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Effect of the punch geometry on the character of force waveforms in blanking process – case study

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ABSTRACT

The aim of the research in the paper was to determine the influence of the shape of the working part of the punch on the character of changes in the cutting force and their maximum values. Different shapes of punches were used: flat, concave, flat-concave and spherical. For the flat punch, additional investigations were performed with different clearance values. The tests were carried out for sheets of different materials (aluminium, copper, brass and five types of low-carbon and alloy steel) for which the properties were determined in a static tensile test. The research used an industrial blanking tool with the possibility of replacing punches mounted on a hydraulic press with a maximum load of 1 MN equipped with sensors for measuring forces and displacements (first metrological class of measurement). The results were recorded using specialist Test&Motion software from Labortech company. The relative thickness of the obtained blanks was the same and amounted to $g_0/D \times 100 = 2.5$ (where D is the diameter of the blank and g_0 its thickness). On the basis of the obtained results, it was shown that the shape of the working part of the punch affects not only the value of the maximum cutting force, but also the character of their changes as a function of displacement. The analysis of the results presented in the paper may be helpful in developing the technological processes of deep drawing or flanging under production conditions at the stage of preparing the starting material.

Keywords: force, metal forming, clearance, blanking

INTRODUCTION

The process of blanking from sheet metal is mainly used in industry as a preliminary stage for preparing the starting material for these processes as: deep drawing, redrawing [1–2] and ironing of draw pieces [3–4] or flanging of collars [5]. One of its main parameters is cutting force [1–4]. Its maximum value, in addition to the dimensions of the blanking die, determines the choice of a punching press in the technological process [1, 3, 4]. On the basis of the engineering formulas available in the literature [1–4], the theoretical maximum cutting force is decisively influenced by factors such as the type of material (especially the shear strength of the material), its thickness, the cutting line (in the case of a blank, its circumference), and the degree of tool wear (of the blanking die, and especially the punch and die). Unfortunately, these formulas do not take into account the shape of the working part of the punch and the clearance between the punch and the die in the calculations. Under industrial conditions, the flat punch is the most common [3–4]. In recent years, many authors have confirmed in their studies that cutting with this type ensures high cutting accuracy, but requires greater force compared to other shapes [6–8]. They have also shown that concave punches and punches with inclined edges reduce the cutting force [6–10]. Most of the studies they conducted were both experimental and simulation-based for various materials [6–10]. Demir et al. [6] conducted a study of the blanking process of a composite made of DP1000 steel and aluminum sheet using explosive welding. They demonstrated that using punches with rounded edges (different radii) reduces the cutting force compared to a flat punch. In their study, Cug et al. [7] used flat, concave, and 16-degree angle punches to cut 3 mm-thick rolled sheet metal made of AM60 and AZ61 magnesium alloys. The lowest force was obtained for the angular punch, and the highest accuracy of the cut blanks was obtained for the flat punch. Bao et al. [8] used computer simulations (FEM) to investigate the effect of three punch types with different edge angles (single inclined edge, double convex inclined edges and double concave inclined edges) on maximum blanking force. They found that the maximum cutting forces of the proposed punch shapes were lower than those of the punches with flat surfaces. Cabrera et al. [9] also used computer modelling (FEM) without experiment to study the blanking process. They compared cutting with inclined, concave and convex punches in terms of, among other things, stress distribution, material savings, and process efficiency. Jasim et al. [10] conducted experimental studies of the effect of various punch inclination angles (from 0° to 20° in 5° increments) on the blanking force for low-carbon steel (AISI 1008). They employed a very high cutting speed (500 mm/min). They demonstrated that using 10° can reduce the cutting force by 90% compared to a flat punch (0°).

In selected works by other authors [11–16], one can also find information on the influence of other technological parameters (such as process speed or the clearance between the punch and the die) on the course of the blanking process, including accuracy (burr size) and cutting force. Singh et al. [11] developed finite element models of various types of punching and blanking tools. On the basis of these models, they analysed the effect of tool geometry changes on the cutting force and punch deformation. They did not experimentally verify their findings. Tekiner et al. [12] experimentally determined the effect of six different clearances on the accuracy and force when blanking aluminium sheet with a flat punch. The highest cutting force and accuracy were obtained for the smallest clearance close to zero (0.009 mm). Çavuşoğlu in his work [13] used computer simulations to investigate the effect of three clearances (1%, 5%, 10%) and four punch radius settings (0.01, 0.25, 0.5, 1 mm) on cutting accuracy and force when blanking AISI 304 stainless steel sheets. On the basis of the results, he concluded that as the clearance increased, the burr and smooth-to-cracked surface ratio increased, and the blanking force decreased. However, the punching force also increased along with the punch radius, and the cutting accuracy decreased compared to blanking with a flat punch. Adnan et al. [14] evaluated the effect of punching clearance on burr formation in mild steel, brass, and aluminium sheets. Their results showed that the larger the clearance, the smaller the burr size. The smallest burr sizes were observed for brass (compared to mild steel and aluminium) at the same clearance. Baer et al. [15] conducted numerical studies of the effect of process parameters, such as sheet strength and thickness, and the grade of cemented carbide used in the punch, on cutting force. They verified the developed model of the precision blanking process using experimentally measured force from an industrial precision cutting process for spacer discs. Bhoir et al. [16] investigated the effects of sheet thickness, punch-die clearance, tool wear, and punch geometry on the blanking process. They developed a mathematical model of the process and applied the design of experiments approach to predict the optimal punch-die clearance for mild steel. Among many works, there is a special group of them that presents their research results in specific industrial contexts in terms of the use of the cutting process to prepare the input material for further technology [17,18], quality assessment of the obtained product [19] or energy consumption [20].

Summarizing the review of recent literature based on available sources, it was concluded that it would be worthwhile to expand the discussed blanking issue to include studies using other technological parameters (and punch shapes). The primary aim of this study was to determine the effect of punch shape and clearance on the nature of changes in punching force as a function of displacement and the maximum force value for various of materials used in industry. The studies were conducted for various punch face shapes proposed by the author: flat, concave-conical, concave-flat-conical, and convex-spherical. For the purposes of describing the results later in this paper, concave punches were referred to as conical and flat-conical, while convex-spherical punches were referred to as convex. Blanking with different clearances was performed using a flat punch. The materials for testing (three types of non-ferrous metals and five types of steel) in the form of strips cut from sheet metal were selected due to their different mechanical properties (which were determined experimentally) and diverse industrial applications for forming draw pieces of varying degrees of difficulty and purpose.

The scientific novelty of the author's research is that it was conducted for a much wider range of materials – eight types (unlike other authors [6–16], who studied a maximum of two or three) with the same technological parameters and under the same test conditions. This enabled a more in-depth comparative analysis. Furthermore, the research employed flat-conical, conical and spherical punches with geometric parameters (internal concave cone angles and spherical radius) not used by other authors.

Table 1 presents a complete index of the symbols and notation used in paper.

