IJMF, Iranian Journal of Materials Forming, Vol. 5, No. 1, pp 1-18
Printed in The Islamic Republic of Iran, 2018

Simulation and Investigation of Mechanical and Geometrical Properties of St/CP-Titanium Bimetal Sheet during the Single Point Incremental Forming Process

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Abstract: In this study, the incremental forming of explosively welded low carbon steel-commercially pure titanium bilayer sheet has been experimentally and numerically investigated. For this purpose, at first a finite element based analysis was proposed to predict the forming force and thickness distribution to form this material by such process, which showed good agreement with the experimental results. Then, to investigate the effect of vertical step down (ΔZ) parameter on the properties of the workpiece, mechanical tests and microstructural studies were performed on the formed specimens. The results showed that by increasing the vertical step down (ΔZ), hardness and tensile properties of the specimens increased but the thickness reduction in the wall of the pyramidal specimens increased and also the surface quality decreased. In addition, microstructural studies showed that by increasing the vertical step down from 0.1 to 0.3, the grain structure transformed from an equiaxed state to a fibrous state and led to the formation of texture in the microstructure, to which mechanical properties improvements can be attributed. Therefore, if the surface quality of the inside wall of the specimen is not important, with an increase in the amount of ΔZ besides reducing the process time, the mechanical properties of the specimen will be improved.

Keywords: Incremental Forming, Explosive-welded, Bimetals, low carbon steel/CP Titanium.

1. Introduction

In recent years, a new class of sheet forming processes has been developed to reduce the time and cost of production for pre-production or rapid prototyping of the piece. One of these processes is the incremental sheet forming process (ISF) or forming without the mold, in which the sheet metal is deformed gradually [1]. This process was invented in 1967, and the researches have continued so far. In this process a simple ball shaped tool moves along a predefined path to impose local plastic deformation on the sheet. The process is very flexible and can be carried out on a computer numerical control (CNC) milling machine [2, 3]. The name “Incremental Sheet Forming (ISF)” is used for a wide variety of processes all of which are characterized by this fact that at any time only a small part of the product is formed, and that the area of local deformation moves around the entire product [4] (Fig. 1). Typically, two basic methods for the incremental forming process are known. They are called the negative incremental forming and the positive incremental forming [5].

In recent years, many studies have been conducted on this process. Kim et al. [6] investigated the effects of ISF process parameters such as tool shape, tool size, feed rate, friction at the interface between the tool and sheet surface, and the plane anisotropy on sheet formability numerically and experimentally. The results showed that formability was improved by reducing horizontal feed rate and reducing the friction between the tool and sheet surface. Jackson et al. [7] studied the deformation mechanism of the single point incremental forming (SPIF) and two points incremental forming (TPIF) processes

Received by the editors July 10, 2017; Revised October 18, 2017 and Accepted October 22, 2017.
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experimentally using copper sheets. In this regard, strain distribution along the sheet thickness was measured for both methods of the process and then compared them with each other.

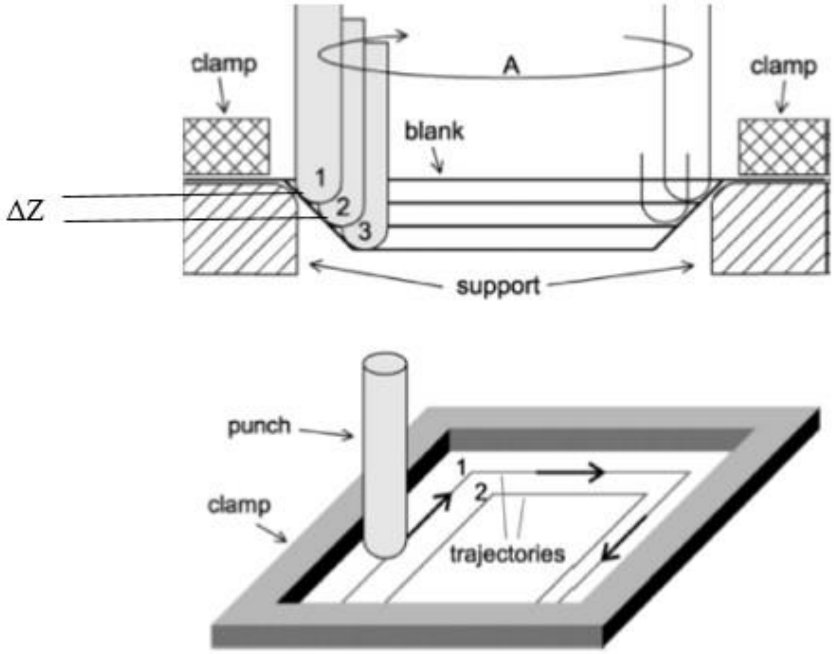


Fig. 1. Schematic illustration of the principles of ISF process [4].

The measurements indicated that the deformation mechanisms in both methods included stretching and shearing in the plane perpendicular to the tool direction. Yan Li et al. [8] presented an analytical model to predict the tangential force in the ISF process, and the forces were empirically recorded during the formation of a cone with variable wall angles. Henrard et al. [9] studied the precision of finite element simulation in predicting tool force during the ISF process. The results showed that three factors affected the prediction of forces: the finite element type, the type of material hardening behavior and the method of determining the parameters of the selected behaviors. Hussain et al. [10] introduced a new parameter called blank stiffness as a criterion for formability in the ISF process. In this criterion, various plates were used with a square-shaped hole and different lengths in the center as a backup sheet for blank. Zemin Fu et al. [11] presented an iterative algorithm for correcting tool path of the ISF process based on Fast Fourier and wavelet transforms. This algorithm was used to reduce the existing error between the manufactured part shape and the designed target shape due to the spring-back of this part after forming. Hussaina et al. [12] examined the effects of different materials properties on the formability in the ISF process. The result of this study was to create a new index for formability in this process and an empirical model was proposed to describe the above-mentioned new index. Ambrogio et al. [13] examined the influence of increasing the horizontal feed rate on the ISF process for titanium grades 2 and 5. Gatea et al. [14] studied the ISF processes taking into account capabilities and limitations of this process. In this research, the effects of process parameters on formability, deformation, failure mechanism, spring-back, accuracy and roughness of the surface were studied and suggestions were presented to improve the process. Neto et al. [15] provided a comprehensive numerical model for analyzing the stress and strain states in the ISF process in the vicinity of the contact area of the tool and sheet surface. Yanle Li et al. [16] provided further understanding of the deformation mechanics of the ISF process and clarified the deformation mechanism in a typical cone-forming process through finite element (FE) simulation approach. Comprehensive FE models with fine solid elements were used in particular, allowing the investigation of different deformation modes including stretching, bending and shearing. The incremental forming process on Ti-6Al-4V sheet using electrical energy was studied by Honarpisheh et al. [17] numerically and experimentally. In this study, the effects of process parameters such as wall angle, vertical feed rate and tool diameter on formability, forming force and thickness distribution of the specimens were examined. Amini et al. [18, 19] studied the incremental forming process of AA 1050 aluminum sheets using ultrasonic vibrations numerically and experimentally. In the aforementioned study, the incremental forming processes with and without ultrasonic vibrations were compared with each other. Formisano et al. [20] compared negative incremental forming and positive incremental forming processes by two finite elements (FEM) and experimental methods. To conduct the experimental tests, conical frusta from aluminum sheets were manufactured using both methods. Then, both methods were simulated using LS-DYNA software, which showed good agreement between experimental and numerical results. Moreover, the results showed that the positive incremental forming method had more formability and more geometric accuracy. Gamadi et al [21] investigated the formability of a cold-bonded Cu/Steel bilayer sheet in the single-point incremental forming process. To reduce the forming force, the sheet was placed under annealing operation on a wide range of temperature and time. The results showed that sheet formability increased with annealing temperature, but the annealing time did not have much effect on the formability. Titanium and titanium alloys are principally applied as materials for chemical reactors and heat exchangers due to their excellent capability of corrosion resistance. However, the cost of titanium and its alloys is very high, especially for structural parts. Partly replacing titanium and its alloys with steel to meet the strength requirements can greatly reduce the production cost. Ti / steel clad plate, on the one hand, makes full use of the capability of corrosion resistance of titanium and high strength of steel; on the other hand, reduces the material cost. Thus it has been widely used in chemical industry, seawater desalination, and flue gas desulfurization (FGD) in power plant [22]. In many applications, particularly for large pressure vessels designed for high temperatures and pressures, titanium or zirconium clad steel construction can be very economical compared to solid constructions. Titanium cost is so high that clad construction is the only economic alternative for most process equipment [23]. Various methods are used to join these dissimilar materials such as roll bonding, diffusion welding and explosive welding. Explosive welding or bonding is a solid-state welding process that is used for metallurgical joining of dissimilar metals [24, 25]. In this study, explosive welding method was used to bond commercial pure titanium with low carbon steel. Although many studies related to the ISF process have been done in recent years, no studies have been performed on the forming behavior of the multilayer sheets in this process. For this purpose, besides studying the forming behavior of multilayer sheets in such a process, this study presented a new algorithm for moving the tool on the sheet to simulate the process. Therefore, the overall aim of this study was to investigate the behavior of the deformation of low carbon steel /commercial pure titanium (St/CP-Ti) bilayer sheet in the incremental forming process. To do so, the afore-said process was simulated using finite element method (FEM) and was compared with the experimental results. Comparison between the numerical method and experimental results, despite demonstrating good agreement between them, predicted higher values in the numerical solution method than the experimental values. This implied that numerical solution could be used as a factor of safety in the prediction of the necessary force for industrial applications.

