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RESEARCH ARTICLE

Effect of cutting clearance in shear-slitting process on the residual stress and cut surface quality of AA6111-T4 aluminum alloy

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ABSTRACT - Currently, production lines lack correct guidelines on how to set the cutting clearance depending on the type of aluminum alloy and its thickness. This leads to defects in the products and accelerated wear of the cutting tools. This paper presents the results of experimental and numerical research related to the process of shear-slitting of t = 1 mm AA6111-T4 aluminum alloy. The impact of cutting clearance on the product quality, determined by the width of the sliding and separation fracture zones, burr height and deviations of the shape of the product are investigated. The first part of the article describes the course of experimental research carried out at an industrial test stand. The widths of zones on the cut surface were determined, such as sheared-burnished, roll-over, fractured and burr. In the second part, numerical modelling of the shear-slitting process was carried out using Finite Element Method (FEM). A three-dimensional model was developed to take into account the rotation of the tools during the process and the length of the cutting line. Based on the numerical modelling, the influence of the clearance value on the stress values in the cutting zone was determined. For the AA6111-T4 aluminium alloy, the highest product quality was obtained using clearances h_c = 0.09 mm and h_c = 0.12 mm. The conducted experimental research can be useful on production lines in the aspect of the correct selection of technological parameters of the process due to the adopted energy and quality criteria.

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1. INTRODUCTION

The use of aluminum and aluminum alloys in many industries has increased significantly in recent years. The increasingly free possibility of shaping using available production techniques, e.g. cutting, opens up various possibilities for the use of aluminum alloys. This applies in particular to the automotive industry, where the mass of manufactured parts largely determines the economic effects of vehicle operation [1]. These materials are used for body plating elements, less for its skeleton. They are usually used to make detachable parts (doors, fenders, covers) and other smaller elements. The use of these materials makes it possible to reduce weight by approximately 30 – 50 %, while ensuring structural properties similar to steel, they also have good energy consumption and corrosion resistance. In cutting processes, the quality of the obtained product is extremely important. Available works related to the subject analyze the process of cutting these materials on a guillotine [2-4], and by blanking [5, 6]. However, there are few related publications with cutting on circular shears [7-9]. The main advantages of this process are the possibility of shaping sheets of any size and cutting line of any length using high speeds.

The main problems encountered when cutting aluminum alloys include the frequent appearance of undesirable random defects in the cross-section of the cut material sheet, which can contribute to significant wear of the cutting tools, as well as lowering the quality of the cut surface and increasing the energy consumption of the process. The low quality of the cut surface is characterized by the presence of defects, e.g. burrs, chips, edge bends and waves, the presence of a cracking zone along the entire thickness and width of the sheet (Figure 1). In some cases, complete separation of the material is not achieved. These defects in many cases prevent further use of the element. Therefore, there are questions about their nature, causes and ways to avoid them. The reasons for the formation of the above-mentioned defects can be multiple and are related to the geometry of the cutting tools, the properties of a given alloy, and the parameters describing the cutting condition [2-4]. It is difficult to determine which of the parameters is responsible for the triggered defect. It should also be considered whether the problem is not dependent on more parameters and to what extent they affect the size and type of defect. Studies of the course of aluminum alloy cutting processes and the physical phenomena occurring at that time may contribute to their better understanding and facilitate the selection of appropriate processing parameters.

In the available literature, the authors analyzed the processes of blanking, edge trimming and guillotining of structural steels. The research concerned the shear mechanisms, the analysis of deformations and stresses in various phases of the process [10-14]. In the work [11], the influence of guillotining process conditions on the formation of burrs on the cut edge was analysed. An analysis of the material hardness in the sheared zone and the occurring cutting forces and their parameter-dependent variation, cutting surface characteristics was determined by tactile measurement. In works [15, 16], the impact of cutting tool wear on deformation of the cut edge and burr formation was analysed. Authors of works [17]

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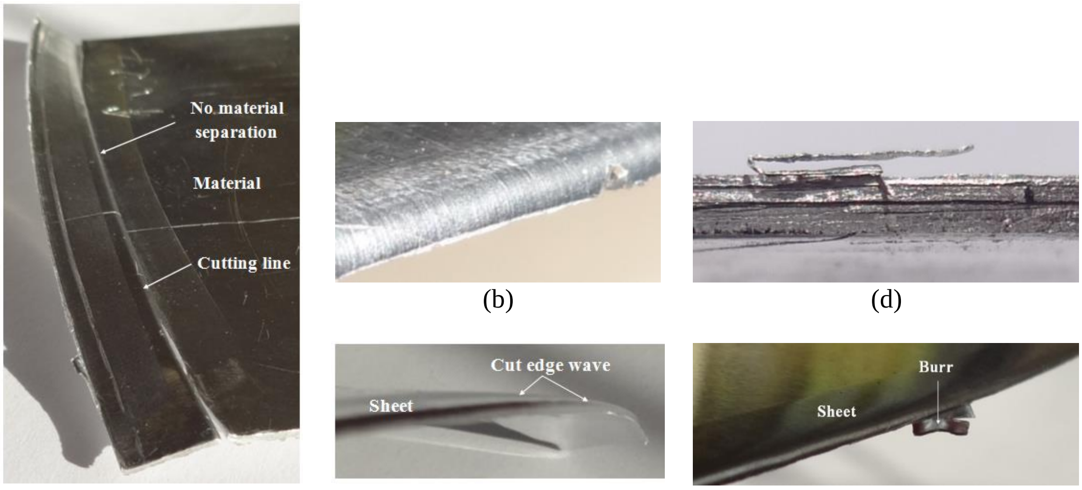
analyzed the influence of the parameters of the trimming process on the course of the plastic flow and cracking phases. Modifications of the tool geometry were proposed to extend the plastic flow phase and reduce cut edge defects. In the work [18], a process of cutting aluminum sheet bundles on a guillotine was analyzed. Numerical models were developed using the mesh-less method SPH (smoothed particle hydrodynamics) and the Euler Lagrange approach. Using numerical models, the course of the cutting force was determined depending on the displacement of the tool.



