Adjusting the Punching Process of Poly Vinyl Chloride (PVC) and Polycarbonate/ Acrylonitrile Butadiene Styrene (PC/ABS) Cable Ducts Using High-Speed Video Recordings

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***Abstract*—Punching of the side recesses is one of the process steps during the production of cable ducts. This process has already been applied successfully for polyvinyl chloride (PVC). However, punching cable ducts made of flame-retardant polycarbonate/acrylonitrile butadiene styrene (PC/ABS) is challenging. Increased burr and film formation occurs. This study aims at visualizing and adjusting the burr and film formation using high-speed recordings and a transparent tool. Thereby, the initial burr and film formation are identified. Subsequently, corresponding optimization steps may be defined. Analyzing the existing burr and film is falsified because the returning punch influences the resulting burr and film. Additionally, the existing punching process for PVC and PC/ABS was compared in order to formulate optimization steps. Therefore, snapshots from the high-speed recordings were assigned to the respective process steps. This revealed the onset of film formation and its causes and shows that PVC and PC/ABS follow different fracture mechanisms.**

***Index Terms*—Polymer blend PC/ABS, high speed recordings, punching process visualization, cable duct**

I. Introduction

During the manufacturing of cable ducts made of the polymer blend polycarbonate/acrylonitrile-butadiene-styrene (PC/ABS), burrs and film formation occur during the punching process. Both reduce the quality of the end product and thus make an additional deburring process necessary. The resulting film can cause difficulties, e.g. in production, if it plugs bearings or similar. The burr that sometimes occurs can injure both, cables and workers [1]. This, in turn can endanger the operational safety of the electrical systems and the work safety in general. Since the additional deburring process is reflected in the product prices, the University of Applied Sciences (HTW) Berlin in cooperation with Stanova Stanztechnik GmbH is aiming at preventing the burrs and film formation by adapting the process.

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PC/ABS is used in cable duct production because the standard material polyvinyl chloride (PVC) releases (Cl-) ions at elevated temperatures of approximately 210 ℃ and higher. These (Cl-) ions can combine with free protons (H+) of the ambient medium to form the hydrochloric acid HCl [2]. In addition, some applications such as rail vehicle construction require compliance with the international UL94 standard for the flammability of plastic materials. Most PC/ABS materials meet this requirement -given the best rating "v-0"- without the addition of halogens [1, 3].

Most studies in this field focus on the optimization and analysis of the PC/ABS material properties. Their aim is to optimize the material behavior by varying the mixing ratio of PC to ABS, the butadiene content in the ABS, the process parameters during extrusion and mixing and optional additives [4-8]. So far, at the adjustment and therefore step-by-step optimization of the manufacturing process has not yet been described.

First investigations of the process revealed that the resulting burrs and film, which occur during punching, are distorted or deformed by the returning punch. Fig. 1 clearly demonstrates that the artefact was bent against the punching direction. Thus, no exact conclusions regarding the respective origin of the artefacts can be drawn from the final burr or film after the punching process. [9]

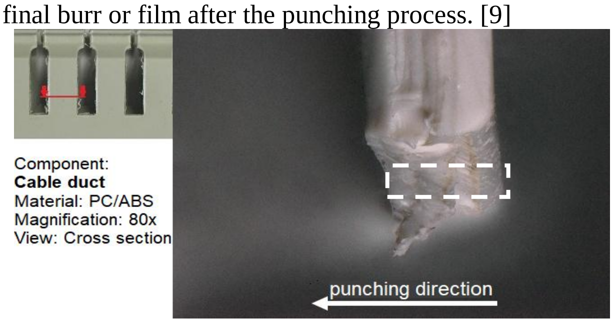

Figure 1. Falsification of burr and film formation on the component bend against punching direction due to the return stroke of the punch [9].

Therefore, the burr and film formation was analyzed implementing a transparent tool and a high-speed camera intending to find possible causes for burr and film formation and subsequently define countermeasures.

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II. Materials and Methods

The characteristics of the materials PC/ABS and PVC as well as the punching process itself were investigated during punching installing a specially constructed transparent tool comprising of a high-speed camera "MotionPro HS-4" from Redlake Inc., Pasadena (today: IDT Inc., Pasadena) and a punching unit "FlexSpee" from Stanova Stanztechnik GmbH, Berlin (Fig. 2).