METHODOLOGY

The experimental investigations used sheets of nominal thickness 1 mm made of three grades of non-ferrous metals (EN-AW 1050A aluminium, Cu-ETP copper and CuZn37 brass) and five grades of steel (S235JRG2, X5CrNi18-10, X6Cr17, DC01 and DX51D). On the basis of the [17] standard, a static tensile test of metals was performed at the stand shown in Figure 1. This stand consisted of a LabTest 5.20SP1 testing machine with a maximum load of 20 kN for 0.5 metrological class and a computer with professional Test&Motion software used in industrial research laboratories for measuring forces and displacements (Labortech company). Figure 2 shows the shape and dimensions of the flat samples compliant with the [21] standard.

The average thickness a_0 and width b_0 of the samples determined on the basis of five measurements with a micrometre screw are presented in Table 2 together with the calculated cross-sections S_0 and the determined average values of the maximum forces F_m obtained in the static tensile test. The changes in tensile force and displacement obtained for selected samples were converted into stress versus relative strain graphs which are presented in Figure 3.

The mechanical properties of the tested materials were determined and presented in Table 3. The highest tensile strength value R_m was obtained for X5CrNi18-10 steel and the lowest for aluminium. The same was true for the yield strength and percentage elongations after fracture A and $A_{11.3}$ (very small difference between X5CrNi18-10 steel and S235JRG2 steel for elongation A).

For experimental blanking tests, strips were cut from 45 mm wide metal sheets using a guillotine shear with sloped edges knives. The punching process was performed on the stand shown in Figure 4. It consisted of the following components – a 1 MN hydraulic press for 1 metrological

Table 1. Complete index of the symbols and notation used in paper

Symbol	Unit	Designation
A	%	Percentage elongation after fracture (for gauge length L_{05})
$A_{11.3}$	%	Percentage elongation after fracture (for gauge length L_{010})
a_0	mm	Thickness of the sample for static tensile test
b_0	mm	Width of the sample for static tensile test
D_0	mm	Diameter of the blank
F_m	N	Maximum force in static tensile test
g_0	mm	Thickness of the blank
h	mm	Width of the sample part to be mounted in jaw chuck
L_0	mm	Total length of the measuring part of the sample
L_{05}	mm	Initial gauge length of $5.65\sqrt{S_0}$
L_{010}	mm	Initial gauge length of $11.3\sqrt{S_0}$
L_t	mm	Total length of the sample for static tensile test
m	mm	Length of the sample part to be mounted in jaw chuck
R_m	MPa	Tensile strength
R_{p02}	MPa	Yield strength
R_t	MPa	Shear strength
S_0	mm²	Cross-sectional area of sample for static tensile test
v	mm/min	Velocity of punch movement

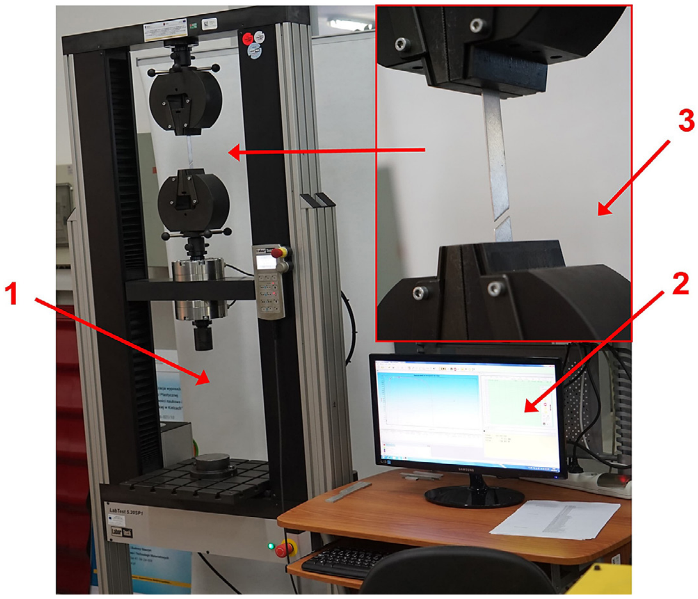

Figure 1. View of stand for static tensile tests, where: 1 – LabTest 5.20SP1 testing machine, 2 – computer stand with Test&Motion software, 3 – the flat test piece in jaw chuck after testing

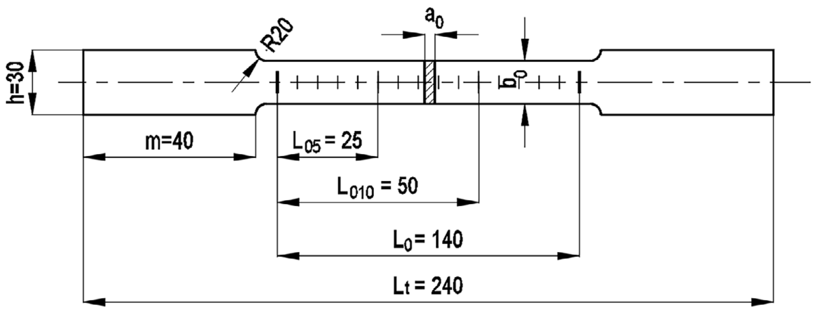

Figure 2. The shape and dimensions of the samples for static tensile tests

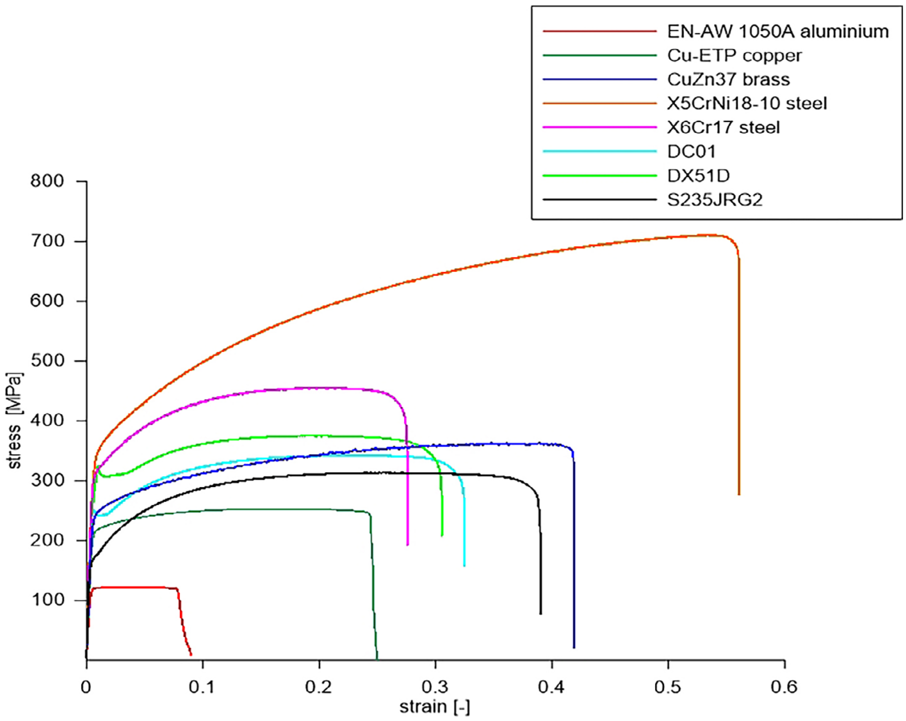

Figure 3. The stress vs. relative strain for different materials on the base static tensile test