(a) (c) (e)

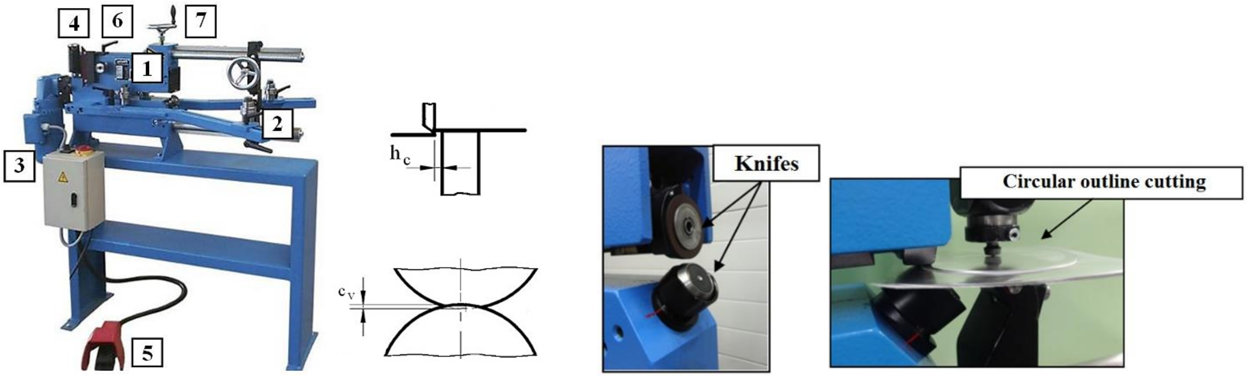
Figure 1. Defects of cut edge of aluminum alloys: (a) no material separation, (b) edge rounding, (c) edge wave, (d) chip and (e) burr

The process of shear-slitting of aluminum alloys is a complex issue. This is due to the occurrence of many physical phenomena during the process and the non-linearity of the process. Current knowledge about the course of the process and the physical phenomena occurring in it is limited. Most of the works concerns the blanking process, where the process is more stable because the sheet is embedded in the die. During shear-slitting, the sheet is moved lengthwise and the tools rotate. Therefore, the process conditions are different and the optimal process parameters must be selected in a different way. In this work, the influence of the value of the clearance between the knives on the course of the cutting process and the quality of the cut surface was examined. The aim of the work is also to develop a numerical model and its experimental verification of the process of cutting aluminum alloys on circular shears. Using a numerical model, stress values in the vicinity of the cut edge were determined. In the case of mechanical cutting processes, there are high stress concentrations on the cut edge that can affect the tribological properties of the steel after the cutting process. Excessive stress concentration on the cut surface leads to edge microcracks. The obtained results enable the appropriate selection of machining parameters in terms of obtaining high-quality products, while maintaining the minimum energy consumption and time-consuming process.

2. MATERIALS AND METHODS

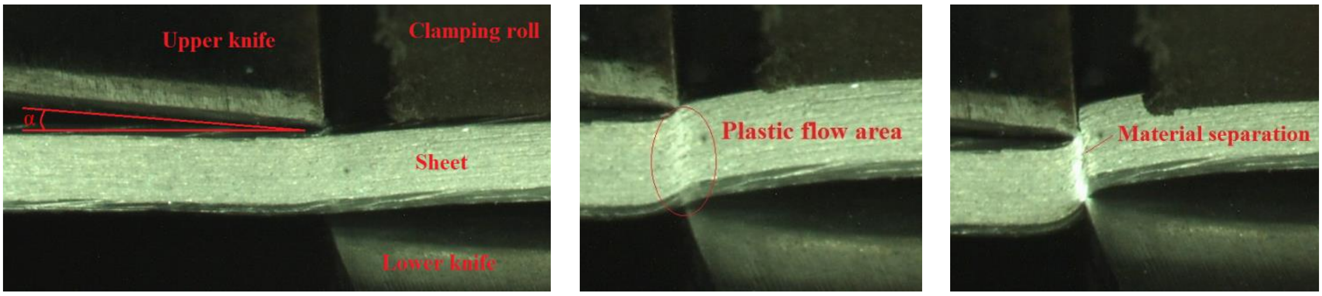
In order to carry out the experiment, a special test stand was designed, shown in Figure 2. The stand is equipped with a cutting device consisting of rotary knives, a motor and special guides and holders for fixing metal sheets. It allows to cut sheets in a straight line and cut out rings or circles (Figure 2(d)). A special roller made of polyurethane allows the sheet to be moved horizontally during cutting. It is possible to precisely set the value of cutting clearance h_c, knife overlap c_v and cutting speed v. The upper knife can be replaced depending on the preferred value of the rake angle α. Before starting the experiments, trial tests of the device were carried out to verify the correct operation. It has been shown that the value of clearance h_c has the greatest impact on the process and the quality of the cut edge. Input, output, disturbing and constant factors were specified. The tests were carried out as follows: prepared aluminum sheets were mounted in the device and fixed with a special needle (Figures 2(a) and 2(d)). Strips were then cut from the sheet at a constant cutting speed v = 4 m/min for the following clearances between the knifes in the vertical plane: h_c = 0.03; 0.06; 0.09; 0.12; 0.15; 0.18; 0.21 and 0.24 mm. Three replicates were used for each trial. The AA6111-T4 aluminum alloy with a thickness of t = 1 mm was used for the tests. The rake angle of the cutting edge of the upper knife was α = 30°. The rake angle of the lower knife cutting edge was α_1 = 0°. The mechanical properties and chemical composition are reported in Tables 1 and 2, respectively.

Figure 3 shows the most important phases of the cutting process recorded with the i-SPEED TR high-speed camera during experiments. The shear-slitting process is characterized by the occurrence of elasto-plastic, plastic flow and fracture phases. After the fracture phase, the cut-off part is separated from the sheet. In the elasto-plastic phase, the most plasticized area is concentrated in the contact areas of the cutting tools with the material (Figure 3(a)). With the increase of stresses caused by the pressure of the cutting edges of the knives, the plasticized zone of the material increases. In the plastic flow phase, stresses exceed the elastic limit of the material, and deformations caused by plastic stresses permanently change the shape of the sheet in shearing area. The effect of this step is to crate roll-over of the cut surface and create areas of less thickness. Further pressure of the cutting tools on the material increases the surface of the plasticized material, which is directed to the inside of the cross-section (Figure 3(b)). As the cutting process progresses, the first cracks appear in the material. The material breaks in the most deformed places, most often in the vicinity of the cutting edges of the tools (Figure 3(c)). In the next stage of the process, complete separation takes place.