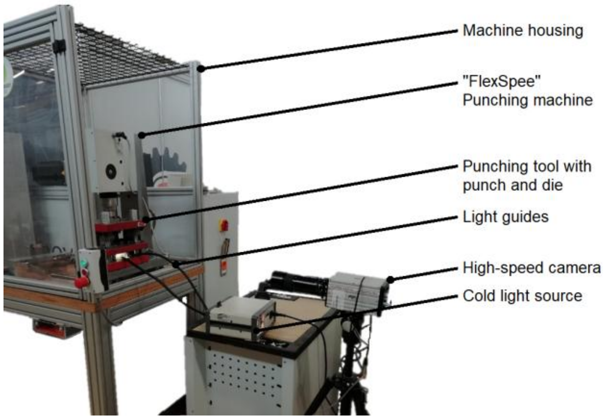

Figure 2. Experimental set-up for the high-speed recordings of the punching process.

The active elements mounted in a punching tool with blank holder are driven by the FlexSpee punching unit via a rack and pinion drive. Punching speeds up to 500 mm/s are possible. The tests were carried out at a punching speed of 350 mm/s offering the most visually evident results. Instead of the actual active elements normally used for the production of cable ducts, punches based on ISO 8020 (Fig. 3), die and guiding bushes based on ISO 8977 with rectangular cross-section (7x7 mm) are used. These represent an alternative offering both, economic advantage and still meaningful results [9].

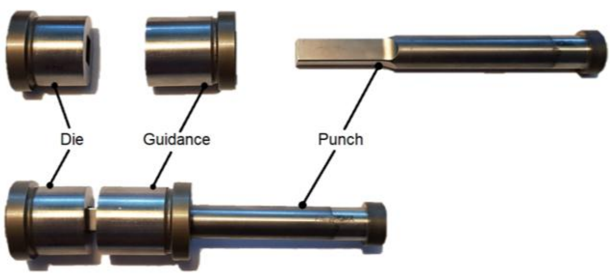

Figure 3. Active elements of the transparent tool.

The die has been provided with a recess. This is used to observe the punching process. Die as well as die holder must necessarily be machined to enable the study (Fig. 4). In addition, it is possible to mount a transparent insert onto the die holder. This insert is used as a replacement of the fourth cutting edge. It enables to survey the punching process form the backside (closed cutting line). Without this insert, the cross-section of the punching process is visible (open cutting line).

Extruded PC/ABS and PVC materials provided by Covestro AG, Leverkusen were used as test material. These were supplied as cable ducts and converted into flat material by chipping. Both materials meet the required properties regarding flame retardancy and extrudability in order to be used for cable ducts production. The present PC/ABS meets the necessary requirements for the flame retardancy "v-0" according to the UL94 standard valid for the use in rail vehicles. The material thickness of the PVC is 1.2 mm and those of the PC/ABS 1.4 and 3.0 mm. In fact, both of these materials have already been applied for the production of cable ducts.

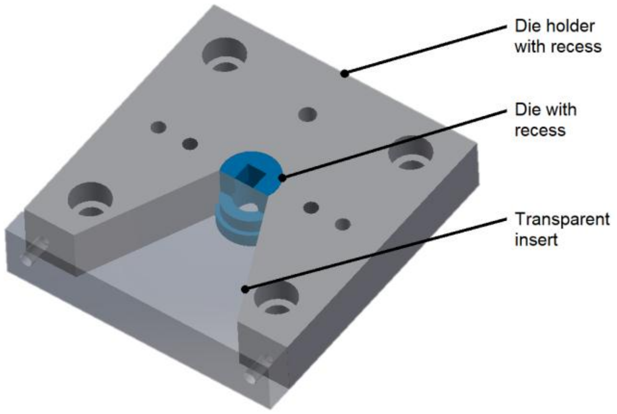

Figure 4. Cutting die and corresponding holder each with recess.

III. Results

A total of 73 high-speed recordings were filmed, of which 3 are described in detail below. For a better understanding of the snapshots the section considered is explained in detail (Fig. 5).

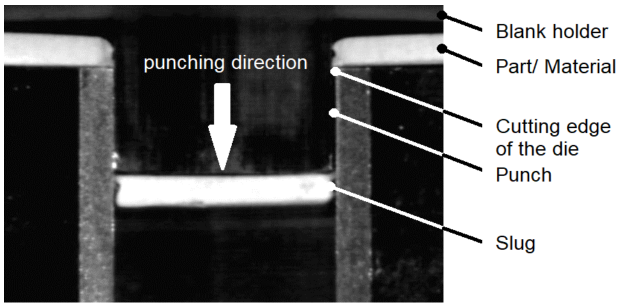

Figure 5. Display of the elements visible in the high-speed recordings.