2. Materials and Methods

2.1. Materials

In this research, commercial pure titanium (CP Ti Grade 2) and low carbon steel sheets with dimensions of 1000mm×1000mm×1mm were connected to each other using explosive welding process. Chemical compositions of commercial pure titanium and low carbon steel sheets used in this research are given in Table 1. To eliminate the effects of texture caused by rolling process, both sheets were annealed.

Table 1. Chemical compositions of low carbon steel and commercial pure titanium.

Low Carbon Steel	C	Mn	Si	P	S	Fe
	0.09	0.32	0.073	0.019	0.012	Balance
Pure Titanium	C	N	Fe	O	H	Ti
	0.011	0.004	0.08	0.14	0.0026	Balance

2.2. Experimental procedure

To simulate the process using FEM analysis, it was necessary to determine the behavior of true stress-true strain in the plastic deformation region of each layer of the explosively welded bimetal sheet, as well as the co-efficiency of the friction between the tool and sheets. To determine the behavior of true stress-true strain, the uniaxial tensile test was performed for both steel and titanium sheets at ambient temperature using an Instron Testing Machine. Measuring the changes in the length of tensile specimens (ΔL) and in the force was carried out by an extensometer and the load cell in the range of 5000 (N) respectively. Specimens were elongated up to the failure point and then the true stress-true strain curves were obtained. To reduce the deviations in the results, three specimens from each sheet were tested. Tensile test specimens were extracted from the primary metal sheets using a wire cutting machine. Tensile test specimens and their dimensions are shown in Fig. 2. True stress-true strain curves of both low carbon steel sheet and commercial pure titanium sheet studied in this research are illustrated in Fig. 3. Furthermore, to determine the effect of the process variables (vertical step down, ΔZ) on the mechanical properties of the produced specimens, the micro-hardness and tensile tests were performed on the specimens. In this regard, tensile test specimens were extracted from the inside of the vertical wall of the pyramid piece using a wire-EDM machine (Fig. 4).

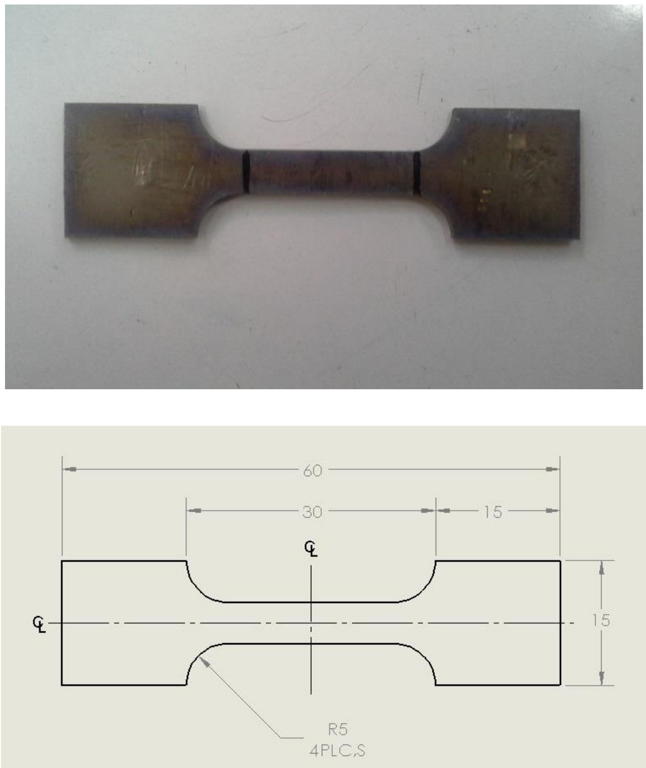


Fig. 2. Tensile test specimens and their dimensions (Dimensions are in millimeter).

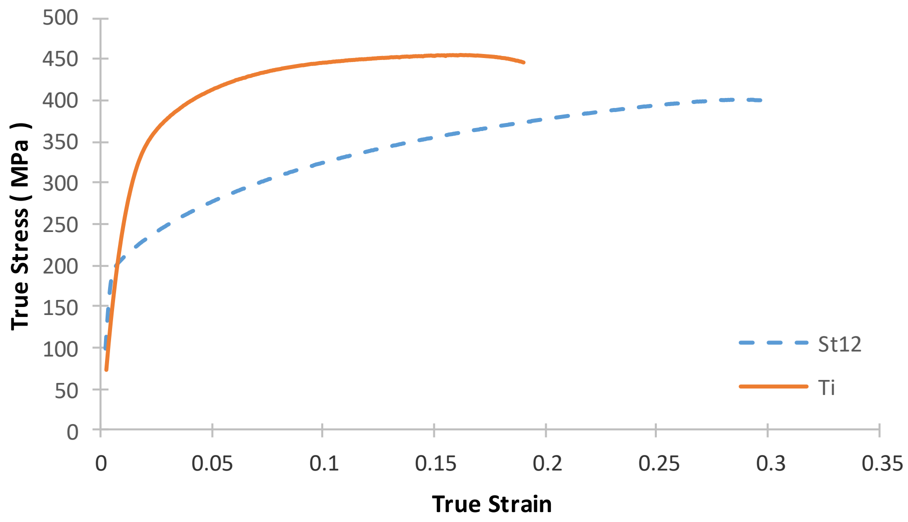


Fig. 3. True stress– true strain curve of low carbon steel (St12) and commercial pure titanium.

