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INFLUENCE OF TOOL GEOMETRY ON SURFACE CONDITION OF V-BENT ALUMINUM SHEET

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Abstract

Bending is one of the processes, which are most commonly performed in sheet metal forming. It is quite difficult to determine the moment of formation of defects in the form of cracks on the surface of the sheet metal. This is very often the criterion for the rejection of the product. For this reason, it is important to evaluate the state of the surface of the sheet metal along with the line of bending, because there are the largest deformations, leading to the formation of defects such as localized necking or cracks.

Application of 3D digital microscope is presented to evaluate the surface condition of the V-bent specimens. The parameter W_{max} obtained from the analysis of the geometry of the sheet metal surface with the usage of the 3D visualization is introduced. In contrast to the surface roughness parameters, it does not average the highest and the lowest points in the given area. Its value depends directly on the deepest localized necking currently occurring in the study area, which may be followed by a crack initiation. Due to this, it makes possible to define better the moment of cracking. Images of surfaces of V-bent specimens made of aluminum sheets EN AW-2017A (PA6) commonly used in the automotive and aerospace industries were subjected to detailed analysis. Using computer modeling of the bending process, the values of strain have been determined at the surface of the sheet in the bending line. On this basis, the analysis of dependence of the parameter Wmax on thickness of sheet metal as well as geometry of the tools has been conducted.

The presented possibility of determining the moment of crack initiation allows to safely perform the bending process by avoiding formation of defects on the surface of the aluminum sheet.

Key words: V-bending, tool geometry, 3D digital microscope, computer simulation (FEM), surface condition, grooves, cracks

1. INTRODUCTION

Bending is one of the most commonly performed processes in metal forming. The variety of materials and tooling geometry in the process of bending makes it difficult to determine the moment of the formation of defects on the surface of the sheet metal. Such defects are very often the criteria for the rejection of the products. For this reason, it is important to evaluate the condition of the sheet metal surface along the bending line, because the greatest plastic strain occurs just there, leading to the formation of defects in the form of grooves or cracks as shown by Davidkov et al. (2012), Mattei et al. (2013), Sarkar et al. (2001), Sarkar et al. (2004). For this purpose, observations of the surface condition of the bent aluminum sheet have been carried out by means of the microscope. There have been many attempts made to use the computer simulation for studying the effects of process parameters (e.g. material thickness, punch radius) on spring-back or spring-go (Bakhshi-Jooybari et al., 2009; Thipprakmas & Phanitwong, 2011; Thipprakmas & Rojananan, 2008). In this paper, the results of microscopic examinations of surface condition of V-bent specimens were related to plastic strains obtained from the computer simulations of the V-bending process. It has been helpful to understand the formation of deep grooves and cracks along the bending line. On the basis of the analysis, some recom-

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mendations have been presented for understanding any state of the aluminum sheet surface subjected to a V- bending process.

2. PREPARATION OF SPECIMENS

Aluminum sheet EN AW-2017A (PA6) has been chosen for this research work. It is a common material applied in the aerospace and automotive industries. Specimens for bending were cut out from the 2 mm thick sheet with a length of 60 mm and a width of 40 mm. V-bending process was carried out on a press brake AMADA HFE M2. The press brake was equipped with a punch with radius r = 0.5 mm and a die opening width w = 12 mm, see figure 1a. All specimens were bent along the rolling direction on the selected angles ranging from 0° up to the angle where the crack was visible with an unaided eye.

the sheet metal surface taken from the 3D visualization. These outlines have been approximated by using a second-degree polynomial curve. Then, the distances h between geometry outlines and polynomial curve were calculated for all of measurement points. Distribution of h values is shown in figure 1b. The biggest differences (heights) between surface elevations and the deepest grooves are defined as W_{max} values. They are different for various surfaces to be analysed. It was assumed, that the parameter W_{max} is calculated between the distribution points equal to 0.1 %. These values take into account the possibility of the measurement errors caused, for example, by a dirty surface.