(a) (b) (c) (d)

Figure 2. Experimental equipment and main parameters: (a) shear-slitting device: 1 – cutting tools, 2 – sheet holder, 3 – engine, 4 – clearance knob with scale, 5 – drive pedal, 6 – cutting speed knob with scale, 7 – knife overlap regulator (b) main slitting parameters, (c) zoom of cutting tools and (d) example process of circular outline cutting



(a) (b) (c)

Figure 3. Main shear-slitting phases: (a) elasto-plastic, (b) plastic flow and (c) fracture

Table 1. Mechnical properties of the adopted material

Properties	Values	Units
Density	2800	(kg/m^3)
Young’s modulus	70	(GPa)
Yield strength (Rp0.2)	165	(MPa)
Elongation (A_{100})	28	(%)
Tensile strength	265	(MPa)
Poisson ratio	0.33	-

Table 2. Chemical composition of the adopted material [% weight]

Si	Cu	Zn	Cr	Mn	Ti	Mg	Fe
0.6-1.1	0.5-0.9	0.15	0.1	0.1-0.45	0.1	0.5-1	0.4

During the cutting process, after the end of the cracking of the material, a cut surface is formed, which includes: the surface of the separating fracture and the sliding fracture. The share of the sliding fracture in relation to the thickness of the formed alloy is one of the factors that determine the quality of the workpiece. The sliding fracture consists of sheared-burnished zones *b* and roll-over *a*. Separation fracture consists of: fracture zone *c* and burr h_z (Figure 4(a)). To measure the width of zones after cutting the OLYMPUS LEXT OLS4000 confocal laser microscope was used. The device enables the creation of 3D images of the analyzed surface, precise measurement of the distance between zone transition points and the creation of surface profiles (Figures 4(b) and 4(c)).

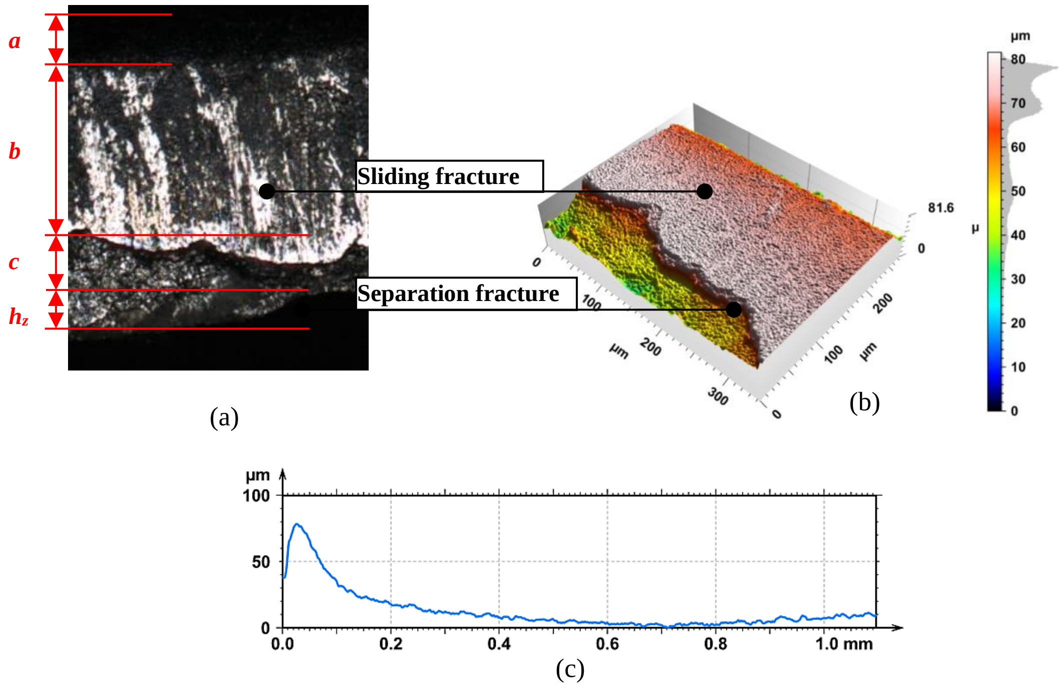


Figure 4. Sheared edge characteristic features and it's measurement: (a) image of the cut surface, (b) geometric structure of the cut surface and (c) profile of bottom sheet surface with visible burr area

3. RESULTS AND DISCUSSION

3.1 Influence of Clearance on the Quality of the Cut Surface

The results of the measurements are shown in Figures 5 and 6. The widths of the individual zones on the cut surface were measured at random locations along the cut line of the samples and then averaged.The conducted tests show that in all considered cases a greater share of the sliding fracture was obtained in relation to the separation fracture (Figure 5).

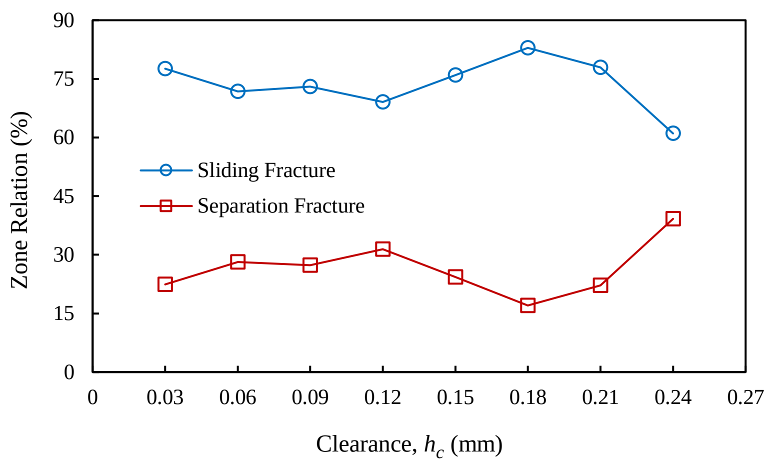


Figure 5. Influence of clearance on formation of sliding and separation fracture

The sliding fracture area ranged from about 61 % to 83 % of the material thickness. The highest values of the sliding fracture were obtained during cutting with clearances h_c = 0.03 mm (77 %), h_c = 0.15 mm (76 %), h_c = 0.18 mm (83 %), and h_c = 0.21 mm (78 %). It should be noted, however, that for larger clearance values, when h_c > 0.15 mm, there was a significant increase in roll-over and a decrease in the sheared-burnished (Figure 6). Therefore, the suitable quality of the cut surface was obtained using clearances h_c = 0.03 mm (large share of the sheared-burnished, small fractured area) and h_c = 0.09 mm (small burr and roll-over). The lowest quality of the workpiece was obtained using the clearance h_c = 0.24 mm (the share of the sliding fracture was 61 %). For this cutting case, the sheared-burnished zone on the cut surface did not occur. However, the product had a large burr (h_z = 0.35 mm) and a large roll-over (a = 0.65 mm).