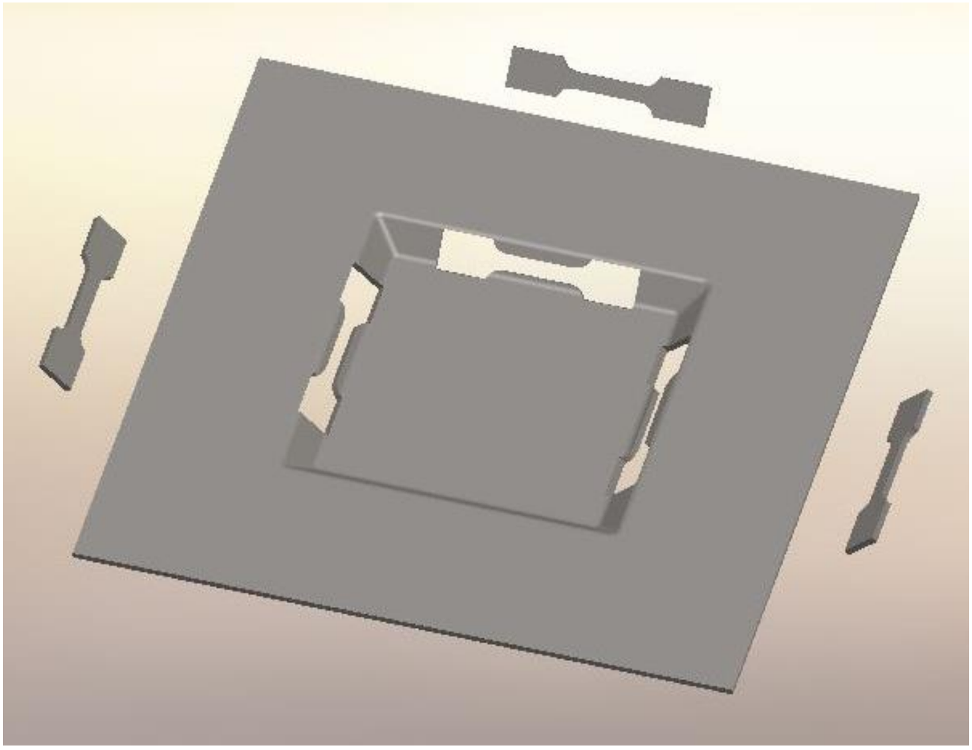


Fig. 4. Schematic illustration of the Extracted tensile test specimens from different positions of the pyramidal samples.

To investigate the effect of vertical step down, ΔZ on the process of deformation and the forming force, microstructural studies were performed on the produced specimens. For this purpose, the specimens were cut from the inner wall of the pyramid workpiece, where the deformation was created, using the wire cutting machine (wire-EDM), and then the metallographic test samples were prepared. After mounting the specimens, mechanical polishing was done to achieve flat and glossy surfaces. Then etching operations were performed in Nital etchant for steel layer, and finally the microstructures of deformed zones were observed and recorded using optical microscope (OM). In this regard, the average grain size was measured using image processing techniques. To ensure the repeatability of the results, three specimens and five random points on each of them were evaluated. Besides, to evaluate the surface quality in three vertical steps down, the scanning electron microscope (SEM) was used.

Incremental forming process was conducted by a triaxial vertical milling machine equipped with a numerical control system. The used setup is shown in Fig. 5 which consisted of a clamping plate, a backing plate including a square hole with 130 mm long, a bottom plate and finally two supports. To measure the forming force during the process, a dynamometer with KISTLER mark was used. All of the forces in X, Y and Z directions were obtained using a Dynoware software. To obtain data, the sampling rate was adjusted to 10 Hz. To analyze the data and then draw the graphs, the obtained data were exported to an excel file by Dynoware software. The initial blank size and its effective surface were 200 mm × 200 mm and 130 mm × 130 mm respectively and was fixed in the fixture so that no flow would happen in the forming area. The variable parameters during the test included the vertical step down (ΔZ) 0.1 and 0.2 mm. The arrangements of layers in the bilayer sheet were considered as the St-Ti modes. (St layer is in contact with the tool head). Horizontal feed rate of the tool during the process was considered about 700 mm/min constantly.

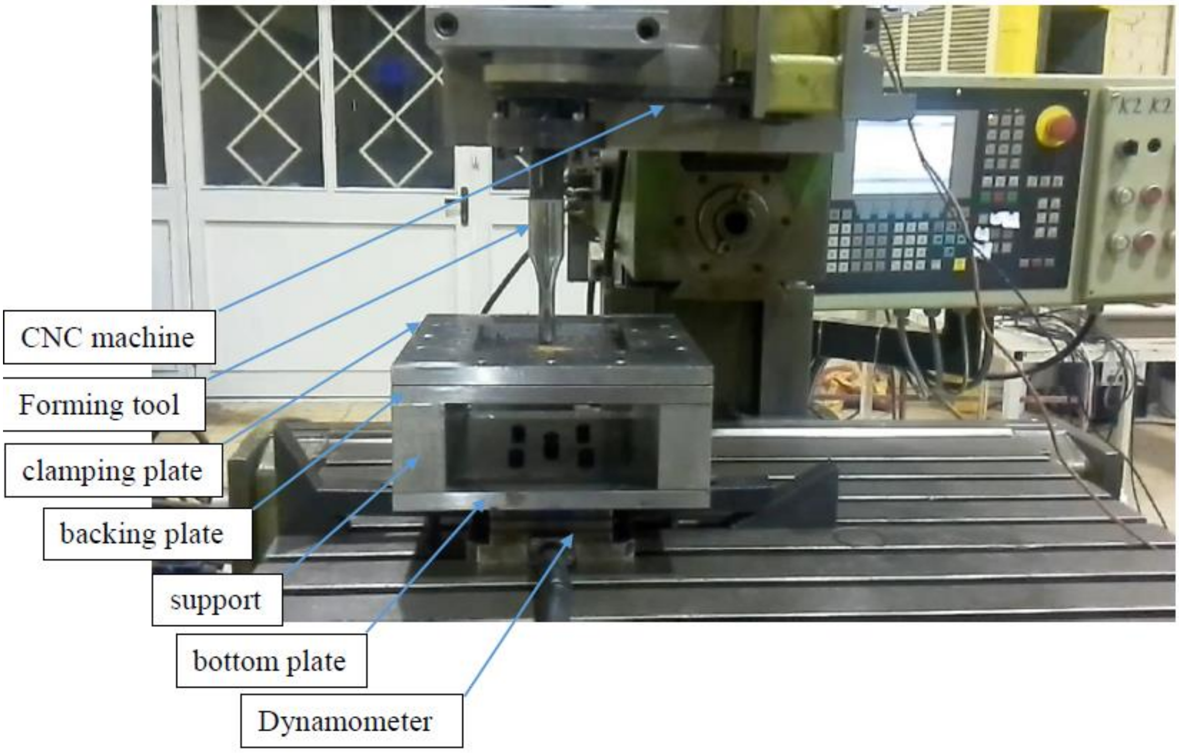


Fig. 5. SPIF experimental setup mounted on a CNC milling machine.

To perform experimental testing of the single point incremental forming process, a frustum shape (lopsided pyramid) was chosen. Specifications and geometrical parameters of such a shape are introduced in Table 3. The formation of pyramidal specimens is shown in the Fig. 6.

Table 3. Geometrical parameters of the pyramidal shape.

L_1 (mm)	L_2 (mm)	H (mm)	α (deg)
200	108	10	45

.

Fig. 6. Formation of a pyramidal specimen during the process.

3. Finite Element Simulation

In the present study, ABAQUS standard software was used to simulate the deformation process and predict the forming force. Due to the little thickness of the bimetal sheet compared to its length and width, the SR4 shell element was used to mesh the sheet. To simulate the bimetal sheet, one section was defined for each layer and the material properties of each sheet were attributed to each section. Then, both sections were attached to each other using a tie constraint. This was done in order to simulate the interface between two sheets. The blank size in the simulation was selected according to the size used in the practical experiment (200 mm x 200 mm). Moreover, the forming tool was modeled as a rigid body with a hemispherical head. A node was considered as a reference point on the tip of the tool and during the simulation process all of the forces were obtained at this point. To simulate the clamping effect of the plate clamped in the fixture, an Encastre constraint as a boundary condition was considered for the outer area of the plate. To describe the interaction between the tool and bimetal sheet, the surface to surface contact model was used. For defining the effect of friction, penalty method was applied and the behavior of the material was considered isotropic. Fig. 7 shows the assembly of the tool on the bilayer sheet for the simulation.