In contrast to roughness parameters, it does not average the heights of the highest and the lowest points in the given area. Its value depends directly on the deepest grooves currently occurring in the

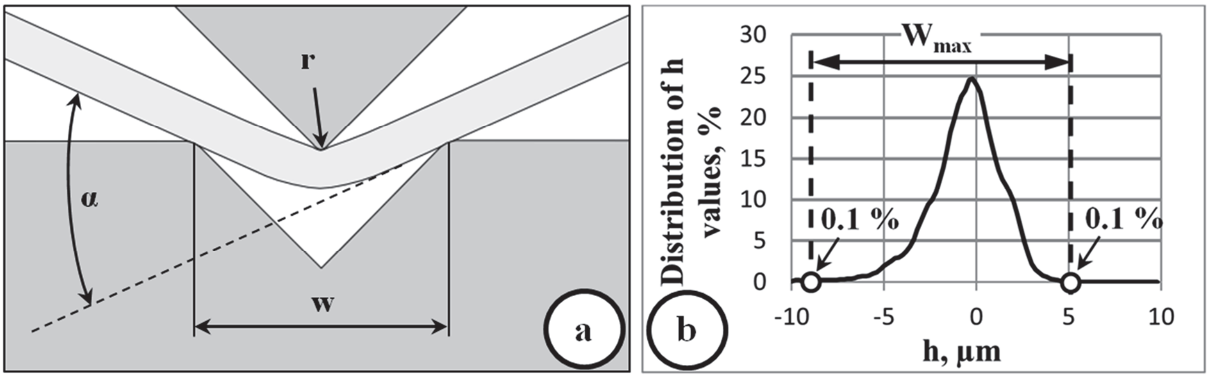

Fig. 1. Geometry of the press brake equipment (a) and distribution of h values (b).

3. EXAMINATION OF THE SURFACE CONDITION

Increasingly used macroscopic vision systems can detect the existing cracks and enable possible rejection of the defective product. However, these systems cannot evaluate the current condition of the surface of the sheet metal and predict the moment of cracking. For this reason a detailed knowledge of the actual 3D geometry of the surface is needed, which can be obtained by using 3D digital microscope. The experimental set-up with a microscope gives a possibility to create a 3D visualization of the surface (figure 2a) from the analysis of the image sharpness and a traditional 2D image (Morawiński et al., 2013). 3D visualization allows the evaluation of the surface condition of the sheet metal in a qualitative way. To clearly evaluate its condition in a quantitative way, the parameter W_{max} was introduced. It is derived from the analysis of the geometry outline of

image study area, which may be followed by a crack initiation. Thus, it is possible to define the moment of cracking more precisely. Figure 2b shows the results of measurements of the bent specimens. Each of the dots on the graph represents a result of the analysis of 3D visualization (figure 2a) from which the value W_{max} was obtained. On the basis of the 3D visualizations and the values of the W_{max} parameter assigned to them, we can identify significant changes taking place on the outer surface of the bent sample. Deep grooves characteristic for the moment before the formation of cracks have been found at the bending angle 36^{o}. The first cracks found by means of microscope appeared at a bending angle equal to 40^{o}. On the other hand, the macroscopic examinations enabled the detection of cracks only at much higher bending angle 44^{o}. The obtained information was compiled with computer simulation results in order to assign plastic strain values for the given condition of the surface of the bent aluminum sheet.