Table 2. Dimensions and maximum values of forces obtained in static tensile test

Material	a_0 (mm)	b_0 (mm)	S_0 (mm²)	F_m (N)
EN-AW 1050A aluminium	0.970	20.10	19.50	2377.84
Cu-ETP copper	0.997	20.08	20.02	5071.86
CuZn37 brass	0.995	20.06	19.96	7278.10
S235JRG2 steel	0.980	20.01	19.61	6150.92
X5CrNi18-10 steel	0.985	19.87	19.57	13912.62
X6Cr17 steel	0.998	19.96	19.92	9094.82
DC01	0.990	20.02	19.82	6787.64
DX51D	1.01	20.05	20.25	7607.23

Table 3. Mechanical properties of materials used in the blanking process

Material	R_m (MPa)	$R_{p0.2}$ (MPa)	A (%)	$A_{11.3}$ (%)
EN-AW 1050A	121.9	117	16.3	12.5
Cu-ETP	253.3	209	41	32.8
CuZn37	364.6	235	54.1	44.9
S235JRG2	313.7	176	62.0	49.6
X5CrNi18-10	710.9	314	61.7	53.7
X6Cr17	456.6	298	45.7	36.9
DC01	342,5	248	58.3	42.3
DX51D	375.67	299 (R_{eH})	53.9	41

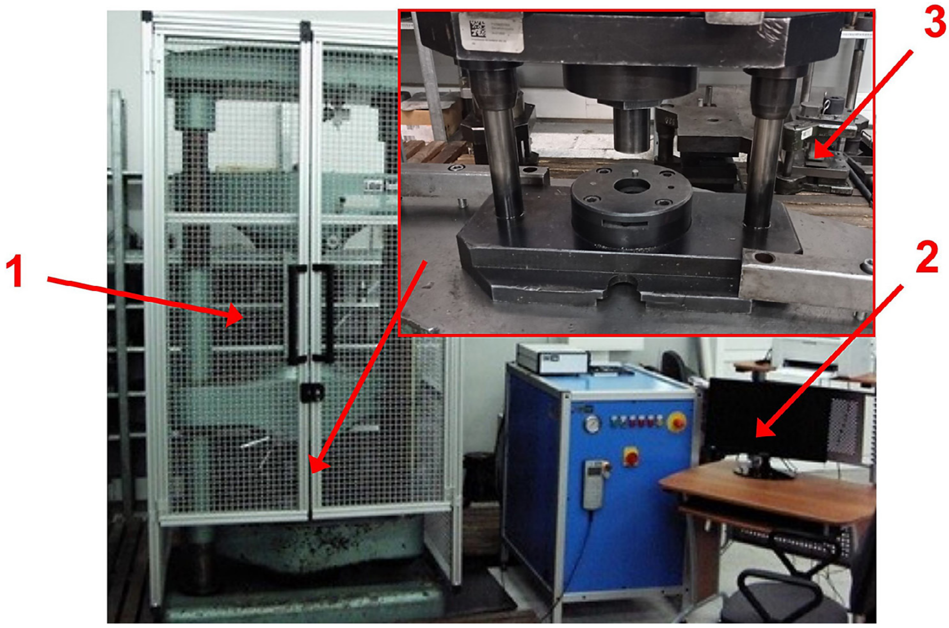

Figure 4. Stand for investigations of blanking process, where: 1 – hydraulic press with a maximum load of 1 MN, 2 – computer stand with Test&Motion software for measuring forces and displacements (LABORTECH), 3 – the blanking die

class, the blanking die, and software for measuring forces and displacements. The scheme of the industrial blanking die used in the investigations is shown in Figure 5.

The blanking die uses replaceable punches, the shape of which is shown in Figure 6 (a-d). The die diameter was the same in all cases and was 40.3 mm. The first set of punches had a diameter

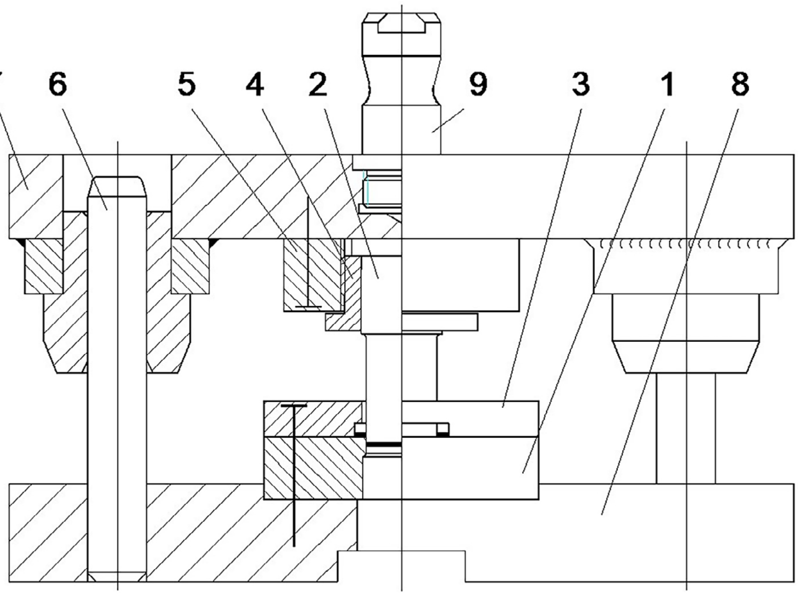

Figure 5. The blanking die, where: 1 – die, 2 – punch, 3 – sweep-off gear, 4 – clamp nut of the punch, 5 – holder of the punch, 6 – leader pin, 7 – upper plate, 8 – lower plate, 9 – die shank