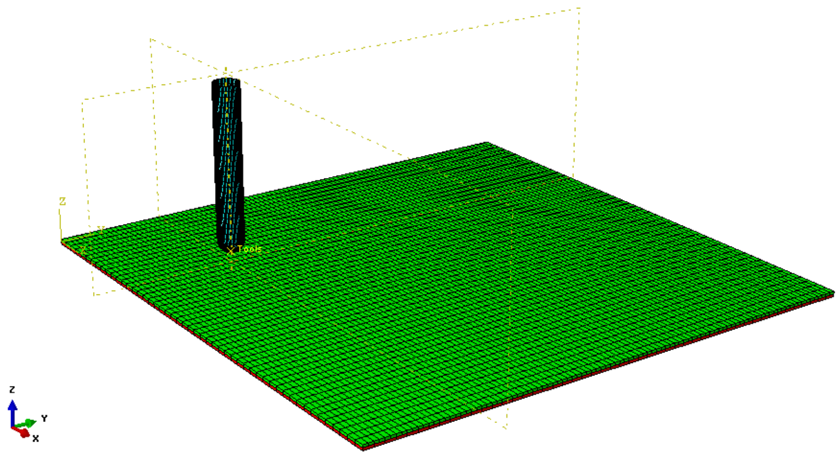


Fig. 7. Assembly of the tool on the bilayer sheet in ABAQUS environment.

Having a constant speed of the tool movement, supposedly, a time series of x, y and z coordinates of the tool head with programming between the dots near to it in a certain direction could be achieved. In this case, the tool moved in three directions x, y and z respectively with velocities defined as v_1, v_2 and v_3, which any of these velocities formed a time series as (t, x), (t, y) and (t, z) with programming in an excel environment obtained as boundary conditions of the forming tool in the load module from the ABAQUS software. Figure 8 indicates the velocity boundary conditions on the tip of the tool head. Figure 9 describes the algorithm for determining the velocity boundary condition of the tool as a function of the process time.

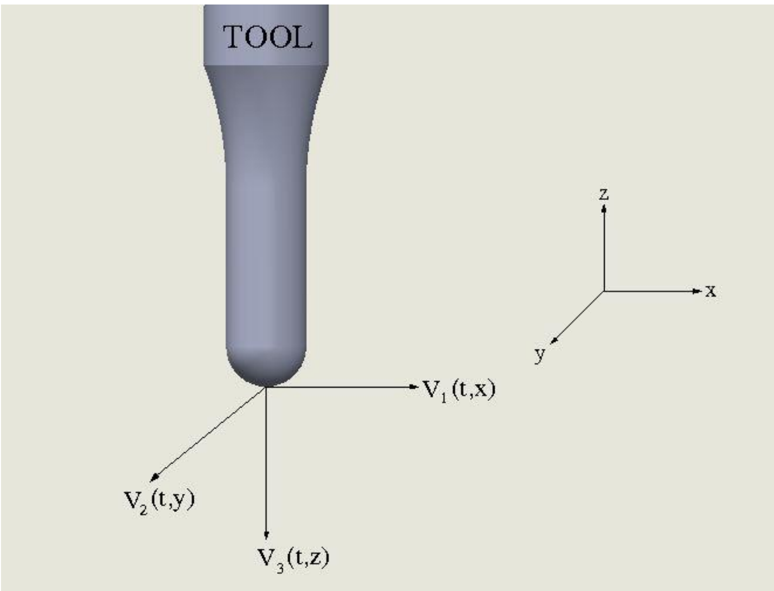


Fig. 8. Velocity boundary conditions on the tip of the tool head.

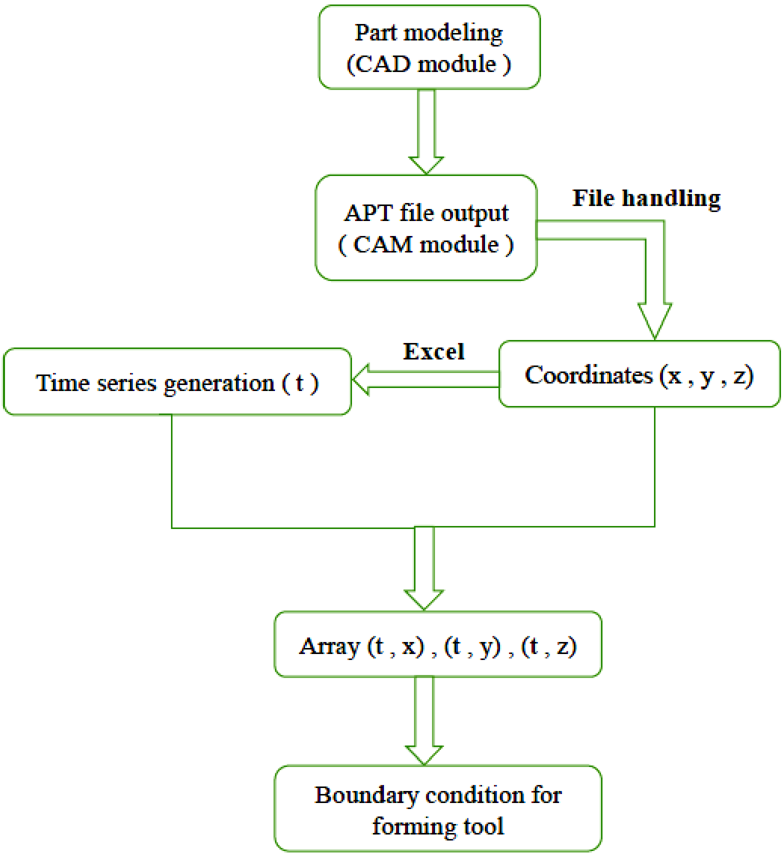


Fig. 9. Algorithm for determining the velocity boundary condition of the tool.

4. Results and Discussion

The truncated pyramid generated by the experimental method and simulated using ABAQUS software is shown in Fig. 10.

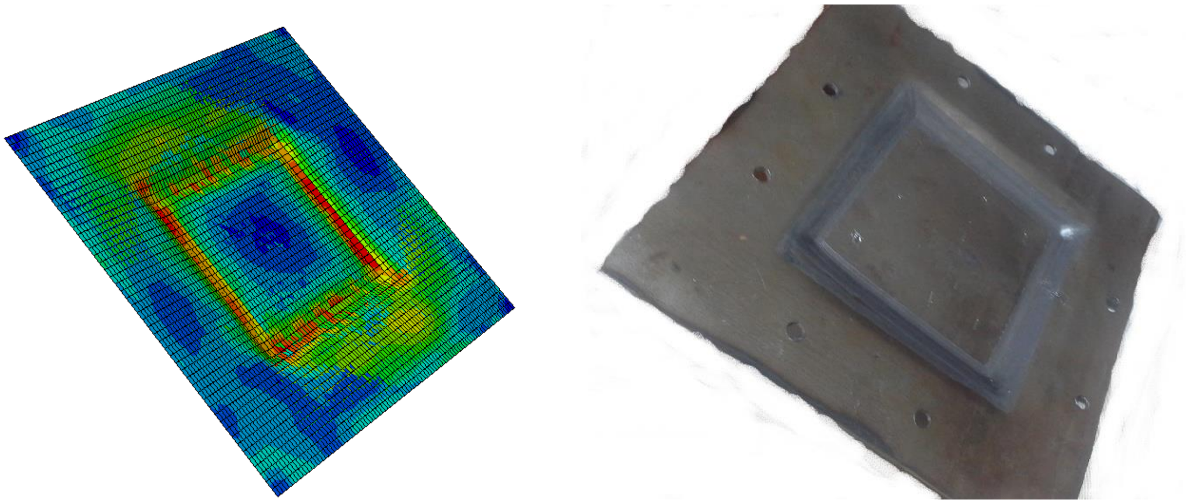


Fig. 10. Created and simulated truncated pyramid.