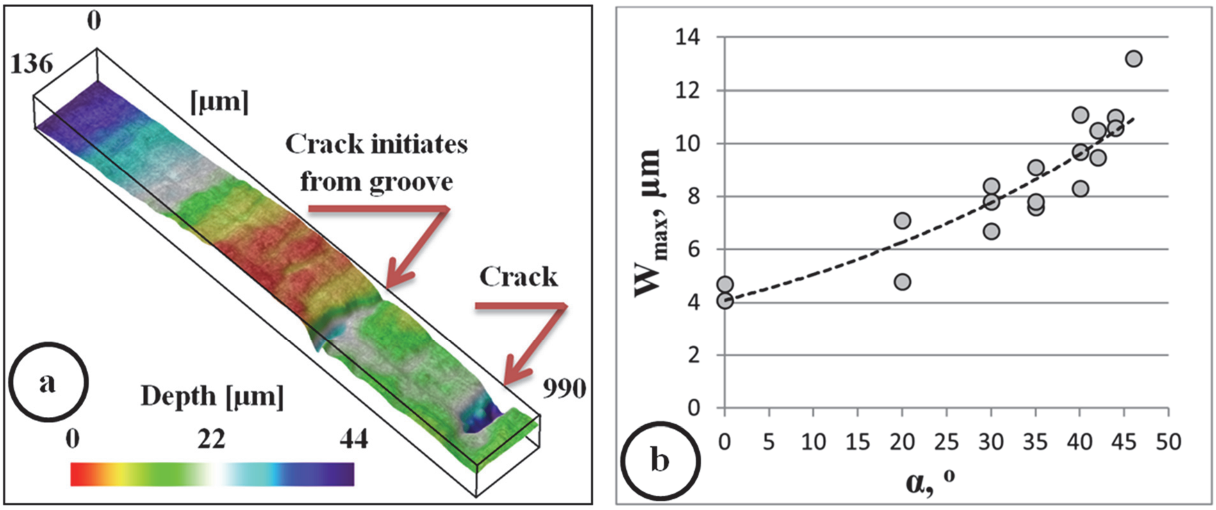

Fig. 2. *3D visualization of the surface of the sample subjected to a V-bending process (a), values of parameter W_{max} from analysis of the 3D digital microscope visualizations (b).*

4. COMPUTER SIMULATION OF THE V-BENDING PROCESS

The change of the sample surface along the bending line is connected with the occurring plastic strains. In order to know the values of these plastic strains, computer simulations of the V-bending process were performed by means of FEM. The material properties used in the simulations were obtained from the uniaxial tensile tests of the aluminum sheet EN AW-2017A. The variety of geometrical parameters of the bending tools used in simulations is given in the table 1. Each simulation was performed at different punch displacement in order to obtain selected bending angles after spring-back of the specimen. The choice of the tool parameters has been carried out in accordance with the recommendations of the press brake manufacturer. According to these recommendations for sheet thickness of 2 mm, the die opening width (*w*) should be from 10 to 25 mm, and the radius of the punch nose from 1.5 mm to 4 mm. In the computer modelling of V-bending process only the plastic strains crucial for the formation of the defects on the sample surface along the bending line were analyzed. Other disadvantages resulting from the applied geometry of tools such as indentation of the inner surface of the aluminum sheet by the rounded nose of the punch, damage of the outer surface of the aluminum sheet by the die opening surfaces or the s-shaped arms of bent aluminum sheet have been omitted.

Table 1. *Geometry of tools in computer simulations of the V-bending process.*

Simulation number	1	2	3	4	5	6	7	8
w, mm	26	18	12	12	12	12	12	12
r, mm	0.5	0.5	0.5	2	3	4	5	6

Figure 3 shows a relationship between the bending angle and the plastic strains which occur along the bending line and are derived from a computer modeling. Figure 3a shows the results of simulations no. 1-3, using the selected die opening widths to the extent provided by the press manufacturer. The radius of 0.5 mm of the punch nose was used in these simulations. In all of the three simulations, there are only two phases of the V-bending process. The first is just curving of the sheet. During this phase the punch meets only with a limited area of the specimen surface. Then, the process proceeds to the wrapping phase, in which the sheet begins to map the shape of the punch. Wrapping phase lasts until the initiation of cracks in the aluminum sheet. The diagram shows that the increase in plastic strain is related to the die opening width. With the small size of the width the material wraps on the punch nose already at small values of the bending angle. Then the plastic strain increases considerably leading to the initiation of cracks. With increasing of the die opening width, the aluminum sheet wraps on the punch at higher values of the bending angle with a consequent reduction in strain increase. The presence of only two phases of the bending process is due to the small die opening width recommended by the press brake manufacturer for the given sheet thickness. The use of bigger die opening width would cause the transition of the bending process into the final setting phase, during which there is a significant increase of the strain values at only a slight increase in the bending angle.