Figure 6 shows the effect of the clearance on the formation of individual zones that are part of the sliding and separation fracture. The tests carried out showed that changes in the clearance value mainly determine the width of the sheared-burnished zone and the roll-over. An interesting observed phenomenon is a rapid decrease in the width of the sheared-burnished zone during the change in the clearance value from h_c = 0.03 mm to h_c = 0.06 mm, and from

h_c = 0.21 mm to h_c = 0.24 mm. Apart from these cases, for the other clearance settings, the values of the obtained sheared-burnished zone were similar. In all considered cases, there was a burr on the cut surface. As in the case of the sheared-burnished zone, a certain range of clearance values was observed, i.e. between h_c = 0.09 mm and h_c = 0.21 mm, where the heights of the burrs obtained are similar.

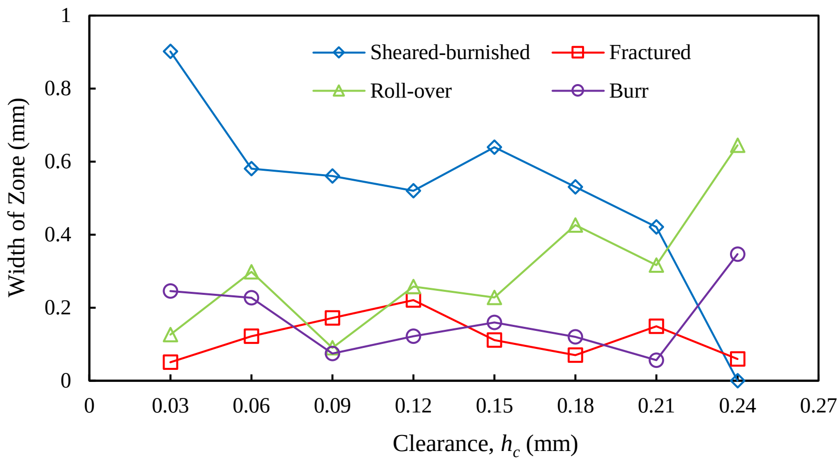


Figure 6. Influence of clearance on the formation of zones on the cut surface

A significant problem encountered when cutting aluminum alloy was the formation of irregular burrs on the cut surface along the cut line (Figure 7). This phenomenon took place especially when cutting with clearances h_c = 0.06 mm and h_c = 0.24 mm. The formation of an irregular burr can be associated with the instability of the material fracture process. For specific values of clearances in the cutting zone, additional tensile forces appeared in certain phases of the process, causing stress concentration material in certain places. As a result, the cracking process occurred parallel to the cutting line, which resulted in local detachment of one part of the material from the other and leaving burrs or voids on the cut surface (Figure 7).

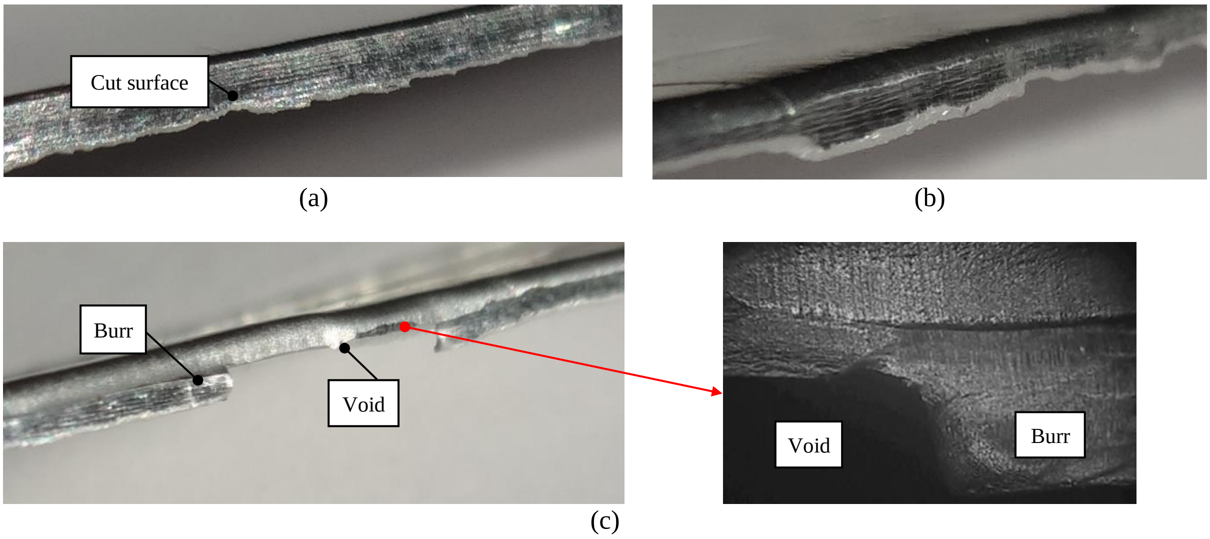


Figure 7. Examples of obtained burrs on the cut surface: (a) regular for h_c = 0.03 mm, (b) irregular h_c = 0.06 mm and (c) irregular leaving a void h_c = 0.24 mm

3.2 Influence of Clearance on Shape Deviations of Products

When analyzing the quality of products after the cutting process, in addition to analyzing the quality of the cut surface, it is also necessary to determine the geometric accuracy of their shape. As a result of the tests, it was found that the specified clearance values caused the edge of the cut surface to bend (Figure 8), which occurred at the end of the cutting line. The smallest values of the bending angle β (Figure 8(i)) were obtained using clearances h_c = 0.03 mm, h_c = 0.09 mm and h_c = 0.12 mm (Figure 9). Using clearances of h_c = 0.06 mm, h_c = 0.15 mm and h_c = 0.24 mm caused the greatest shape deviations. For a detailed analysis of the causes of this defect, images recorded from the camera during the process were analyzed (Figure 10). Observations show that the bend is formed in the final phase of the process. At this point, the process of cutting aluminum alloys on circular shears may become unstable due to the very high concentration of deformations on a small section of the shaped material, and the increase in the impact of the cut part, which is not fixed and undergoes initial bending (Figure 10(a)). In the further phase of the process, a rapid increase in the bending moment can be observed, which caused the sheet to bulge and round (Figure 10(b)). In the next phase (Figure 10(c)), the material may be completely separated due to the pressure of the knifes or tear immediately before the impact of the knifes (cases h_c = 0.15 mm and h_c = 0.24 mm). This is evidenced by the irregular burr formed on the cut surface at the end of the cut line (Figure 11(b)).