4.1. Forming force

The forming forces in the different vertical steps down, ΔZ, are compared in the experimental conditions and FEM. In the next section, the created microstructural changes in specimens due to applying the different vertical steps down are discussed as a reason of the force difference. The diagrams of the variations of forming forces in x, y and z directions versus time (F_x, F_y, F_z) obtained from experimental tests and simulated by finite element in the vertical step down of 0.1 and 0.2 are displayed in Figs. 11 and 12. The study of the behavior of the force component along the z axis (Fz) based on the process time, is as follows: during the early stages of the process, the force is increased with a high slope, and then with the continuation of the process this slope is decreased. The reason of this behavior can be attributed to the effect of the two mechanisms of bending and stretching in the early stages of deformation mechanisms [26], while slowing the slope of force increase in later stages of deformation is due to the interaction of wall thinning (force reduction) and work hardening (force increase) [27]. As can be seen through the comparison of forces in the different vertical steps down, by increasing the vertical steps down, the level of the forces increases and the process time decreases, which could be attributed to an increase in the amount of work hardening due to the application of the higher vertical steps down. After the completion of one contour, the Fz component first drops to zero when the tool moves to the next contour radius, then reaches its peak value at the step down and finally stabilizes when the tool moves along the contour. Fx and Fy forces change between their minimum and maximum values in a sinusoidal way according to the tool position relative to the dynamometer axis within one contour [28,29] (Fig. 11). By comparing the force-time curves for both experimental and numerical solution methods, it could be found that firstly a good agreement was obtained between the two solution methods and secondly, the FEM results usually predicted a higher forming force for this process. This increase in force was about 15% different from the real amount in experimental conditions, and could be more or less according to the conditions. Therefore, it could be concluded that the choice of machine capacity to do the process using the results of FEM was somehow considering a safety factor for carrying it out successfully.

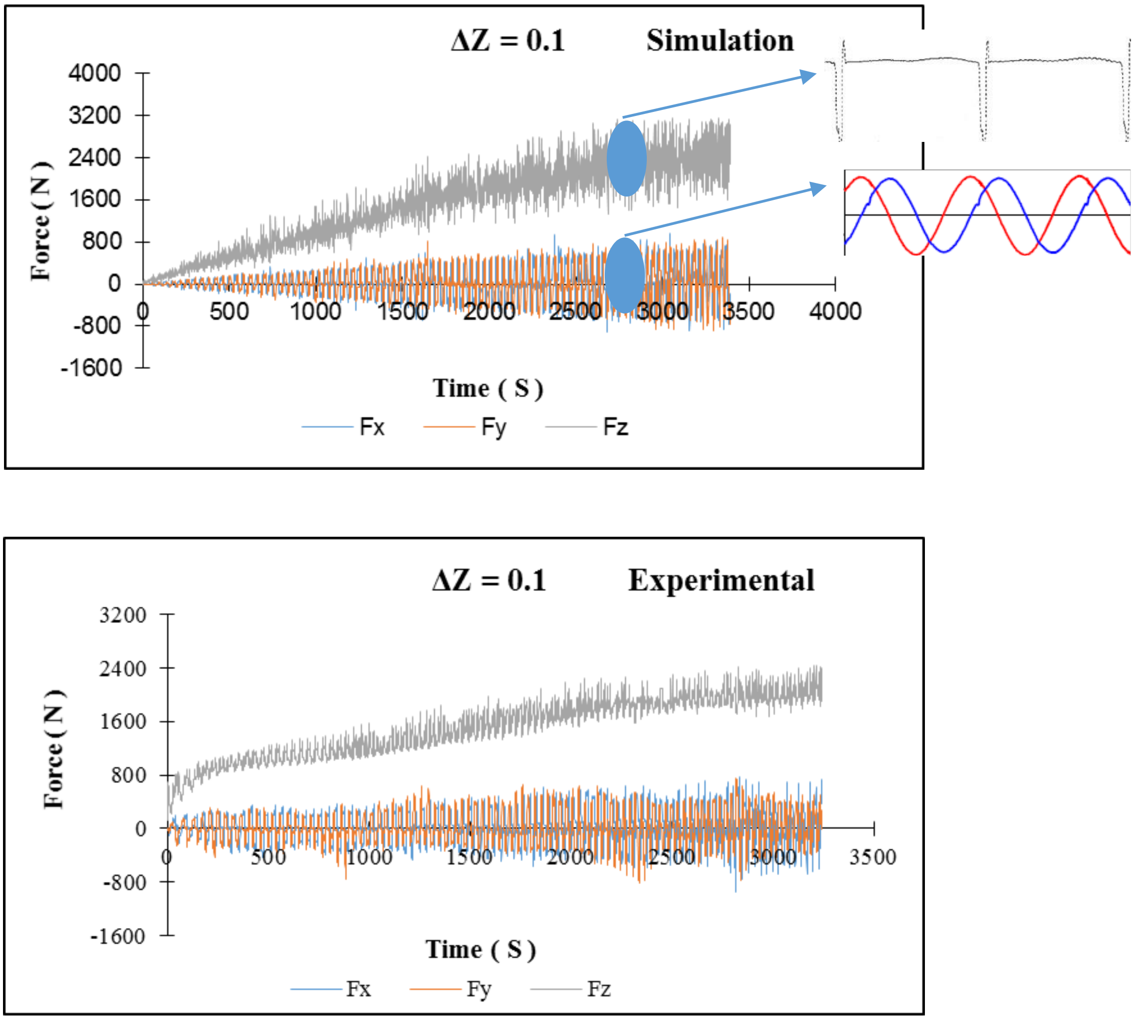


Fig. 11. Forming forces versus time (ΔZ = 0.1).

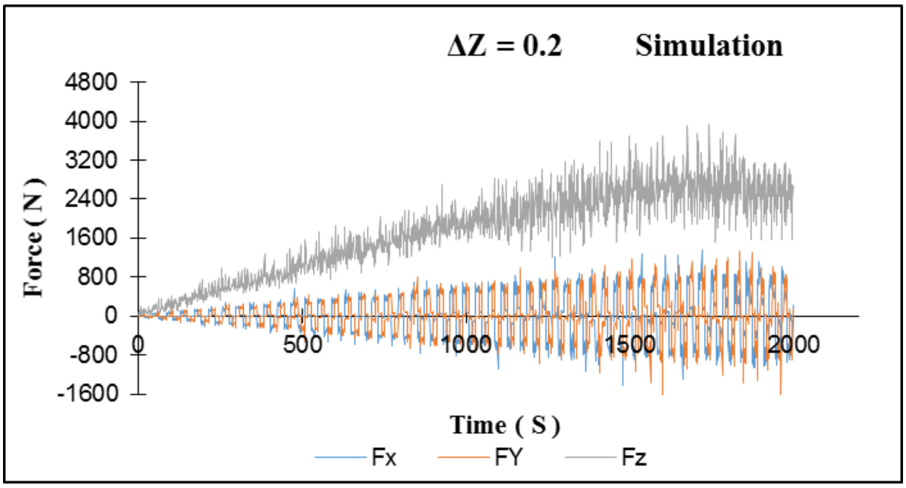
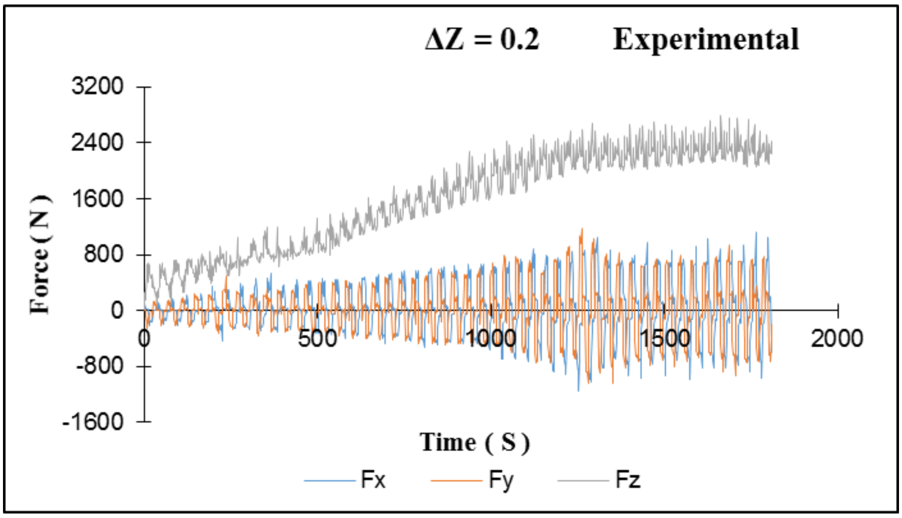


