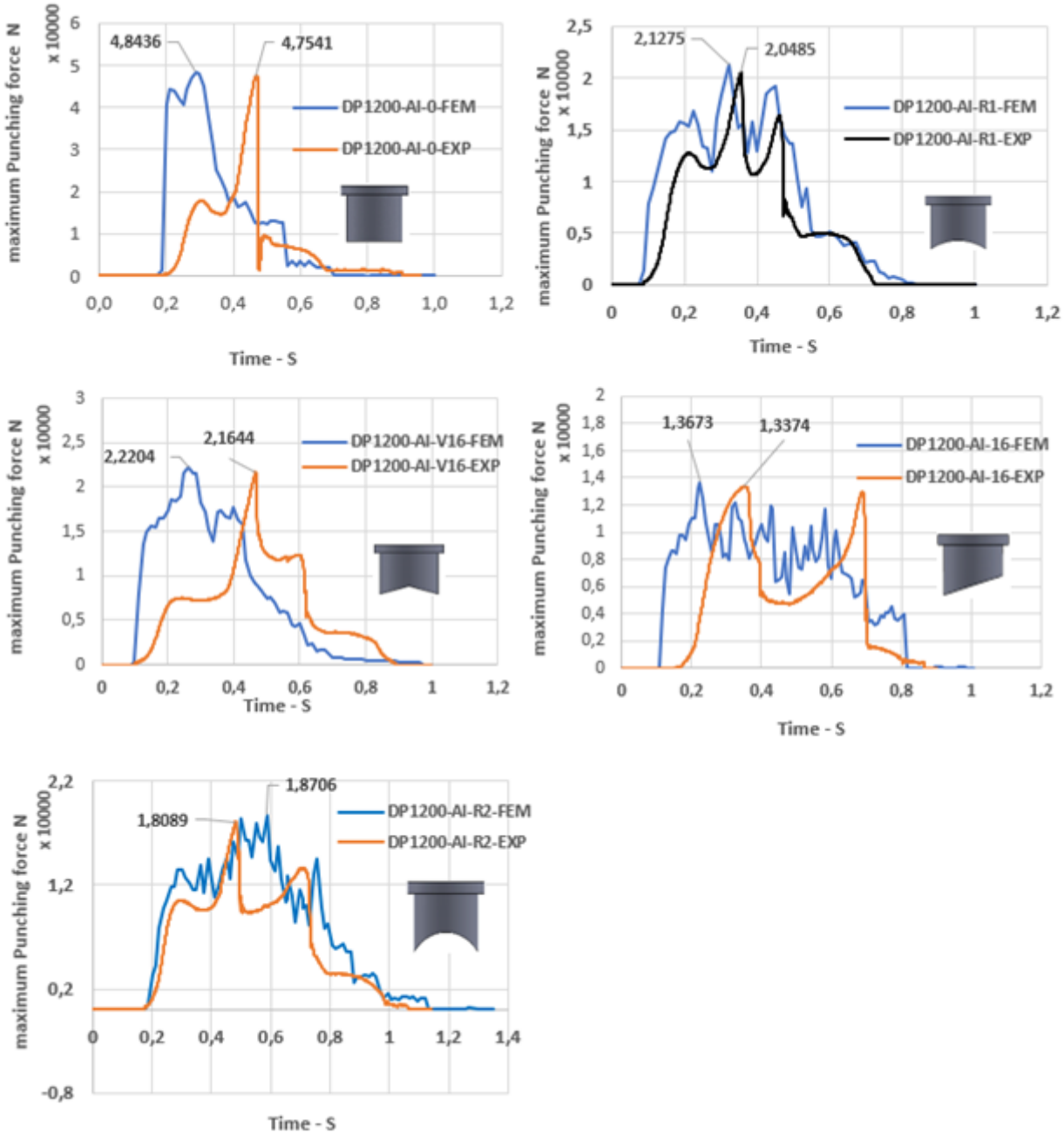


Figure 7

Comparison of the shearing forces obtained from experiments and FEM analyses for DP1200-AA1100 plate composite by using different punches shown with the picture on graphic