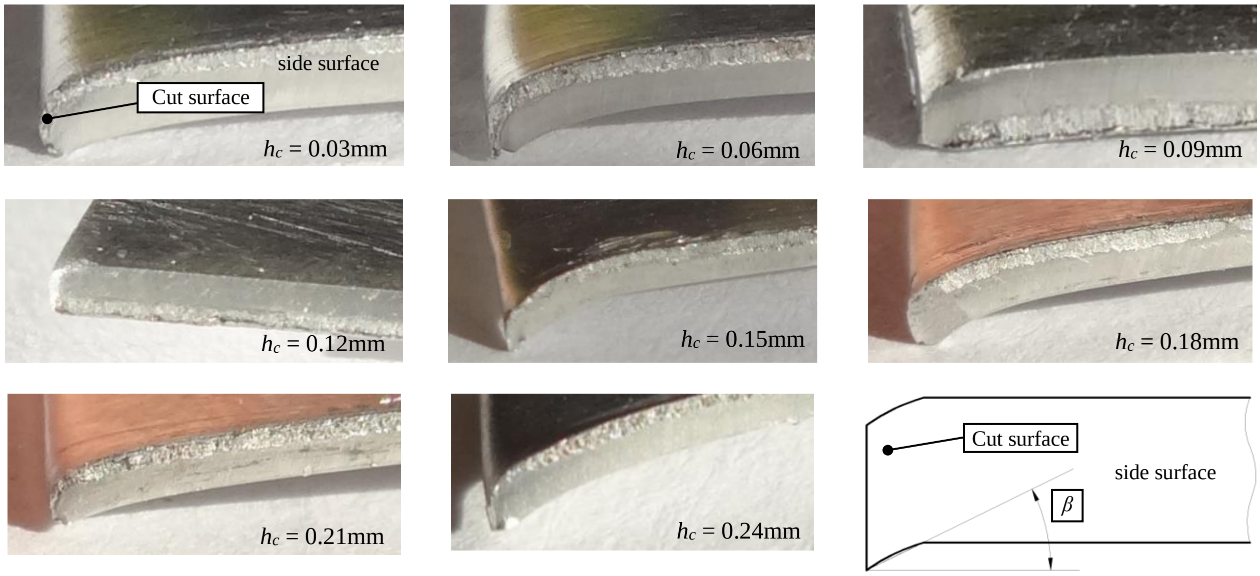


Figure 8. The effect of clearance on the bend of the edge of the cut surface

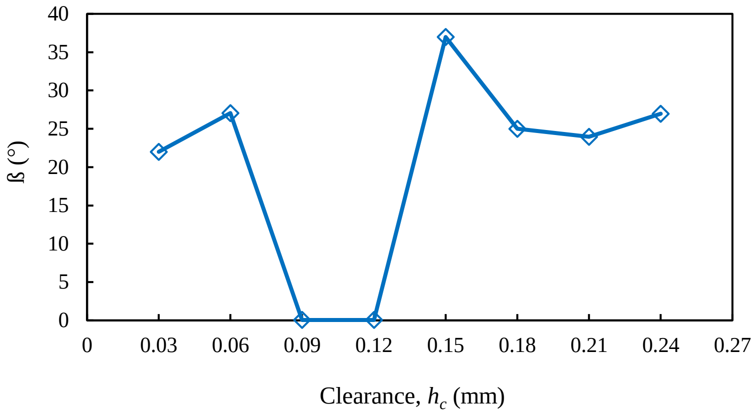


Figure 9. The effect of clearance on the bend angle

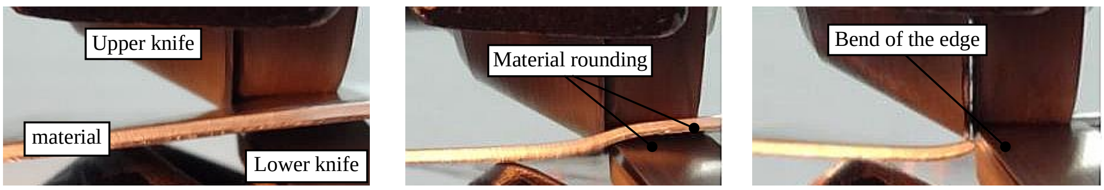
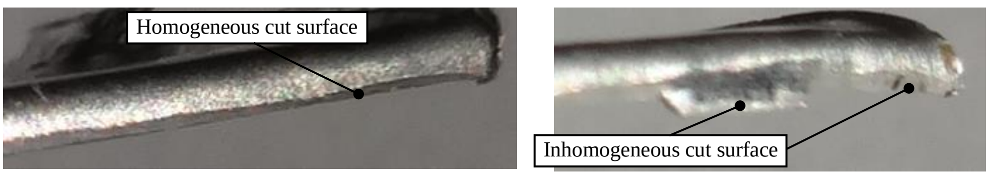


Figure 10. The moment of formation of the bend of the cut surface recorded during the process



(a) (b)

Figure 11. Influence of clearance on the stability of the cutting process in the final stage: (a) h_c = 0.12 mm and (b) h_c = 0.15 mm

4. FINITE ELEMENT MODEL OF SHEAR-SLITTING PROCESS

4.1 Model Description

Modeling the cutting process of aluminum alloys is a complex problem due to the fact that it is necessary to use an incremental description and to take into account many physical phenomena in numerical simulations, such as geometric and physical non-linearities, large deformations or material cracking. Currently, an important problem in the literature is to determine the stress and strain values in the area of the cut surface depending on the adopted machining parameters. Excessive values of stresses and strains accumulated on the cut surface cause the formation of local micro-cracks of the cut edge and the formation of burrs. In order to analyze the stress and deformation values, a numerical model of the process was developed, taking into account all relevant process characteristics and parameters, such as value of the rake angle α, knives radius values, knife overlap, length of the cutting line and method of supporting the sheet (Figure 12).