The cross-section of the punching process with an open cutting line for PC/ABS of 1.4 mm and for PVC of 1.2 mm thickness is demonstrated in Fig. 6. Immediately after the punch was conducted and a slight deformation took place. These phenomena are attributed to inital so-called crazing where white lines develop due to micro cracks within the polymer microstructure. Crazes are common for PVC [10], and are caused by excessive local plastic deformation indicating that the material has been pre-damaged. Next to microcracks enlongated polymer fibers locally concentrate and coagulate causing an altered reflection of light. Instead of the original color the material appears in white color.

The processing comprises 5 main steps. During step 1 the blank holder sets down on the material to be punshed. The punch in step 2 deforms the material elastically. The elastic deformation is intensified during step 3 where the characteristic white lines first appear. Plastic deformation (step 4) then results in failure (step 9). This is classified as a shear fracture with low ductility due to slight macroscopic plastic deformation of the component and the orientation of the load in an angle of approximately 3 degrees to the white lines. In step 9 the failing fracture occurs separating the material into 2 parts. At this point the punch has moved through approximately 50 % of the material thickness. Afterwards the slug is removed by the downward movement of the punch. During the last process step, the punch moves back towards its initial position. The material is lifted against the punching direction. A shear droop can be detected on the punched material in step 10. Slightly angled but smooth cut surfaces can be detected on the slug and the punched-out surface.

The material behavior of PC/ABS is comparable to PVC up to step 2. In steps 3 and 4, however, no white lines that reveal or crazing occur but a strong elastic-plastic deformation of the material. From step 5 onward the shear strength of PC/ABS is locally exceeded, whereby the first signs of cracks occur on the respective cutting edges of the punch and the die. During step 6 the cracks grow towards each other and form a macroscopic visible cut surface. Step 7, however, clearly indicates that despite the expectation the crack formed on the punch does not grow in lateral direction of the lower crack initiated at the die. Instead, the crack propagates almost horizontally. The lower crack, on the other hand, follows a constant angle until the failure occurs. At this point, the punch has passed approximately 100 % of the material thickness. Finally, the slug is removed and the punch retracted identically to PVC. Here, the material is also pulled upwards during the return stroke of the punch by friction between the punch's outer surfaces and the punched-out surfaces of the material. A shear droop can also be detected at the upper side of the material. However, this is followed by a near horizontal crack. The slug, on the other hand, has a constant angle over an even surface for the majority of its cut surface. Only at the upper part of the slug a change of the angle or a residue of the last material connection between component and slug can be detected.

Overall, PVC and PC/ABS have two different separation mechanisms. For PVC, the failure mechanism under shear stress is based on a spontaneous brittle forced fracture; for PC/ABS it is based on a crack propagation resulting in ductile fracture. PVC already shows first signs of crazing after little deformation. The number of crazes increase until final failure. The fracture itself shows little plastic deformation, so that shear fracture with little ductile deformation is determined as the cause of failure. PC/ABS on the other hand shows plastic deformation until the shear strength of the material is exceeded locally. Initial cracks form, which then propagate and expand throughout the material. A residual brittle fracture surface is not present. Rather, the cracks grow until they seem to then converge until the load applied exceeds the strength of the residual cross-section of the material. The passing punch then separates the last physical conjunction of component and slug. Since the cracks do not grow directly towards each other, a concave cut surface is created.

In addition to the results demonstrated above, the blank holder oscillates in the punching axis after being placed on the material for the first time temporarily preventing hold-down. Furthermore, deriving from the material disappearing inside the blank holder in step 11, the blank holder does not hold down the material in the close vicinity of the punch-out.

Besides observing the cross section, the backside of the punching process can also be made visible by using a transparent insert (Fig. 4). In this case, punching is performed with a closed cutting line. Initial tests have shown that a small clearance (relative to the material thickness) leads to increased film formation. This effect was activated on purpose in the following tests. Therefore, the material thickness was increased, thus deliberately causing deterioration. The aim was to gain insights into the formation of PC/ABS film. The rest of the test set-up is identical to the previous one. Due to the transparent insert and the resulting reflections, the punching process itself could not be visualized. Nonetheless, interesting information regarding the formation and propagation of film can be taken from the snapshots (Fig. 7).

During the first step, the slug can already be detected completely. In other words: The punch has already moved through the material. In the following steps, the punch moves further down to remove the slug. In contrast to previous results, however, a large flake of film is formed. Its formation is apparently a result of elastic-plastic deformation. The film is connected to both the slug and the material (steps 2 to 4). As the punch moves down further the film is elongated more and more until it is finally separated from the material or the component (step 5). The slug and the film are removed by downwards movement.