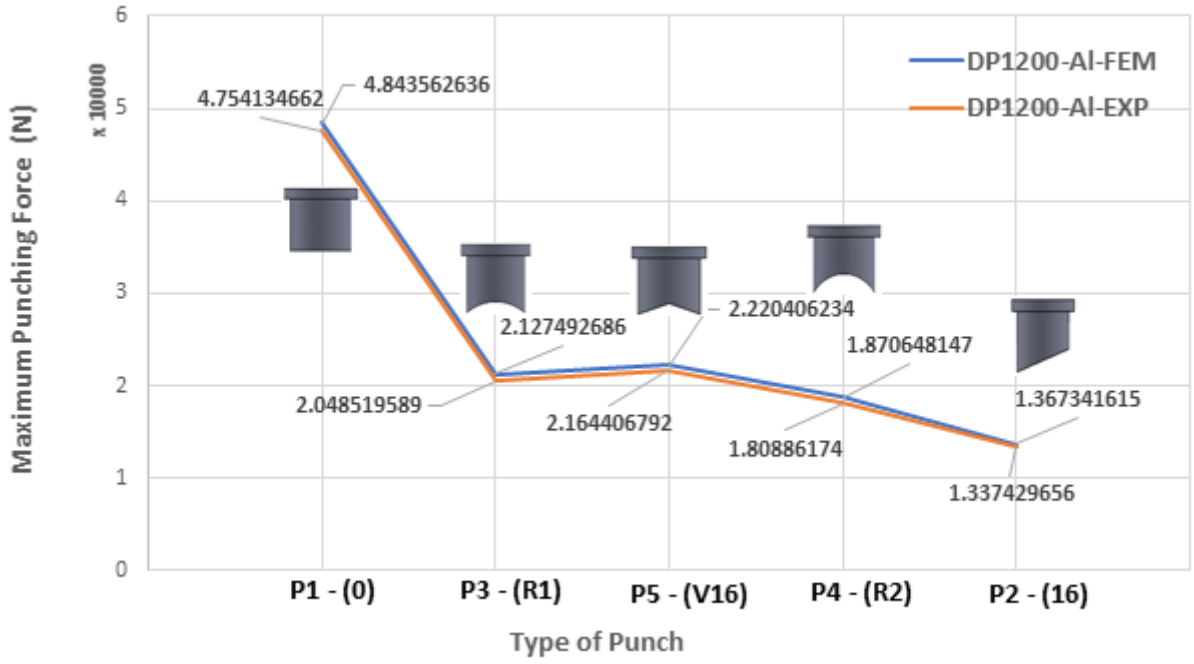


Figure 8

Comparison of the shearing forces obtained from experiments and analysis for DP1200-AA1100 explosive welded sheet material