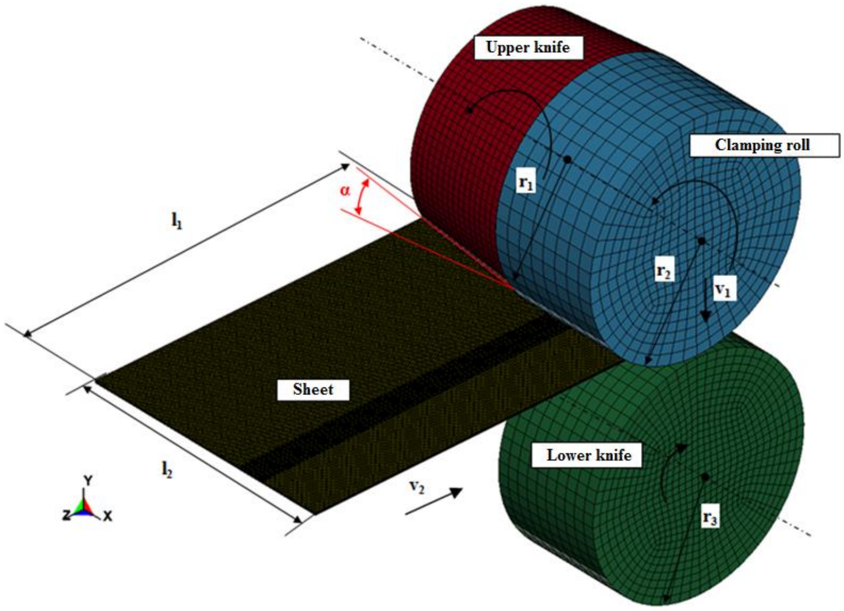


Figure 12. FEM model of the shear-slitting process

Numerical tests were carried out in accordance with the initial-boundary conditions, representing the tests on the experimental stand. The 8-node SOLID 164 element type with hourglass control and reduced integration was used for discretization. Analyzes of the sensitivity of the model to the change in the degree of finite element mesh density were carried out, as a result of which the optimal dimensions of the finite elements were determined both in the contact areas of the cutting tools with the material and outside the contact zone.

Modeling the cutting process is inherently related to the need to define the moment and conditions of material fracture. The applied Johnson-Cooke constitutive equation allows to determine the dependence of yield stresses on plastic deformations, taking into account cracking of the material. The literature [19] presents functionals that allow to determine the plastic deformations that we consider critical, i.e. the achievement of which can be interpreted as the beginning of cracking. In addition, the model also takes into account the effect of strain rate and temperature on the yield stress values according to the following relationship:

$$\sigma_Y = (A + B \cdot \varepsilon^n)(1 + C \cdot ln\dot{\varepsilon}^*)\left[1 - \left(\frac{T-T_r}{T_m-T_r}\right)^m\right] \tag{1}$$

where, A is the yield strength of the material, B is the strain hardening constant, C is the strain rate strengthening coefficient, σ_Y is the yield stress, ε is the equivalent plastic strain, $\dot{\varepsilon}^*$ is the normalized effective plastic strain rate, m is the thermal softening coefficient, n is the strain hardening coefficient, T_m is the material melting temperature, T_r is the room temperature [19]. For AA6111-T4 aluminum alloy: A = 324.1 [MPa], B = 113.8 [MPa], C = 0.002 [-], m = 1.34 [-], n = 0.42 [-]. Sample results of the simulation of the shear-slitting and their comparison with the results of the experiment are shown in Figures 13 - 17.

4.2 FEM Results

Figure 13 shows the moment of forming the rounding of the sheet metal edge in the numerical model and the experiment. In both cases, an increase in the bending moment and the formation of a rounding in front of the contact area of the cutting tools with the material are visible. As a result, after the process, the cut edge is characterized by a bend (Figures 14 and 15).

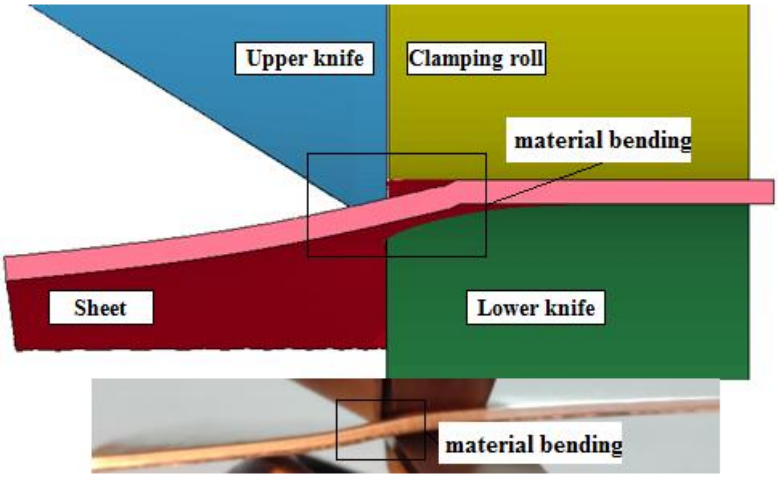


Figure 13. Comparison of the results of the simulation tests with the results of the experiment at the moment of the formation of the bend of the cut surface: (a) simulation model and (b) real process recorded with a camera (h_c = 0.06 mm)

A major difficulty in modeling the shear-slitting process is the appropriate mapping of the process course, taking into account the shift of the sheet in the horizontal direction. This is necessary for the correct prediction of the moment of formation of the bend in the material and the formation of the cut edge. In selected cases of the cutting process, the behavior of the material was similar to the experiment, especially in the final stages of the process, manifested by an increase or decrease in the degree of bending of the cut edge. As the research carried out in [2, 17] has shown, on the example of the trimming process, aluminum alloys are particularly susceptible to deformations and excessive deformations even in the phase of plastic flow, which can be disturbed by local microcracks and tearing of the material causing the formation of burrs and bends, which is strongly related to the cutting clearance, cutting speed and tool geometry. Figure 16 compares the values of the cut surface bend angles obtained as a result of the experiment and simulation. The obtained results are close to each other. The differences are related to the density of the FEM mesh and the material model used.