Figure 3b shows an influence of the punch radius on the process of the V-bending. There are the results of the simulations 3-8, in which the radii of the punch varied at a constant die opening width of 12 mm. For all radii the bending process is identical in the curving phase. The differences begin in the phase of wrapping. Wrapping the material on the punch causes the increase of strains dependent on the radius of the punch. The smaller the punch radius is, the more it can move in the direction of the die causing an increase in plastic strains. Wrapping the sheet metal around the front of the punch results in defining the plastic strain on the constant level, which is visible in the form of separating lines. The lines for the punches with r = 0.5 and 2 mm are identical until the end of the process. This is due to the fact that the sheet metal in both cases does not have a possibility to wrap the punches with such a small radius before finishing the bending process.

The results for V-bending process with different die opening widths w = 12 and 26 mm and the same punch radius r = 0.5 mm are shown in figure 4. The figures show the moment of the V-bending process in which plastic strain along the bending line for aluminum sheet EN AW-2017A reached values causing the creation of cracks detected by macroscopic vision systems. By comparing the figures, it can be noticed that bending angle between the specimen arms is much smaller in figure 4a than in figure 4b.

Increasing the punch nose radius from 0.5 mm to 6 mm with keeping the same die opening width 26 mm, bottom position of punches and bending angle, resulted in decreasing plastic strain in the outer layer of bent specimen, figure 5. These two specimens have quite different surface condition. As for the specimen shown in figure 5a, macroscopic cracks occur. However, the sample shown in figure 5b hasn't had even deep grooves.

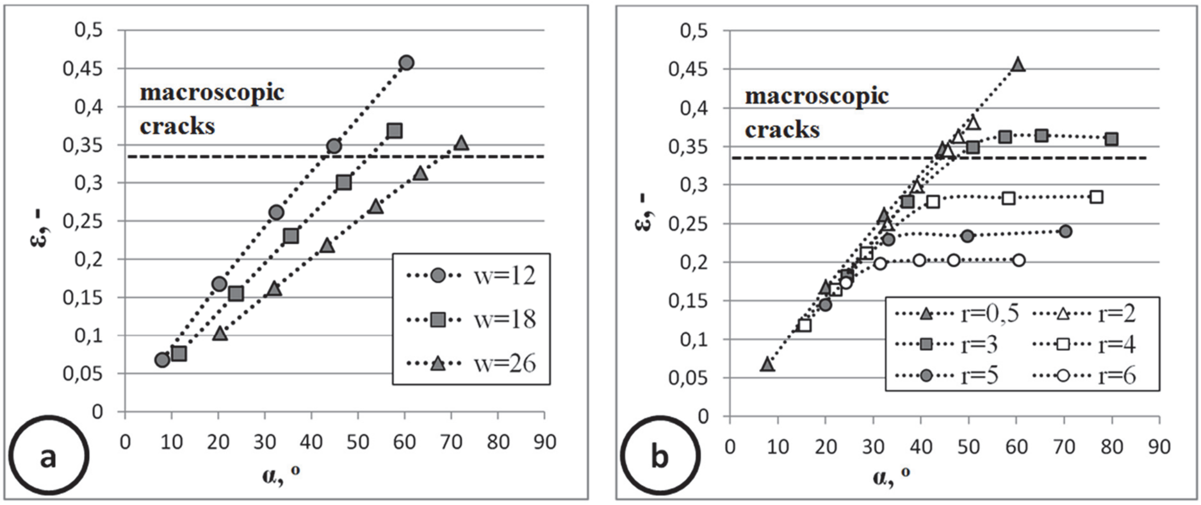

Fig. 3. The relationship between the bending angle α and plastic strain occurring along the bending line for selected die opening widths w and radius of the punch nose 0.5 mm (a), and for selected punch radii and the die opening width of 12 mm (b).