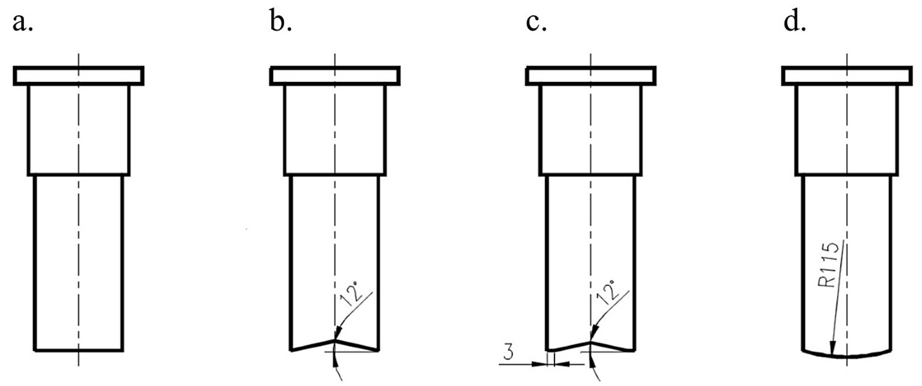

Figure 6. Various shapes of punches used in the research: a) flat, b) concave, c) flat-concave, d) convex

of 40.2 mm (Figure 6 a-d). This allowed for a 0.1 mm clearance between the punch and the die during cutting. In industrial practice, the so-called one-sided clearance is usually given [1, 3, 4, 22]. In this case, it was 0.05 mm. The second set used flat punches (Figure 6a) with variable diameters: 40.1 mm, 40.15 mm, and 40.2 mm. In this case, the clearances during cutting were 0.2 mm, 0.15 mm, and 0.1 mm, respectively (i.e., one-sided clearance: 0.1 mm, 0.075 mm, and 0.05 mm). The clearance assumed for industrial cutting with punches generally depends on the thickness of the material being cut. It is most often assumed to be approximately 10% of this thickness, depending on the required cutting accuracy [22]. For a one-sided clearance of 0.05 mm, the relative thickness of the obtained blanks was $g_0/D_0 = 0.025$ (where s_0 is the material thickness and D_0 is its diameter).

The shape of the punches for the tests was developed based on the analysis of problem, general literature guidelines [22] and a series of computer simulations of the blanking process conducted by the author for various punch shapes [23]. The shape of the punch's front surface significantly influences the adhesion of the cut material to the punch surface, which can disrupt the normal operation of the blanking die. This phenomenon can be especially dangerous in large-scale and mass production, as it hinders automation. Creating a slightly convex cylindrical surface on the punch's front (Figure 6d) promotes the separation of the cut material from the punch surface [22]. The modelling conducted by the author demonstrated the possibility of blanking without defects for flat, concave, and convex punches [23]. The boundary conditions determined in the modelling, in the form of the shapes of the front surfaces of the punches, their dimensions, and technological parameters, were used for the experimental studies of the blanking process described in this paper. The punches for the tests were made of NC11LV steel on an AVIA CNC machine. They were then hardened to approximately 56HRC. A view of the punches is shown in Figure 7. During the tests, the punches moved at a constant speed of v = 80 mm/min.

In the case of the concave, flat-concave and convex punches, shallow technological blind holes are visible, created in their main axis of symmetry. These holes were necessary to properly shape the front cutting surfaces using a micro-carbide insert (HORN, Germany). These holes had no effect on the blanking process because they were not located on the cutting edges of the punches.

RESULTS AND ANALYSIS

The tests involved cutting blanks with a relative thickness of $g_0/D_0 = 0.025$ using a blanking die (Figure 5) mounted on a stand shown in Figure 4, with forces and displacements measured. The results included the samples shown in Figure 8 and the finishing passes shown in Figure 9.

In the first stage of the study, blanks were cut with flat punches (Figure 6a) at various one-sided clearances: 0.1 mm, 0.075 mm, and 0.05 mm, respectively. Graphs of force versus displacement for various materials are presented in Figure 10. Their nature is similar regardless of the material type. For all materials, the increase in force corresponds to the following phases: elastic deformation, elastic-plastic deformation, and plastic flow (in this phase, material hardening occurs). When the force reaches its maximum value, the blanks fracture along the circumference, followed by a force drop to a value necessary to eject the object from the material waste. The maximum cutting force values at various clearances for individual materials are summarized in Table 4. In each case, the highest blanking forces were observed at the smallest one-sided clearance of 0.05 mm.

As clearance increased, the maximum cutting force decreased, regardless of the material type.

Figure 7. View of the punches used in experiment

Figure 8. Exemplary blanks made from different materials after cutting with punches of various shapes at constant one-sided clearance (0.05 mm)

Figure 9. Sheet belts with finishing passes from various materials

This percentage reduction in cutting force at one-sided clearances of 0.05 mm and 0.1 mm was not uniform for individual materials. The largest reduction was for aluminium, approximately 34%. For the rest of the materials, it ranged from approximately 5–7% (X6Cr17, Cu-ETP, CuZn37, and DC01) to approximately 11–15% (X5CrNi18-10, S235JRG2, and DX51D).

It was observed that in the vast majority of cases, the smaller the one-sided clearance during cutting (Figure 10), the greater the force required to remove the blank from the material waste in the final phase of the process. Only for two material grades (CuZn37, DC01) was this force at a one-sided clearance of 0.05 mm similar to that at a clearance of 0.075 mm. Additionally, summary graphs of force versus displacement were generated for all materials at individual one-sided clearances and are presented in the following figures: 0.1 mm (Figure 11), 0.075 mm (Figure 12), and 0.05 mm (Figure 13), respectively.

Considering Figures 11–13 and the data in Table 4, it was noted that the lowest maximum cutting force values were obtained for the blanks made of non-ferrous metals (aluminium, copper, brass), while the highest values were obtained for the remaining five steel grades. By far, the highest force at a clearance of 0.05 mm was obtained for X5CrNi18-10 steel, and the lowest for aluminium samples. The relative percentage difference (relative increase) in this case was as much as 350%. In the remaining cases (for S235JRG2, X6Cr17, DC01, and DX51D steels) at a one-sided clearance of 0.05 mm, the differences compared to aluminium were not as significant, ranging from 119% to 185%. With increasing clearance, the relative percentage difference between the force for X5CrNi18-10 and for aluminium increased: for a one-sided clearance of 0.075 mm, the relative percentage increase was 443%, and for a one-sided clearance of 0.1 mm it was 505%. For the other steel grades, these differences also increased and ranged from 184% to 265% at 0.075 mm and 206% to 307% at 0.1 mm, respectively.

In the second stage of the tests, blanking was performed using punches of the same diameter of 40.2 mm (with a one-sided clearance of 0.05 mm), but with different shapes of the working part, as shown in Figure 6a-d. The obtained changes in force as a function of displacement are shown in Figure 14.

It is worth noting that the blanking process discussed earlier, both with different clearances and with different punch shapes, occurred over a relatively short displacement distance of approximately 2–4 mm. The observed nature of the changes in cutting forces (Figure 6a-d) revealed (especially under high magnification) for most materials a phenomenon of rapid force increases to maximum values for flat, flat-conical, and conical punches during the elastic, elastic-plastic, and plastic flow phases, and a slightly more gradual increase for the convex punch. To compare the maximum force values for different punches and materials, they are summarised in Table 5.