Fig. 12. Forming forces versus time (ΔZ = 0.2).

Figure 12 continued.



4. 2. Thickness variations

Reducing the thickness or thinning of the sheet plays a major role in the incremental forming process. Due to the special conditions of stress and strain governing this process, the critical thinning, that is, the greatest amount of thinning before the failure is greater than the other common sheet forming processes [30]. It is obvious that to develop a proper design and control of the incremental forming process, precise modeling is necessary to check the thinning of the sheet in this process. In order to investigate the thickness distribution, the formed specimens were divided into two halves by means of wire-EDM machine (Fig. 13) and the variations of specimen thickness were measured according to the distance from the center of the floor of the pyramid. Figure14 shows the thickness variations in the simulated specimen. As shown in this figure, red-colored areas and blue-colored corners are related to the areas with no changes in thickness and with a decrease in thickness respectively. The performed measurements were compared with the results of the finite element simulation. Figure 15 displays the results of the thickness measurement of the pyramid wall and its comparison with the FEM results. As seen in these diagrams, the reduction of the thickness increases with the increase of the ΔZ. Therefore, by decreasing the amount of the vertical step down, ΔZ, more uniform thickness distribution would be achieved, and as a result thinning occurs less. Besides, good agreement was observed between the results of simulation and the practical tests.

Fig. 13. The pyramidal specimen to evaluate the thickness distribution.

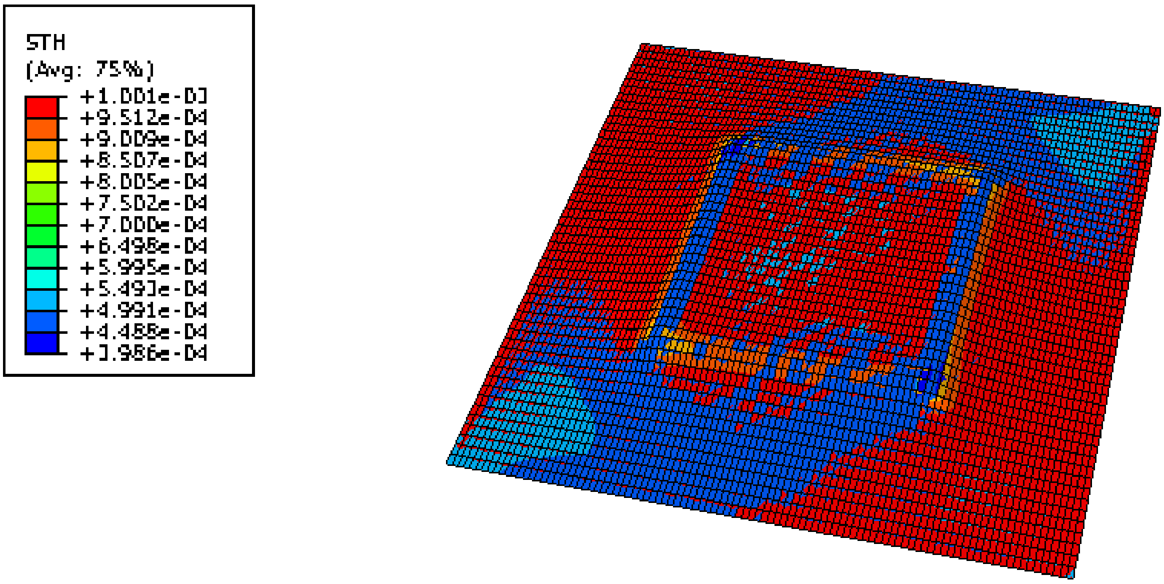
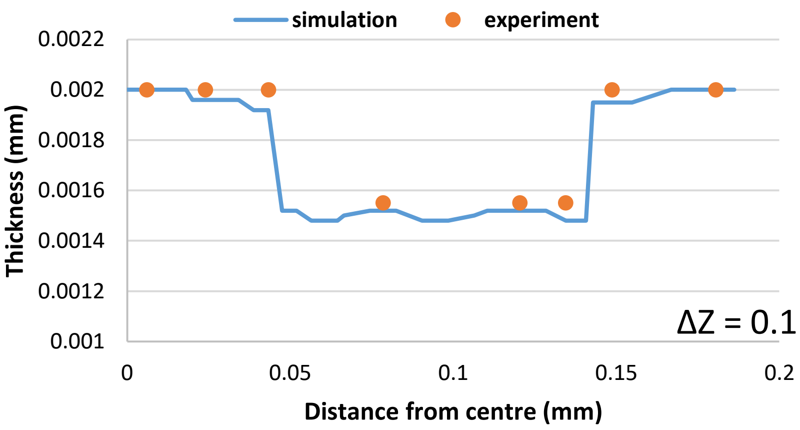


Fig. 14. Thickness distribution in simulated sample.



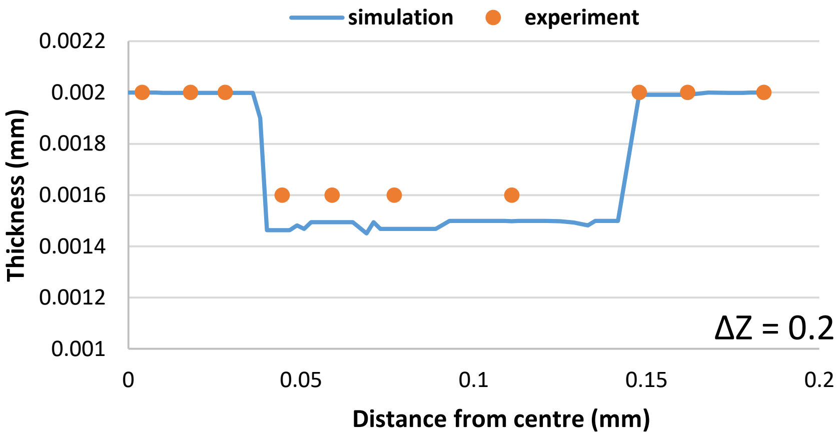


Fig. 15. The effect of vertical step down on thickness variations.

Figure 15 continued.