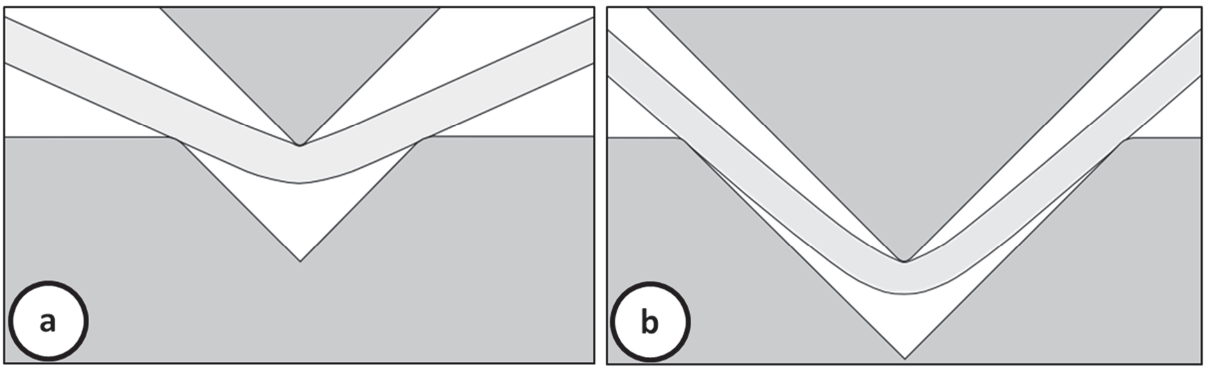

Fig. 4. The V-bending process at the time of the formation of the macroscopic cracks for geometry of tools r = 0.5 mm and w = 12 mm (a), r = 0.5 mm and w = 26 mm (b).

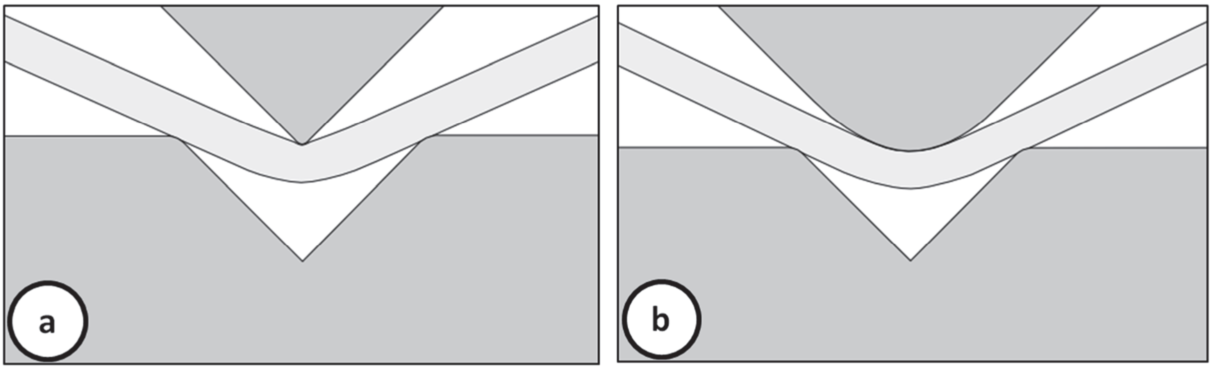

Fig. 5. The bottom positions of the punches enabling to obtain the same bending angles for punch nose radius r = 0.5 mm, w = 26 mm (a) and r = 6 mm, w = 26 mm (b).