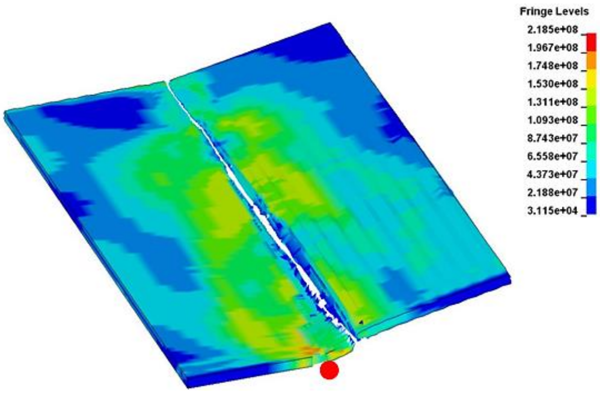


Figure 14. Huber-Mises equivalent stress [Pa] distribution after the cutting process (h_c = 0.06 mm)

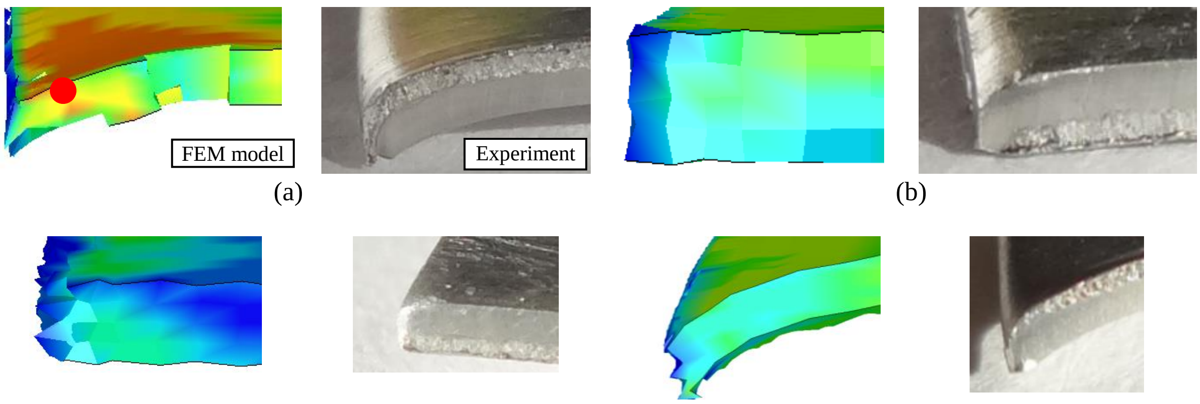


Figure 15. An exemplary comparison of the bends of the cut surfaces obtained as a result of the experiment and simulation: (a) h_c = 0.06 mm, (b) h_c = 0.09 mm, (c) h_c = 0.12 mm and (d) h_c = 0.24 mm

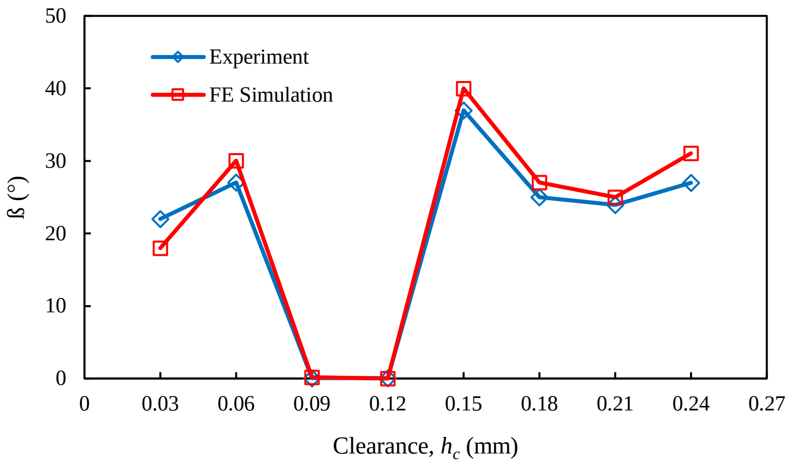


Figure 16. Comparison of the values of the bend angles of the cut surface obtained as a result of the experiment and FEM simulation