The highest cutting force values were recorded with a flat punch for the samples made of EN-AW 1050A, CuZn37, X5CrNi18-10, DX51D, and S235JRG2, respectively. In the case of the samples made of Cu-ETP, X6Cr17, and DC01, cutting was performed with the highest force with a flat-conical punch, while for Cu-ETP and DC01 the differences compared to the flat punch were relatively small and amounted to about 4% (4.11% and 4.15%, respectively). The lowest cutting force values were

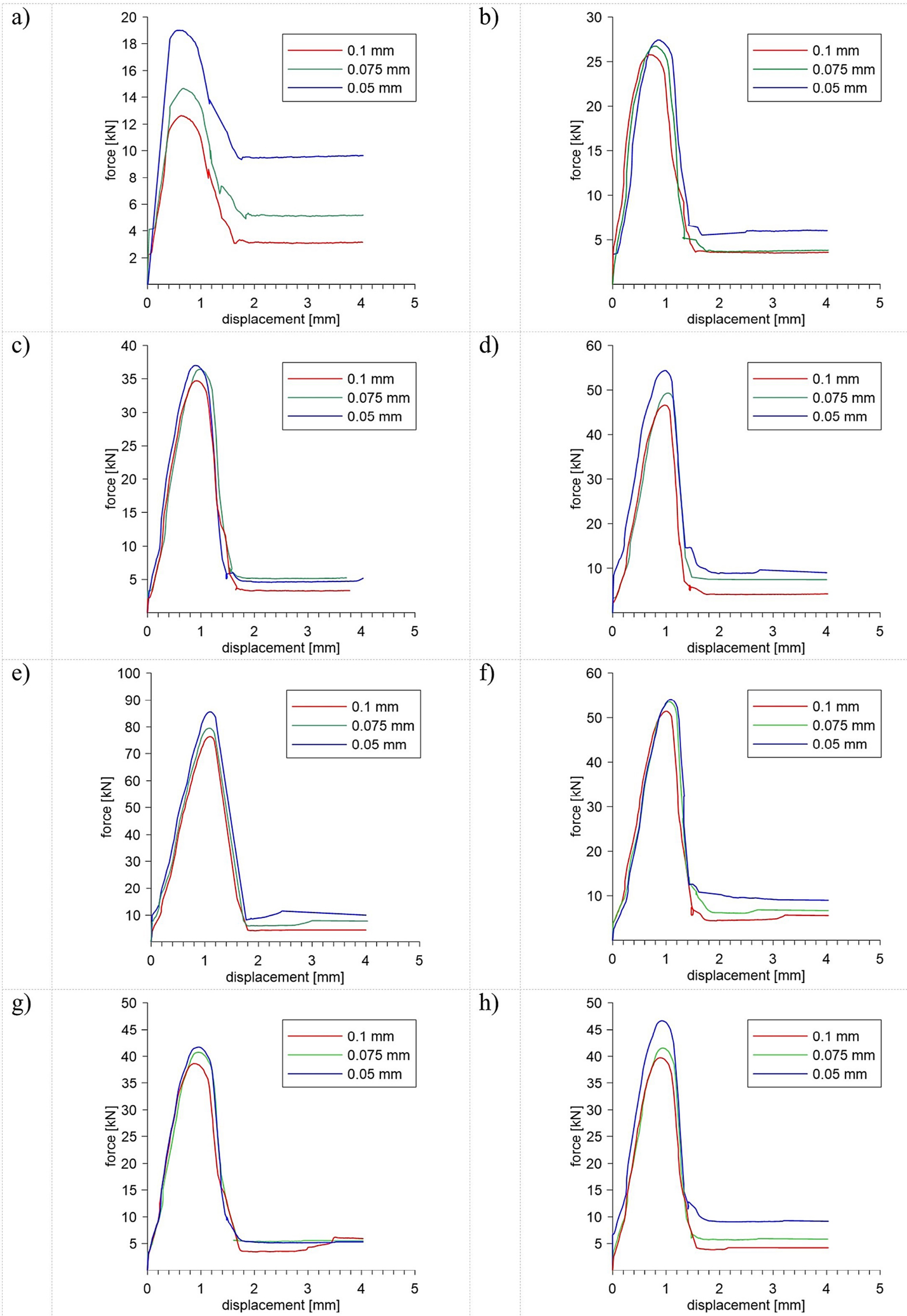

Figure 10. The force vs. displacement obtained for blanking tests at flat punch with one-sided clearances (as follows: 0.1 mm; 0.075 mm and 0.05 mm) for different materials: a) EN-AW 1050A, b) Cu-ETP, c) CuZn37, d) S235JRG2, e) X5CrNi18-10, f) X6Cr17, g) DC01, h) DX51D

Table 4. The maximum values of the experimental blanking forces (N) with a flat punch at different values of the clearance between the punch and the die

Material	One-sided clearance		
	0.05	0.075	0.1
EN-AW 1050A	19019.15	14647.75	12631.18
Cu-ETP	27405.06	26725.7	25771.16
CuZn37	37043.63	36398.66	34694.54
S235JRG2	54305.61	49323.66	46639.19
X5CrNi18-10	85537.44	79535.01	76413.41
X6Cr17	54097.79	53454.27	51391.83
DC01	41707.40	40752.86	38657.46
DX51D	46683.63	41541.14	39733.82

Table 5. The maximum values of experimental blanking forces (N) for different shape of punches and 0.05 value of the one-sided clearance between the punch and the die

Material	Shape of the punch			
	Flat	Concave	Flat-concave	Convex
EN-AW 1050A	19019.15	13012.42	12982.32	12542.32
Cu-ETP	27405.06	27403.63	28697.84	26224.07
CuZn37	37043.63	35058.58	35578.85	36127.78
S235JRG2	54305.61	52848.01	49461.25	49451.23
X5CrNi18-10	85537.44	80929.55	83271.48	84591.49
X6Cr17	54097.79	54418.84	56686.23	53120.32
DC01	41707.40	40704.13	43441.63	41135.54
DX51D	46683.63	41126.94	44231.34	42491.39

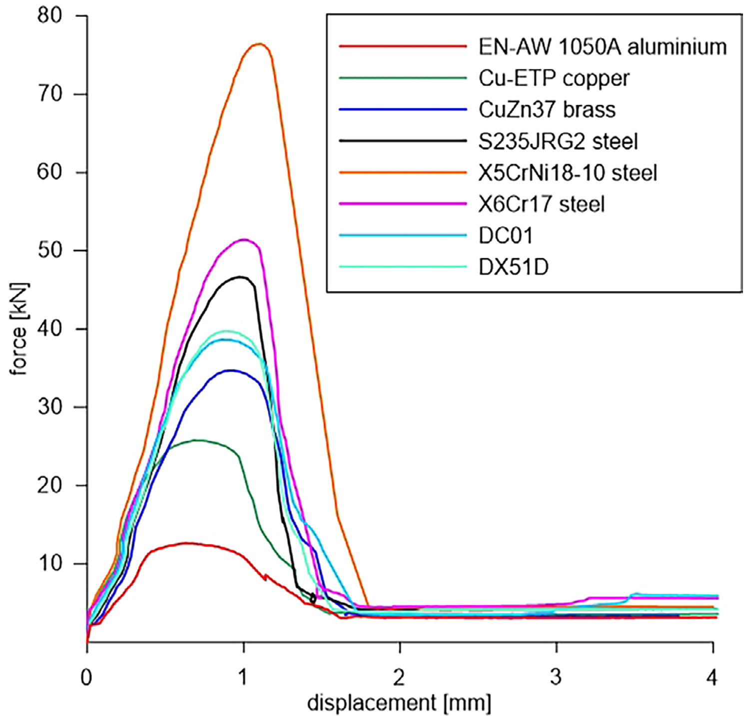

Figure 11. The force vs. displacement obtained for blanking tests at flat punch with 0.1 mm one-sided clearances for different materials