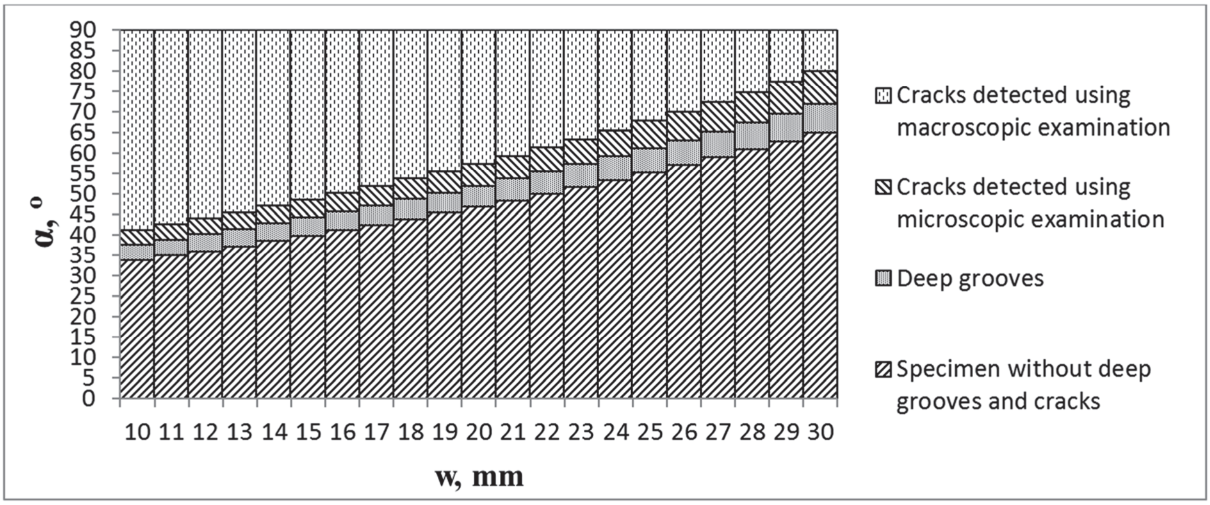

Fig. 6. Changes in the surface condition of the aluminum sheet EN AW-2017A for a selected range of die opening width w (punch nose radius r = 0.5 mm).

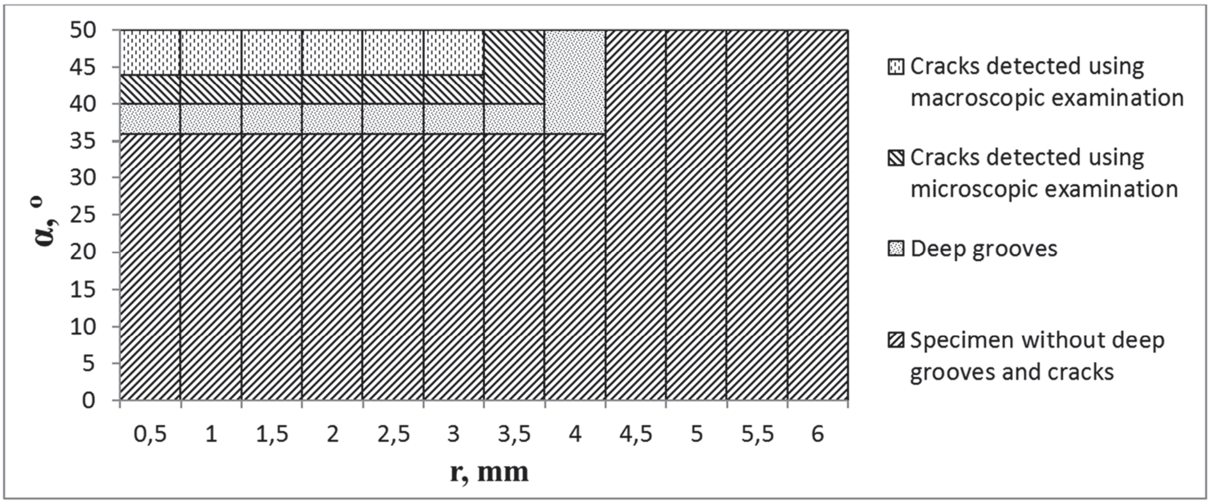

Fig. 7. Changes in the surface condition of the aluminum sheet EN AW-2017A for a selected range of the punch radii r (die opening width w=12 mm).

5. DISCUSSION OF RESULTS

Combining the results of numerical simulations and microscopic examinations has opened the possibility to prepare guidelines in the form of diagram shown in figure 6. There are presented changes of the surface condition of the aluminum sheet for a selected range of bending angles α, depending on the die opening width w. With the increase of the die opening width, the grooves and cracks are observed at bigger bending angles α.