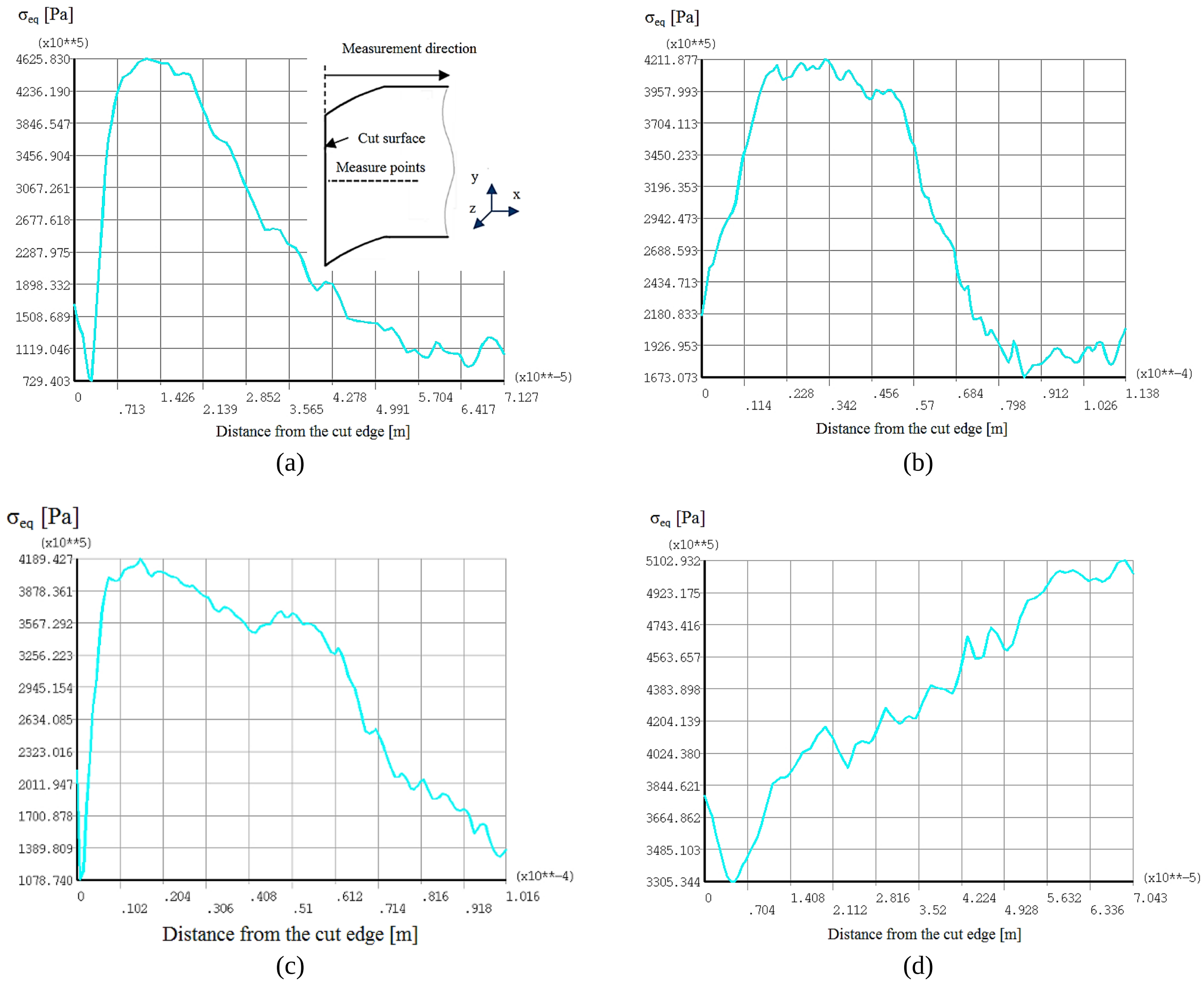


Figure 17. Influence of cutting clearance on Huber-Mises equivalent stress values in the area of the cut edge for: (a) h_c = 0.03 mm, (b) h_c = 0.09 mm, (c) h_c = 0.15 mm and (d) h_c = 0.21 mm

In addition to the need to obtain appropriate geometrical features of the cut edge in mechanical cutting processes, a very important aspect is also to reduce the negative impact of stresses generated by the process in the surface area of the cut. The high residual stress causes the occurrence of delayed cracking and the reduction in fatigue strength of finished parts. In press blanking, high tensile residual stress is caused around the blanked edges. The generation mechanism of residual stress at the press-blanked and laser-blanked edges of the 1.5 GPa ultra-high strength steel sheet was investigated in study [20]. In paper [21] the effect of different process variants and process parameters on the residual stresses and the fatigue behavior under a pulsating bending load in near-net-shape blanking processes was analysed. The authors of the papers showed that after blanking, the material is deformed and internal stresses accumulate, which in some cases cause defects in metal structures, which directly affects the durability of the resulting products. By means of the appropriate selection of machining parameters, the concentration of maximum stresses can be controlled, but this is a complex problem [16, 21]. The results obtained in this work showed a significant impact of the cutting clearance on the values and stress distributions in the area of the cut edge (Figure 17). In the cutting process with circular knifes, the pressure caused by the tools is local and the contact surfaces of the tools with the material are much smaller than in the case of punching and blanking. Compared to the results of other authors analyzing the punching and blanking processes after the shear-slitting, the concentration of maximum stresses was obtained directly at the cut edge (Figures 17(a) and (b)). This condition does not cause accelerated fatigue wear of details. If clearances h_c = 0.03 mm, and h_c = 0.06 mm are used, the maximum stress concentration is approximately 0.07-0.1 mm from the cut edge. In these cases, there is a rapid decrease in stress values outside the area of maximum concentration. If the cutting clearance is h_c = 0.09 mm, the width of the maximum stress concentration zone is increased and amounts to about 0.5 mm. Outside this area, there is also a decrease in the stress value. A similar trend occurs when the cutting clearance is h_c = 0.15 mm (Figure 17(c)). The sheet bending angle β increases, causing the zone of maximum stress to shift and expand. In this case, the width of this zone is about 0.6 mm. An unfavorable case of cutting is the variant with clearance h_c = 0.24 mm, because the sheet is bent and the stress value in the area of the cut edge increases as it moves away from it (Figure 17(d)). The width of the maximum stress zone is the largest in this case.

5. CONCLUSION

The results of experimental studies confirm the possibility of using the shear-slitting process for machining aluminum alloys and obtaining a high-quality cut edge. However, this requires appropriate knowledge and experience, because it is necessary to select the appropriate machining parameters depending on the type of alloy and its thickness. Currently, on production lines, there are great difficulties related to the correct selection of the cutting clearance. Too small value of the clearance causes shortening of the plastic flow and shear phase, accelerating the cracking of the material and increasing the width of the fractured zone on the cut surface. Excessive clearance causes increased edge rounding or bending and burr formation. Experimental and simulation analysis of the process for variable cutting clearance were carried out in the work, as a result of which the optimal cutting clearance for the selected aluminum alloy was determined. Based on the research carried out, the following conclusions can be drawn.

i) The range of the analyzed cutting clearances ensured the width of the sliding fracture not less than 60 % (maximum is 83 % for h_c = 0.18 mm) of the sheet thickness. However, for some settings, despite the considerable width of the sliding fracture, workpiece defects in the form of burrs and edge bends were formed.

ii) For clearance values, when $h_c > 0.15$ mm, there was a significant increase in roll-over and a decrease in the sheared-burnished zones.

iii) The suitable quality of the cut surface was obtained using clearances h_c = 0.03 mm (large share of the sheared-burnished, small fractured area) and h_c = 0.09 mm (small burr and roll-over).

iv) The lowest quality of the product was obtained using the clearance h_c = 0.24 mm. Excessive burr and edge rounding may occur in this case in production lines.

v) Due to the possibility of local irregular burrs, for variants of cutting clearances h_c = 0.03 mm and h_c = 0.06 mm, it is recommended to use clearances with the values h_c = 0.09 and h_c = 0.12 mm. For these variants, the width of the sliding fracture is within the acceptable range and the products are free of excessive burrs and rounded edges and bends. The width of the stress zone is acceptable.

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