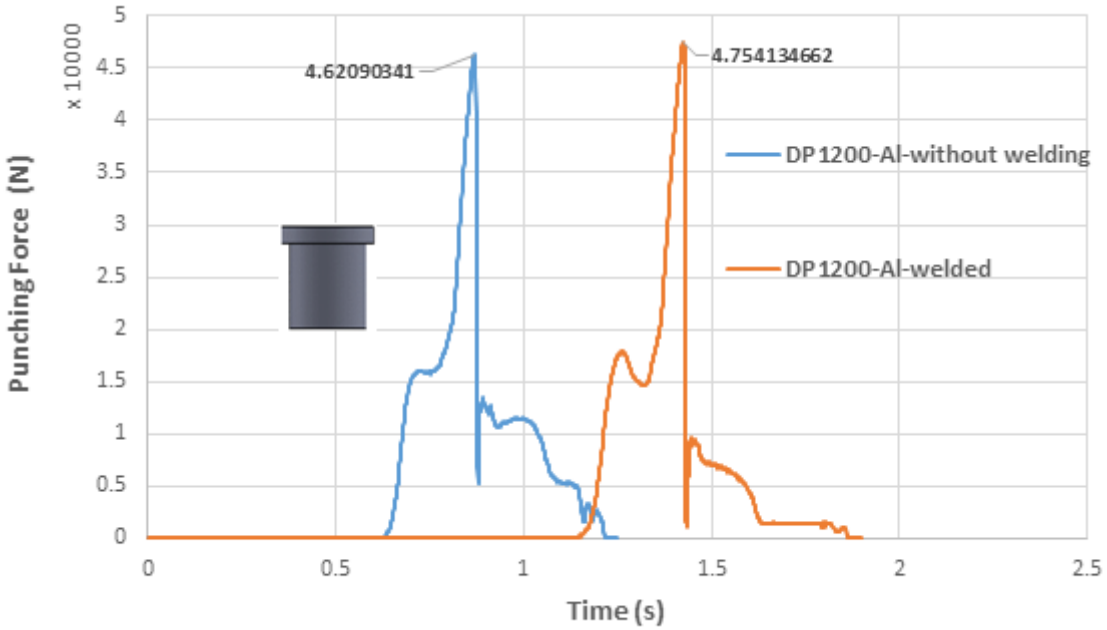


Figure 9

The comparison of forces vs time results of the experimental and FEM studies of Piercing

of the DP1200 – AA1100pairs (welded by explosive and without welding)