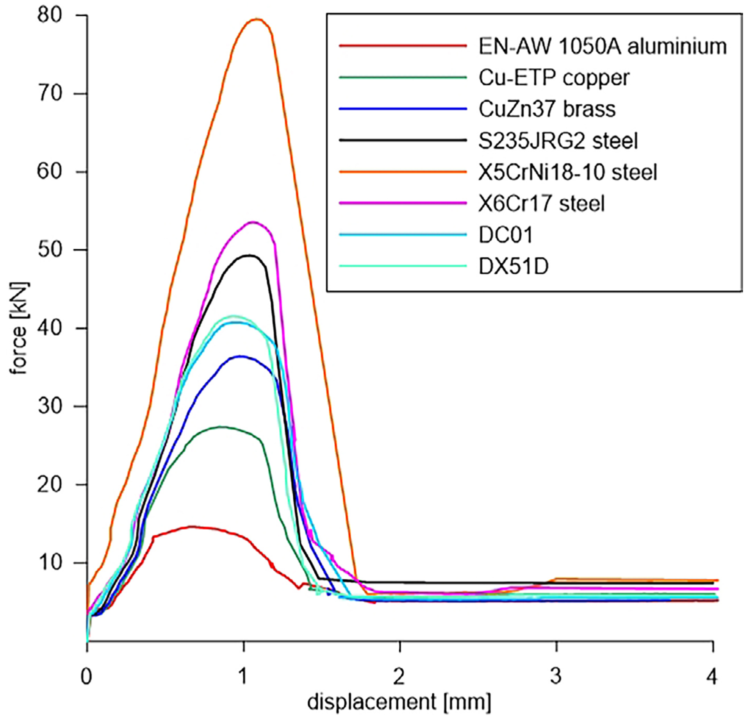

Figure 12. The force vs. displacement obtained for blanking tests at flat punch with 0.075 mm one-sided clearances for different materials

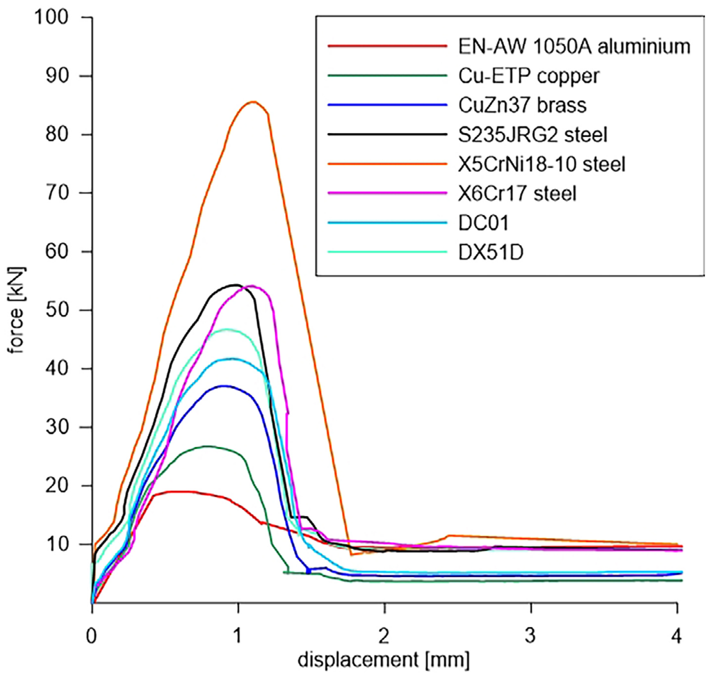

Figure 13. The force vs. displacement obtained for blanking tests at flat punch with 0.05 mm one-sided clearances for different materials

recorded with a spherical punch for the samples made of EN-AW 1050A, Cu-ETP, S235JRG2, and X6Cr17, and with a conical punch for CuZn37, X5CrNi18-10, DC01, and DX51D.

By far the largest relative percentage difference between maximum forces (with flat and spherical punches, respectively) was obtained for aluminium samples. This difference was