Each marked area shown in the figure 6 corresponds to a different surface condition of the aluminum sheet. Starting from the bottom of diagram, first there are the V-bending process parameters, for which deep grooves and cracks do not appear. Next area marks the bending angles for which deep grooves are detected on specimen surface. It proceeds with an area where the cracks are initiated in deep grooves. These cracks have a very small size. They are detected only by using the microscopic examinations. The last top area indicates the growth of cracks to the size allowing their detection by using macroscopic vision systems. The further progress of bending leads to an increase of the size of the cracks until they will be visible with the unaided eye.

Figure 7 shows an influence of punch nose radius on the surface condition of V-bent aluminum specimens. Deep grooves appear when the punch nose radius is below 4.5 mm, and the first cracks appear by using the punch nose radius 3.5 mm. The presented possibility of determining the moment of crack initiation allows to safely perform the bending process by avoiding the formation of defects on the surface of aluminum sheet, which would be unacceptable for aesthetic and strength reasons.

6. CONCLUSIONS

The selection of the tools used in the V-bending process of the aluminum sheet is determined not only by the geometrical defects of the product, but also the surface conditions along the bending line.

Information on changes in the surface condition of the bent specimens allows you to predict the moment of creating deep grooves or initiation of cracks and stopping the V-bending process before failure of the material.

Diagrams showing the surface condition of the aluminum sheet would allow the press brake operator to choose the bending angle corresponding with the geometry of tools depending on the surface condition of the aluminum sheet.

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WPŁYW GEOMETRII NARZĘDZI NA STAN POWIERZCHNI BLACHY ALUMINIOWEJ W PROCESIE V-GIĘCIA

Streszczenie

Gięcie jest jednym z najczęściej przeprowadzanych procesów obróbki plastycznej. Różnorodność materiałów i geometrii narzędzi w procesie gięcia powoduje trudności w określeniu momentu powstawania defektów w postaci pęknięć na powierzchni blachy, a to one bardzo często stanowią kryterium decydujące o odrzuceniu produktu. Z tego powodu bardzo ważna jest ocena stanu powierzchni blachy wzdłuż linii gięcia, ponieważ tam występują największe odkształcenia, prowadzące do powstawania defektów w postaci bruzd czy pęknięć.

Bruzdy tworzą charakterystycznie zafalowaną powierzchnię. Wraz z powiększaniem kąta gięcia następuje pogłębianie się bruzd, aż w najgłębszych z nich następuje inicjacja pęknięć. Od tego momentu rozpoczyna się rozrost i łączenie się pęknięć, które mają zasadniczy wpływ na wytrzymałość wyrobu i prowadzą do jego zniszczenia. Stąd określenie momentu powstawania nieciągłości materiału w postaci bruzdy ma kluczowe znaczenie w ocenie stanu powierzchni gietej blachy.

W opracowaniu przedstawiono wykorzystanie mikroskopu cyfrowego 3D do oceny stanu powierzchni próbek z blachy aluminiowej EN AW-2017A (PA6) poddanych V-gięciu. W celu uzyskania wizualizacji 3D powierzchni wykorzystano mapy głębokości uzyskane z analizy ostrości obrazu oraz tradycyjny obraz 2D. Wizualizacja 3D pozwala na ocenę staniu powierzchni blachy w sposób jakościowy. Aby jednoznacznie ocenić jej stan w sposób ilościowy, wprowadzono parametr W_{max}. Uzyskiwany jest on z analizy zarysu geometrii powierzchni blachy pobranej z wizualizacji 3D. Jego wartość zależna jest bezpośrednio od najgłębszych bruzd aktualnie występujących na badanym obszarze, z których może następować inicjacja pęknięć. Dzięki temu możliwe jest precyzyjniejsze określenie momentu powstawania pęknięć. Dodatkowo przeprowadzono modelowanie komputerowe procesu V-gięcia w celu uzyskania informacji o odkształceniach plastycznych w najsilniej obciążonych warstwach materiału gię-

tych próbek dla szerszego niż w przypadku doświadczeń zakresu zmienności geometrii narzędzi do gięcia.

Przedstawiona możliwość określenia momentu inicjacji pęknięć pozwala na bezpieczne przeprowadzenie procesu gięcia poprzez uniknięcie powstawania defektów na powierzchni blachy, które są niedopuszczalne ze względów estetycznych oraz wytrzymałościowych.

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