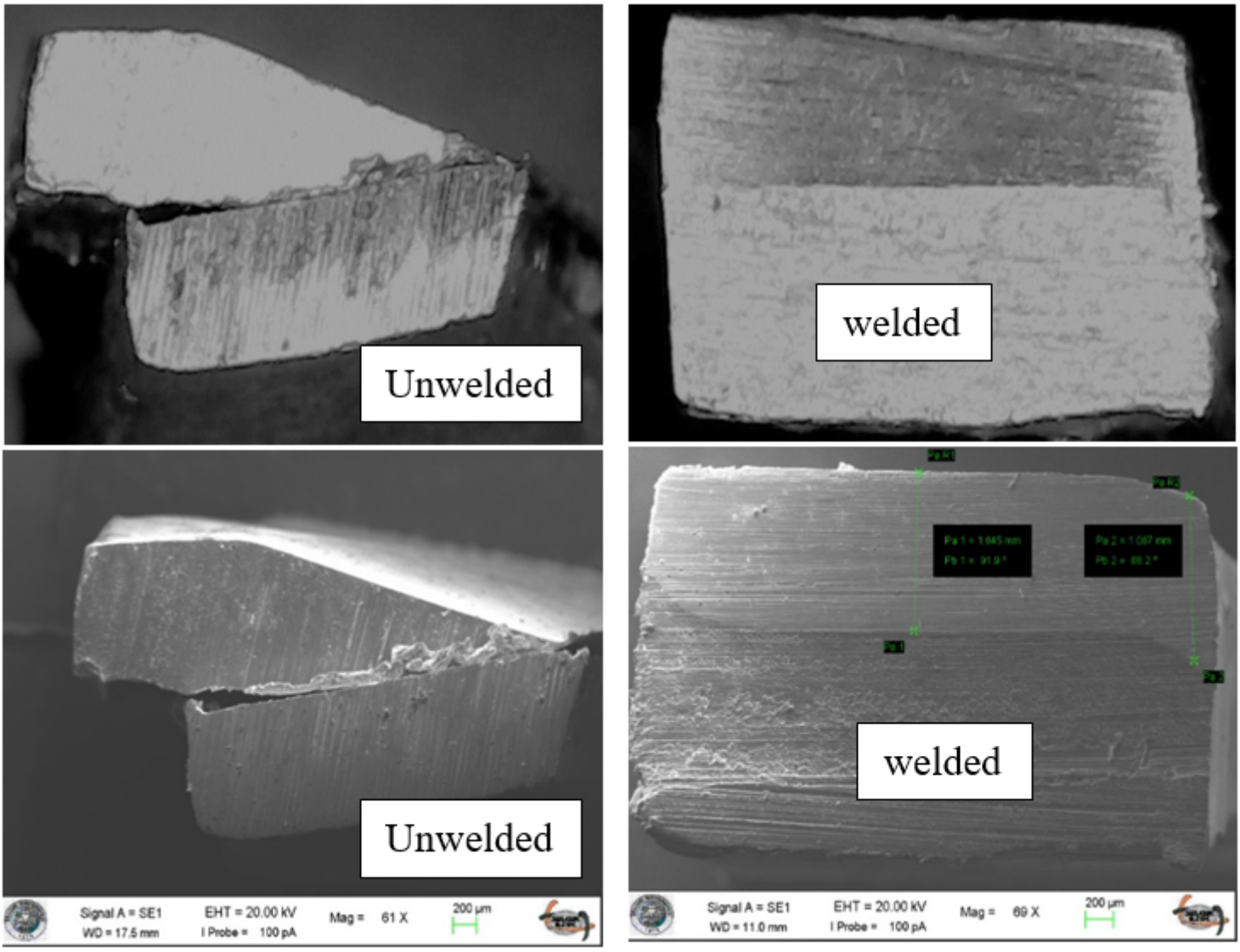


Figure 10

Pierce Sheared surface' images of the DP1200 – AA1100pairs (welded by explosive and without welding)