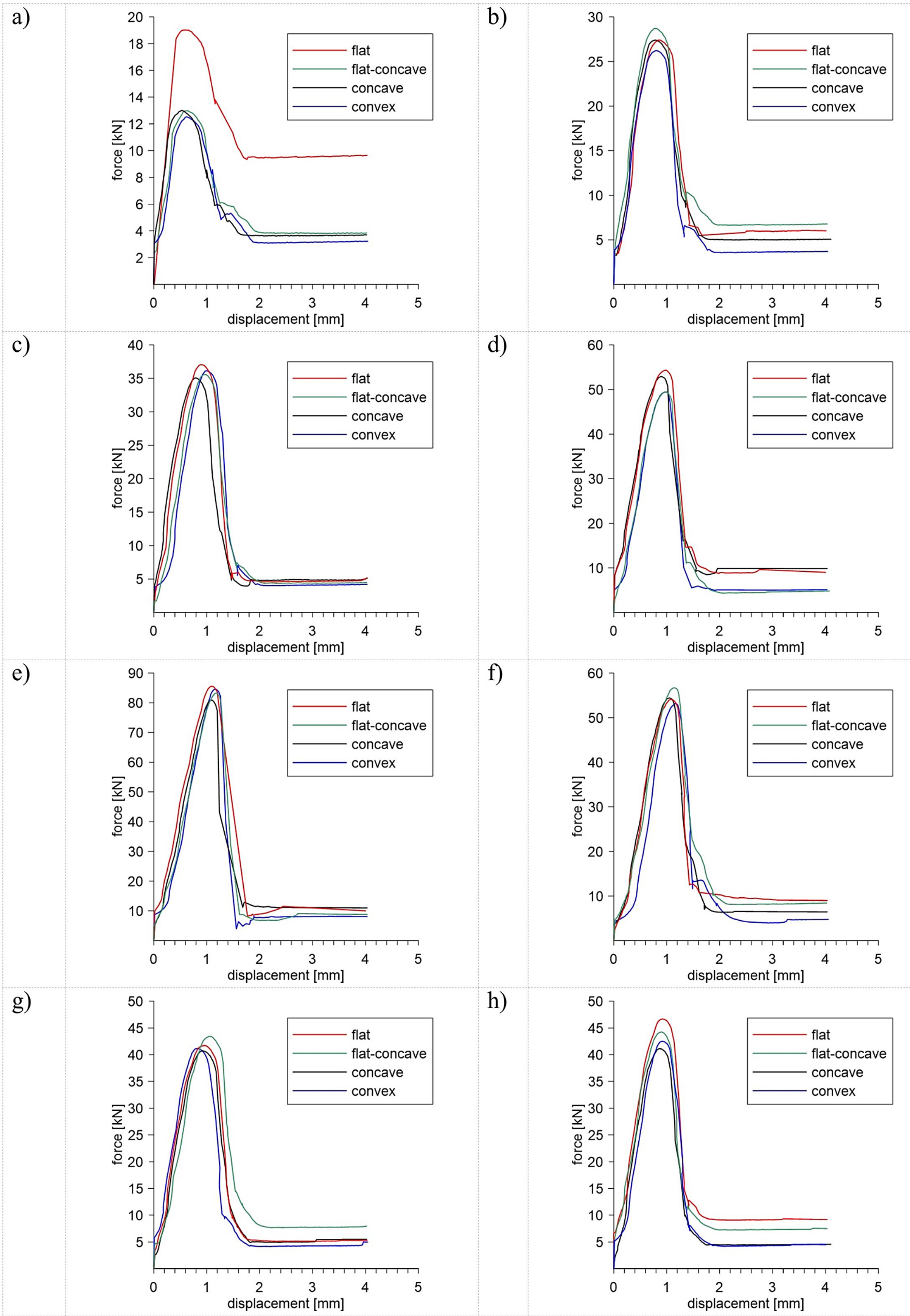

Figure 14. The force vs. displacement obtained for blanking tests at different shape of punch with 0.05 mm one-sided clearances for different materials: a) EN-AW 1050A b) Cu-ETP c) CuZn37 d) S235JRG2 e) X5CrNi18-10 f) X6Cr17 g) DC01 h)DX51D

51.6% (this was an increase in the cutting force with the flat punch compared to the spherical punch). For the other materials, the differences between the highest and lowest cutting forces were much smaller, ranging between 5.7% and 13.5%. These were 5.7% for Cu-ETP, CuZn37, and X5CrNi18-10, 6.7% for X6Cr17 and DC01, 9.8% for S235JRG2, and 13.5% for DX51D, respectively.

Figures 15, 16 and 17 additionally present collective graphs of changes in cutting forces for various materials using individual punches (flat-conical – Figure 15, conical – Figure 16 and convex – Figure 17).

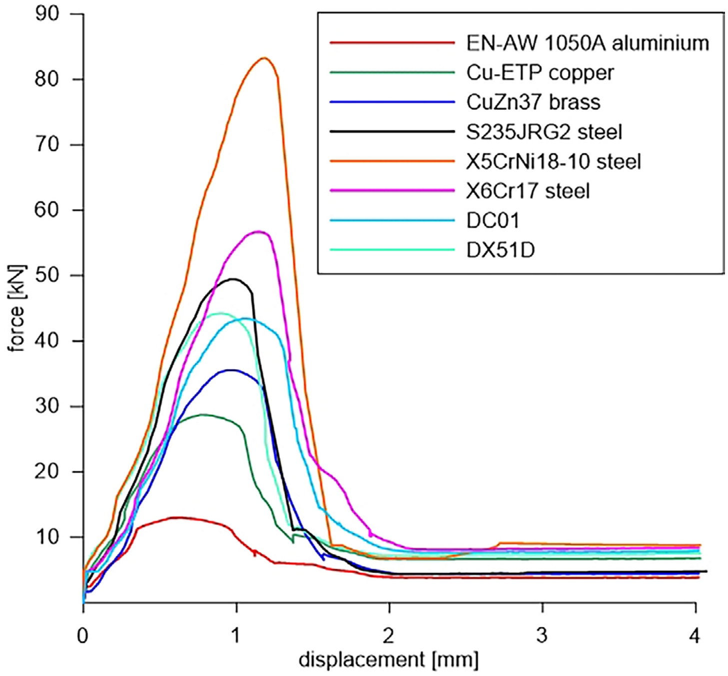

Figure 15. The force vs. displacement obtained for blanking tests at flat-concave punch with 0.05 mm one-sided clearance for different materials

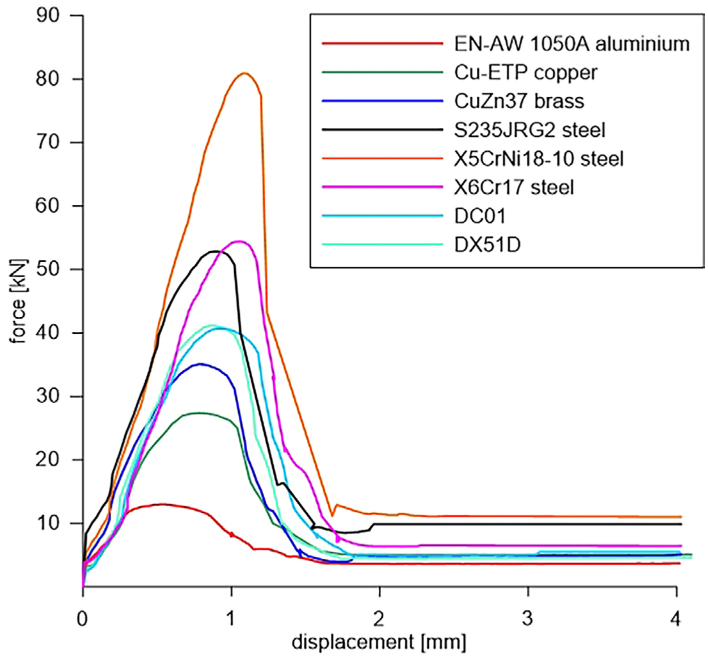

Figure 16. The force vs. displacement obtained for blanking tests at concave punch with 0.05 mm one-sided clearance for different materials

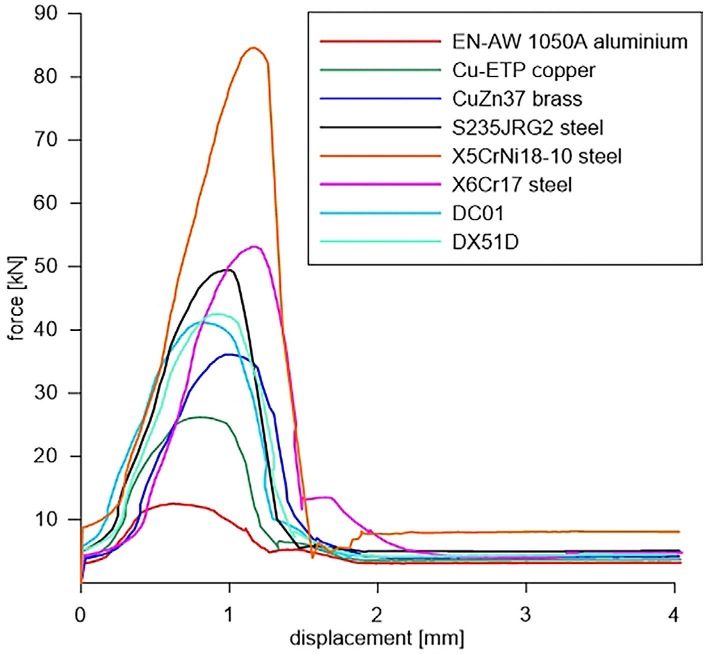

Figure 17. The force vs. displacement obtained for blanking tests at convex punch with 0.05 mm one-sided clearance for different materials