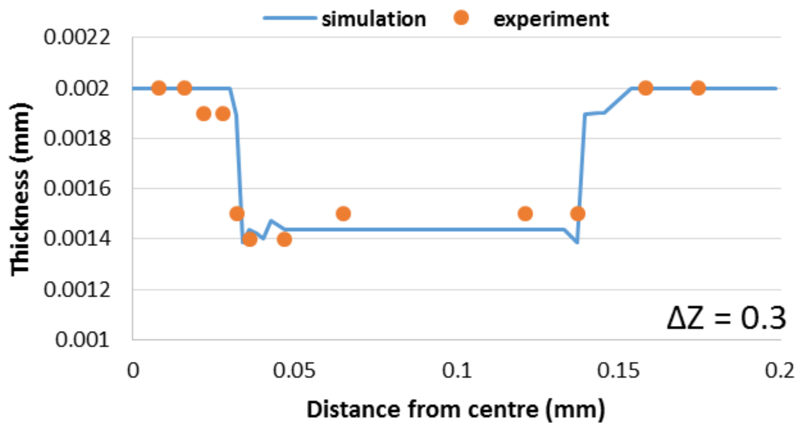


Fig. 15. The effect of vertical step down on thickness variations.

4.3. Mechanical properties evaluation

To investigate the effects of vertical step size on the mechanical properties of the obtained specimens, the tensile and micro-hardness tests were performed on the specimens in the deformed region. Figure 16 and 17 show the results of the above-mentioned tests. According to these figures, it can be seen that by increasing the ΔZ, all of the parameters including tensile strength and hardness increased. As expected, by increasing the ΔZ from 0.1 to 0.3, tensile strength and hardness increased 15% and 13% respectively. This increase in the mentioned parameters can be attributed to the increase in the work hardening caused by an increase in ΔZ value. In fact, increasing ΔZ will result in the increase of the dislocation densities, which lead to an increase in the amount of work hardening and microstructural variation. For a better understanding of this subject, microstructural studies were conducted on the specimens, which will be discussed in the next section.

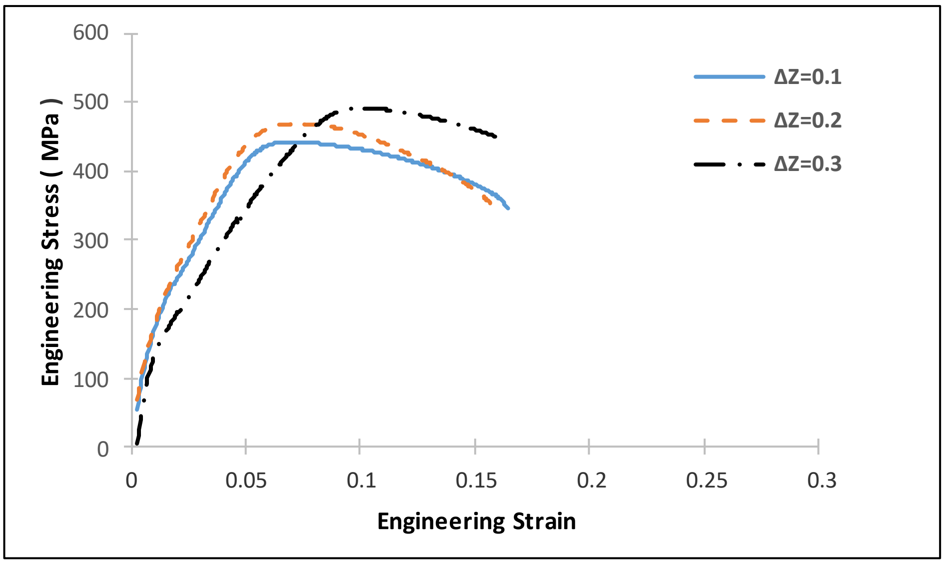


Fig. 16. The effect of vertical step down, ΔZ, on the tensile properties of specimens.

4. 4. Microstructural studies

Difference in mechanical properties of the specimens are due to microstructural changes within the material. Therefore, in order to explain these changes, microstructural studies were performed on the specimens. In this regard, after removing specimens of 1 cm ×1 cm from the inside of the wall of the pyramidal specimens and performing the necessary preparations, microscopic observations were performed. Figure 18 shows the metallographic images of samples. Metallographic images of low carbon steel structure exhibited that the microscopic structure of low carbon steel deformation consisted of ferritic areas and a small amount of perlite distributed along the grain boundaries. By increasing the amount of deformation (increase in ΔZ value), the grains deformed along the direction of the tool movement and grains' sizes decreased slightly. Moreover, many of ferritic grains became distorted and a fibrous structure with a preferred orientation was created inside them. In fact, the mentioned transformations can be attributed to an agent for the increase in the force, tensile properties and the hardness created by the increase in the amount of vertical step down discussed in the previous sections.

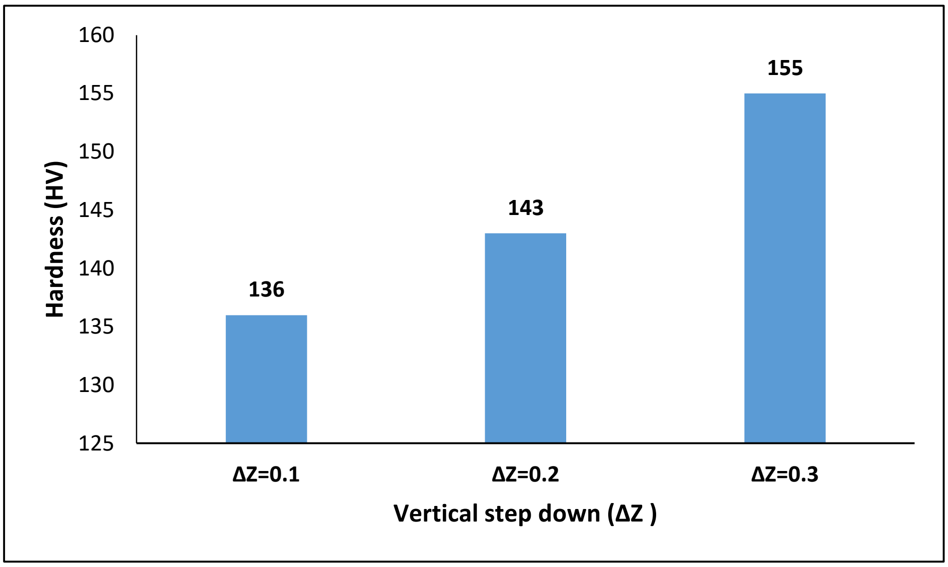


Fig. 17. The effect of vertical step down, ΔZ, on the hardness of specimens.

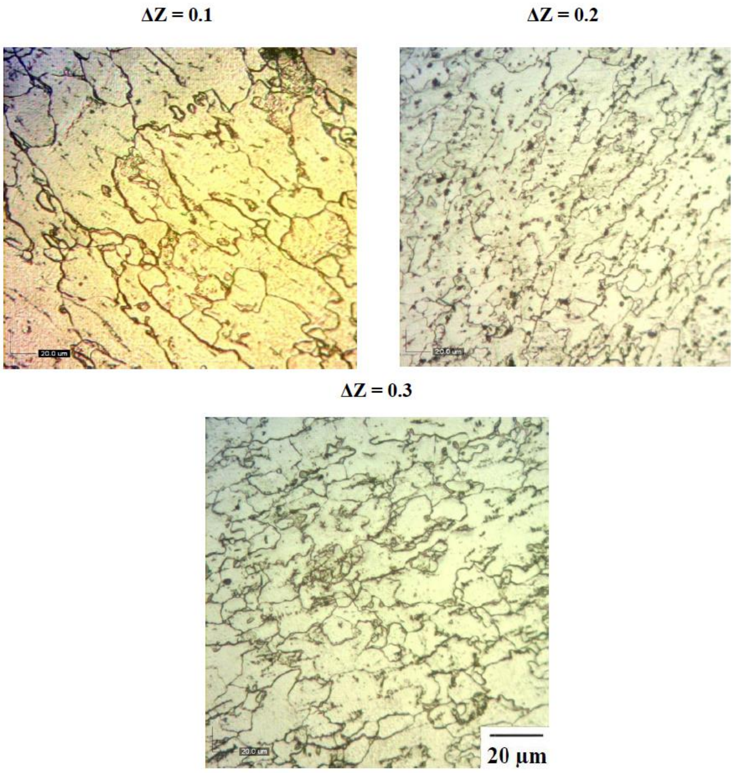


Fig. 18. Metallography images from the deformed specimens.