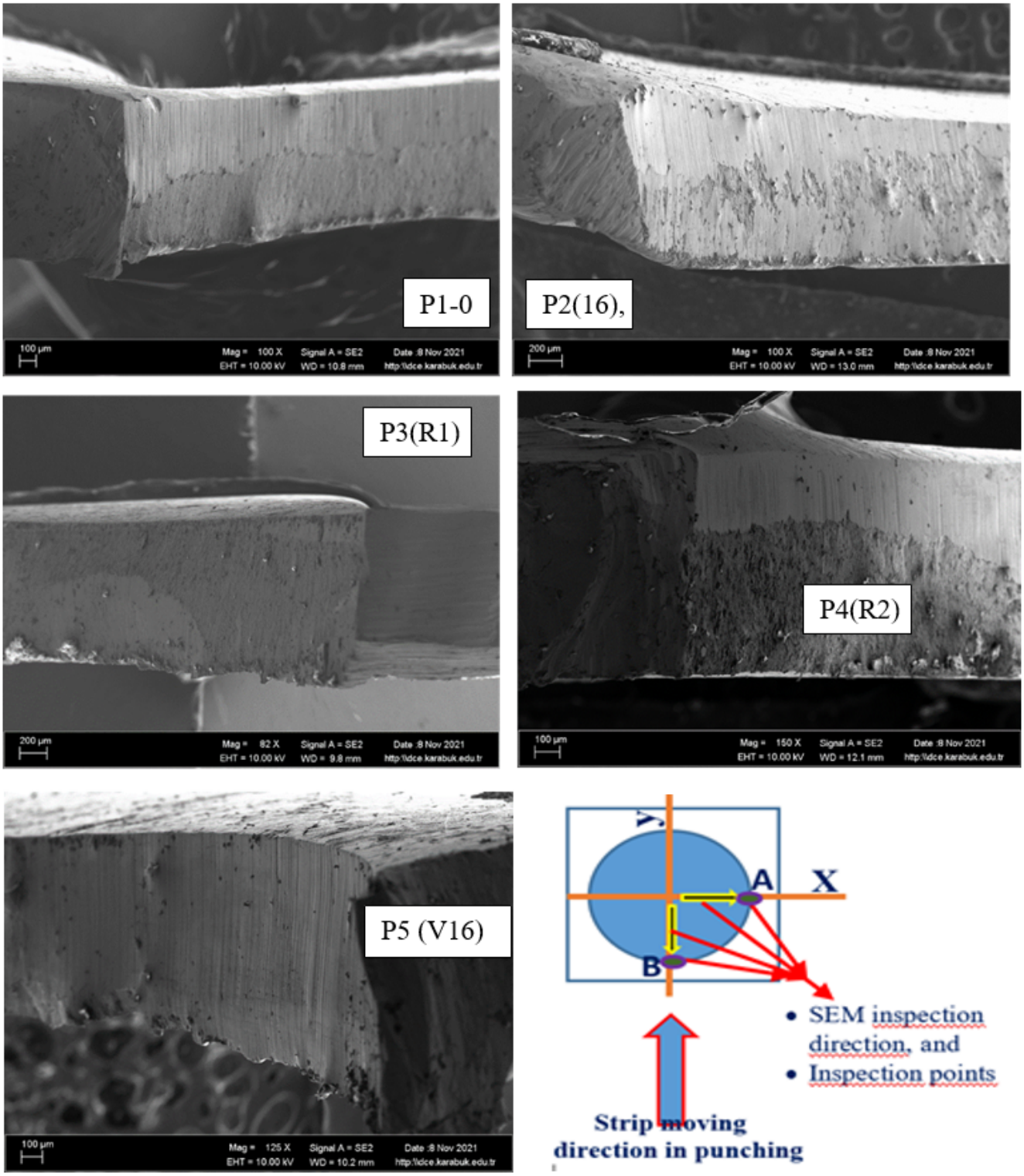


Figure 11

SEM-images cutting cross surface of the DP 1200 plate composite samples

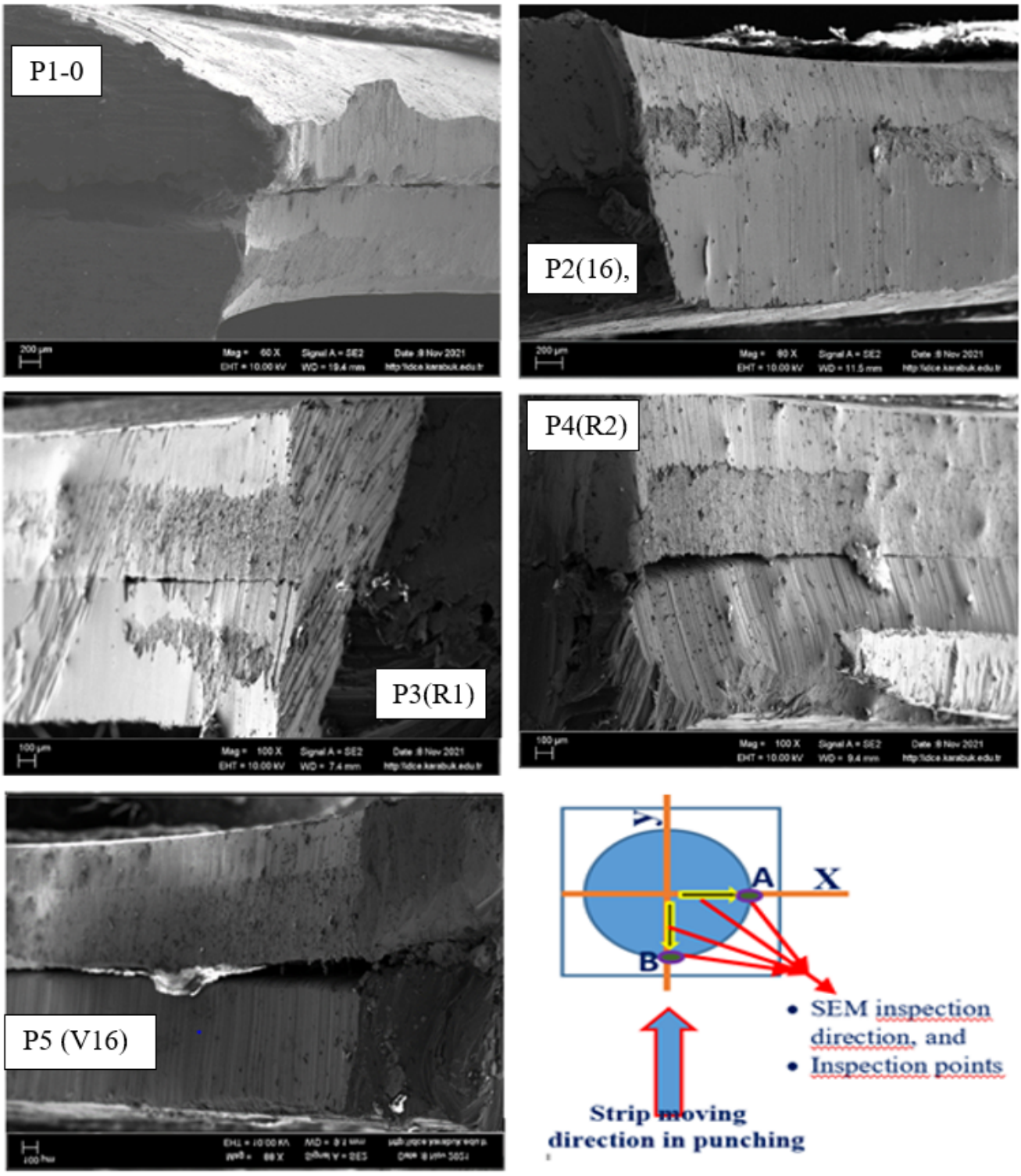


Figure 12