Taking into account the data presented in these and those in Figure 13 (flat punch), it was found that, in general, the lowest cutting forces were recorded for non-ferrous metals, and the highest for the steel samples. Among non-ferrous metals, the lowest maximum forces were obtained for aluminium, and in the case of the steel samples, the highest for X5CrNi18-10. The relative percentage differences between them were approximately 350% for flat punch cutting, 522% for conical punch cutting, 541% for flat-conical punch cutting, and 574% for convex punch cutting (increase in cutting force for the steel sample compared to the aluminium sample).

The fact that the highest cutting force was obtained for the steel samples and the lowest for aluminum for all punches is consistent with the results obtained in the static tensile test (force values F_m given in Table 2 and tensile strength R_m presented in Table 3). The relative differences in the tensile force F_m and strength R_m for these materials were approximately 485% and were greater than those for the blanking forces with a flat punch and smaller than those for the cutting forces with a flat-conical, conical and spherical punch. The cutting force is significantly influenced by the cutting strength R_t of the material, which is related to the tensile strength R_m. Under practical conditions (simplified engineering calculations), R_t is assumed to be approximately $0.8R_m$.

When blanking with flat, conical, or flat-conical punches, no effect of punch shape on the accuracy of blank cutting was observed in terms of shape change or deformation. The situation was different when cutting with a convex punch. For most materials, the blanks slightly bent, forming a small spherical cup, as shown in Figure 18 for the X6Cr17 steel sample. For the purposes of describing the test results, this effect was called the “boat” effect. Regardless of the punch shape, no effect was observed on the shape or accuracy of the finishing passes created in the sheet metal strips after cutting.

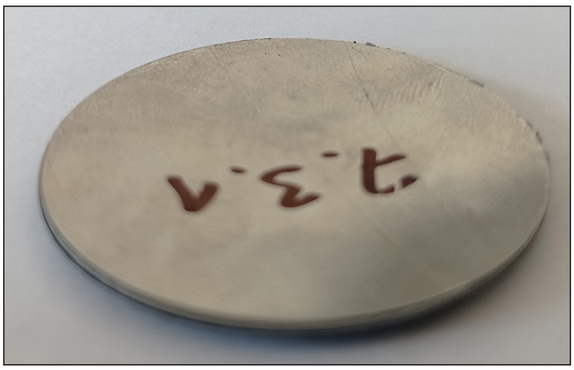

Figure 18. The X6Cr17 steel sample with a delicate “boat” effect, which was cut with a convex punch

The results regarding the highest blanking forces obtained with a flat punch for EN-AW 1050A, CuZn37, X5CrNi18-10, DX51D, and S235JRG2 are consistent with the observations of other authors, among others, in their works for composite made of DP1000 [6], AM60 and AZ61 magnesium alloys [7] and low carbon steel AISI 1008 [10]. However, it is difficult to compare the results of the cutting forces for the remaining punch shapes (flat-conical, conical and spherical) with the results of the mentioned works, because the authors [6–10] used other punch shapes or similar ones in their studies, but with different geometric parameters. In this context, the results of some authors [13] who conducted research only in the field of computer modelling of the blanking process without experimental verification may be controversial. The statement [13] that the cutting force increases alog with the punch rounding radius in relation to the flat punch (radius 0°) is debatable, because it was not confirmed in the research conducted in this paper (spherical punch), nor in the results of other authors [6–11]. The author [13] conducted the research only for AISI 304 stainless.

In the case of the results of this research concerning the effect of clearance on the punching force with a flat punch, the obtained results are consistent with the conclusions of other authors [11–16] in this respect, regardless of the technological parameters they adopted (including the punch travel speed).

CONCLUSIONS

On the basis of the tests carried out on blanking process of blanks with a relative thickness of $g_0/D_0 = 0.025$ from various materials using flat, flat-concave, concave, convex punches at constant clearance and a flat punch with different clearances, the following conclusions were drawn:

The work is a case study because it takes into account selected punch shapes with specific geometric parameters and selected material types. A certain novelty of these studies consisted in the use of parameters (especially geometric punches of conical, flat-conical and spherical shape) not used by other authors.

Regardless of the material type and punch shape, the nature of the changes in cutting force as a function of punch displacement shows significant similarities in the occurrence of four phases: elastic deformation, elastic-plastic deformation, plastic flow, fracture, and final separation of the blank from the waste material. The graphs differ significantly in the maximum values of the cutting forces. In each case, the blanking force for the X5CrNi18-10 steel samples was significantly greater than that for the EN-AW 1050A aluminium samples. For example, the relative percentage differences for these materials when punched with conical, flat-conical, and convex punches ranged from 522% to 574%.

Regardless of the material type, as the clearance between the punch and the die decreases, the blanking force and the force required to eject the blank from the waste material. Both when cutting with different clearances using a flat punch and with constant clearance using punches of different shapes adopted in the test methodology, the highest blanking forces were obtained for steel samples, and the lowest for non-ferrous metal samples.

Cutting with flat, flat-conical, or concave punches does not affect the shape or dimensions of the blank. Cutting with a convex punch creates a “boat-shaped” effect on the blank, but does not change the shape of the finishing pass.

The shape of the punch when blanking influences the maximum cutting force. This effect is not clear for individual material types. The highest forces were achieved when blanking with flat and flat-conical punches. The lowest forces were achieved when cutting with convex and conical punches. Knowledge of the maximum cutting forces for different punch shapes is important when developing deep drawing technologies for production conditions, especially when selecting a press with a specific load.

During the research, certain limitations were noted that could be addressed, but this requires further in-depth testing over time. For the experiment, completely new punches, previously unused, were manufactured. Typically, the punches used under production conditions gradually wear out, affecting, among other things, the shape and dimensions of their front surfaces. According to the author, this fact may have some impact on the test results over time, especially in the range of maximum cutting force values (it appears that the most rapidly wearing punch may be the conical punch, which has “sharp” edges).

According to the author, an area requiring potential improvement in the conducted research is the use of a stand (which could be created in a typical industrial environment) based on an electro-hydraulic press with a maximum load of, for example, 200 kN, providing more precise motion control compared to hydraulic presses. However, the workspace of such a press must allow for the installation of a blanking die of appropriate dimensions. The fact of more precise control of the press movement may be important when blanking samples from materials with very similar mechanical properties.

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