To determine the effect of ΔZ on the surface quality of the specimens, the surfaces of specimens were examined by the scanning electron microscopy (SEM). Figure 19 shows the SEM images from the specimen's surface. Scratches on the surface of samples are related to the effect of the tool movements of the surfaces of specimens which get deeper as the ΔZ increases. This means the quality level decreases as the amount of ΔZ increases. In fact, if the surface quality of the inside wall of the specimen is not important, increasing ΔZ reduces the process time and improves the mechanical properties of specimen.

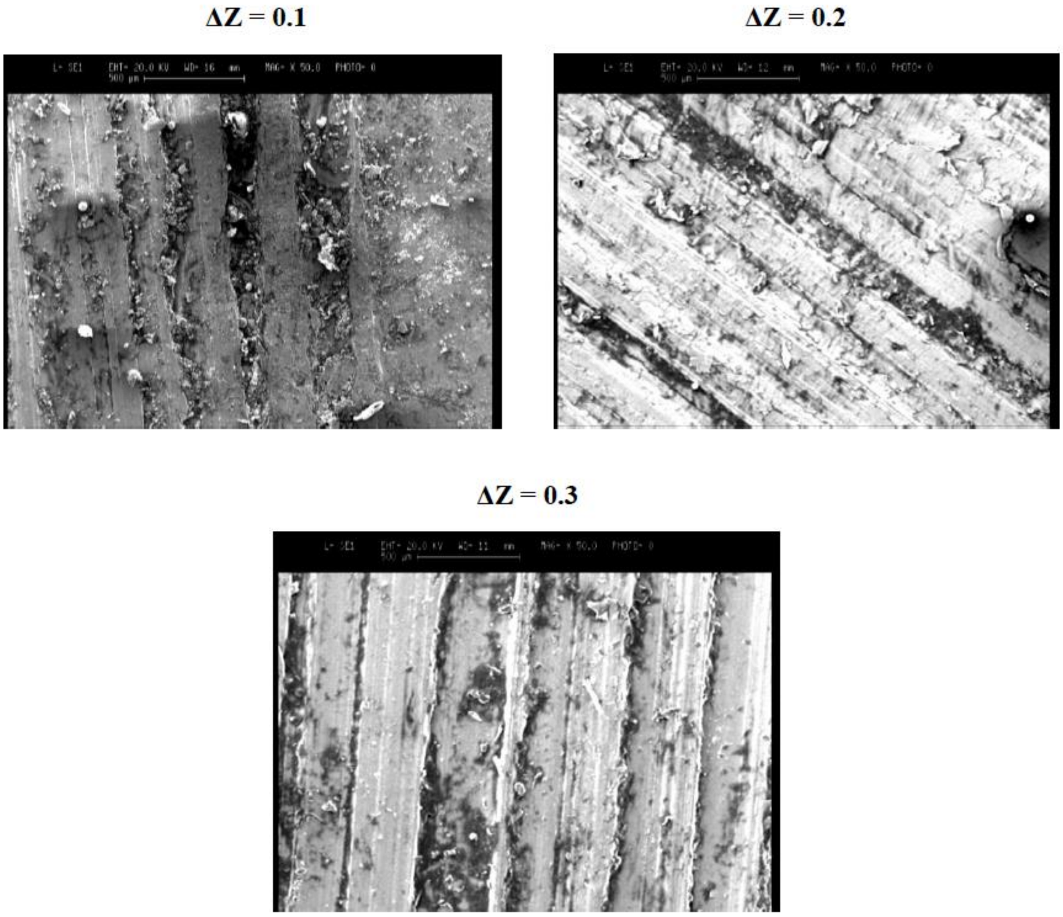


Fig. 19. SEM images of the surface of the deformed specimens (MAG - ×100).

5. Conclusion

1. In this research, a finite element based analysis is developed to predict the required forming force for a bilayer sheet. The proposed analysis predicted up to 15% more force to perform the process, which could be used as a safety factor in determining the force. Furthermore, the experimental results showed good agreement with the results of the numerical solution.
2. Thickness distribution in the formed specimens for different values of the vertical steps down showed more decrease in the thickness with the increase of vertical step down, ΔZ. Besides, in this case, the measurements illustrated good agreement with the results of the numerical solution.
3. The results of mechanical tests of the specimens, indicated increased hardness and tensile strength with increasing the vertical steps down value. These results could be attributed to the amount of work hardening and microstructural changes with the increase in the vertical steps down.
4. By increasing the vertical step down, grains' size decreased and elongated along the direction of the tool movement. Moreover, many of ferritic grains became distorted and a fibrous structure with a

preferred orientation was created inside them, which could be considered as a factor for increasing the forming force as well as mechanical properties.

5. When the vertical step down, ΔZ, increased, the scratches which appeared on the surface of specimens became deeper, due to the tool movement which leads to a decrease in the surface quality of specimens. Therefore, if the surface quality of the inside wall of the specimen is not important, increase in the amount of ΔZ, leads also to process time reduction, and the mechanical properties of the specimen will be improved.

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مطالعه تجربی و عددی خواص مکانیکی و هندسی ورق دو لایه فولاد کم کربن – تیتانیوم خالص تجاری در طی فرآیند شکل‌دهی تدریجی

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چکیده: در این مطالعه، شکل‌دهی تدریجی ورق دو لایه جوش انفجاری شده فولاد کم‌کربن - تیتانیوم خالص تجاری به صورت تجربی و عددی مورد بررسی قرار گرفته است. برای این منظور، در ابتدا یک تجزیه و تحلیل مبتنی بر روش المان محدود برای پیش بینی توزیع نیرو و توزیع ضخامت در حین شکل‌گیری این ماده در فرایند مذکور پیشنهاد شده است که با نتایج تجربی تطابق خوبی نشان داد. سپس برای بررسی اثر متغیر گام عمودی رو به پایین ابزار(ΔZ) بر خواص قطعه کار، آزمایش های مکانیکی و مطالعات ریز ساختاری بر روی نمونه های شکل داده شده انجام پذیرفت. نتایج نشان داد که با افزایش در میزان گام عمودی(ΔZ)، سختی و خواص کششی نمونه ها افزایش یافت، اما کاهش در ضخامت دیواره نمونه های هرمی بیشتر شد و همچنین کیفیت سطح کاهش یافت. علاوه بر این، مطالعات ریز ساختاری نشان داد که با افزایش میزان گام عمودی از $0/1$ به $0/3$، ساختار دانه از یک حالت هم محور به حالت رشته ای شکل تبدیل شده و منجر به تشکیل بافت در ریز ساختار می‌شود که بهبود در خواص مکانیکی را می توان به آن نسبت داد. بنابراین، اگر کیفیت سطح دیواره داخلی نمونه مهم نباشد، با افزایش در مقدار ΔZ، علاوه بر کاهش در زمان فرآیند، خواص مکانیکی نمونه نیز بهبود خواهد یافت.

واژه های کلیدی: شکل‌دهی تدریجی - جوش انفجاری - دو لایه - فولاد کم کربن – تیتانیوم خالص