SEM-images cutting cross surface of the DP1200-AA1100plate composite samples

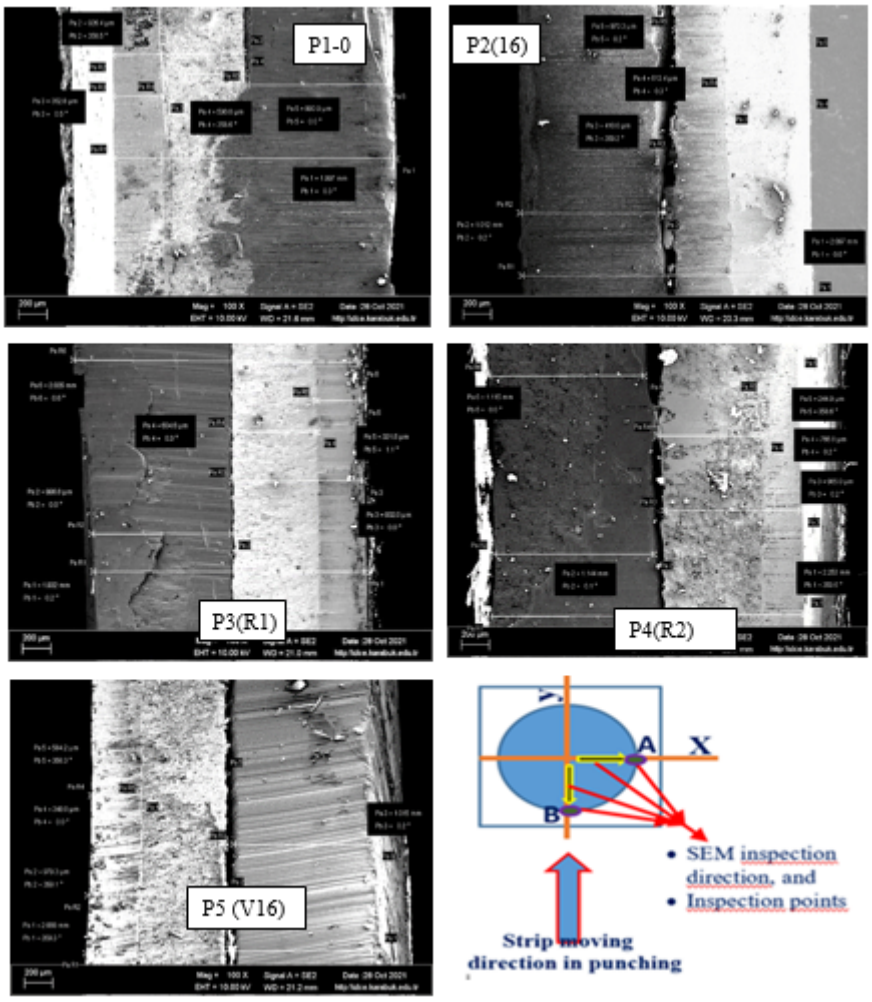


Figure 13

Measurements of sheared surface of samples