IV. Discussion

- PVC: In contrast to PC/ABS, PVC can already be punched successfully with the current machine and process data concept. However, the failure mechanism and the material behavior differ fundamentally. PVC first shows crazing (white lines) after being deformed or exposed to little initial stress followed by shear fracture with little plastic deformation lateral to the white lines. Neither the slugs nor the material show any major plastic deformation. Only white boundary areas, as residues of the crazing, or a locally strong plastically deformed area, are present.

No.	**Process step**
1	Blank holder sets on the material
2	Punch sets on the material; Elastic deformation
3	Elastic-plastic deformation
4	Elastic-plastic deformation
5	Deformation and cut
6	Deformation and cut
7	Deformation and cut
8	Deformation and cut
9	Material separation
10	Slug is removed
11	Return stroke of the punch

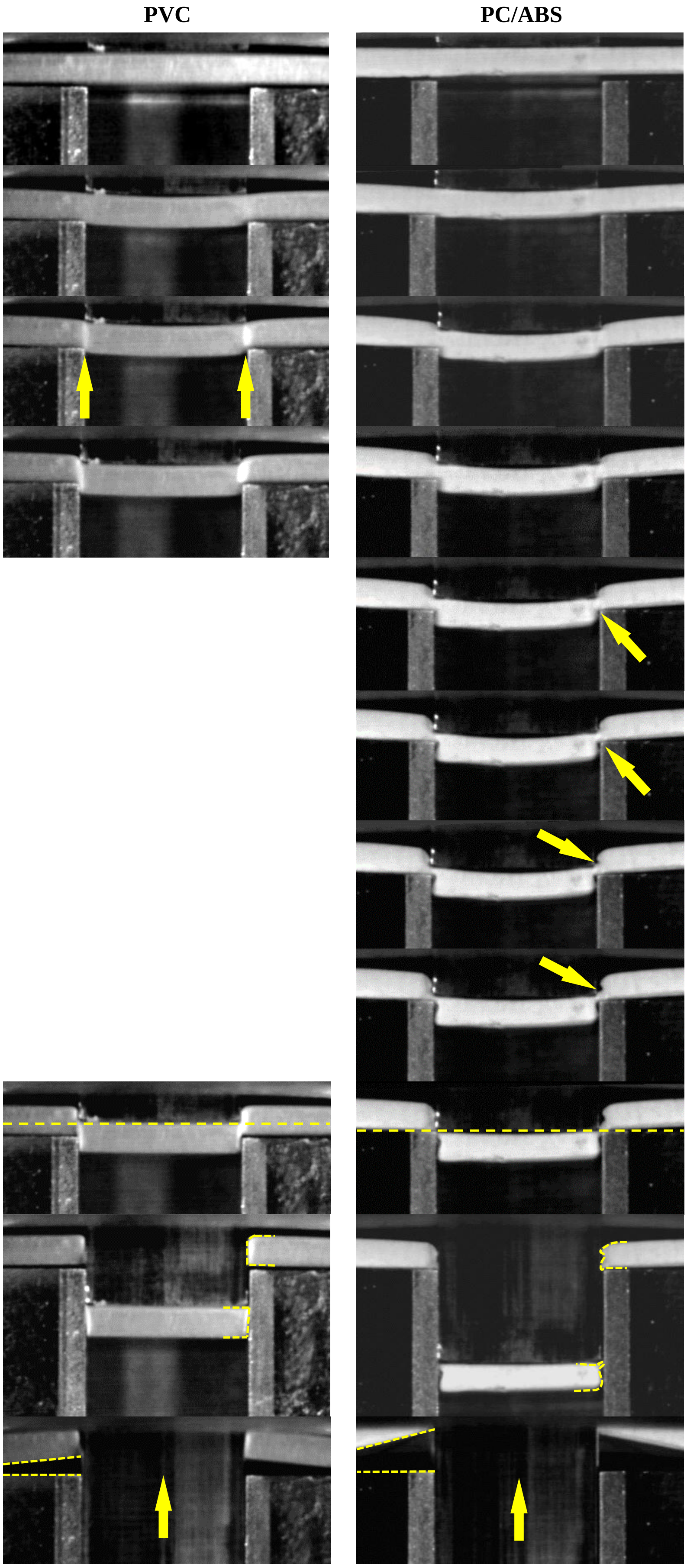

Figure 6. High-speed recordings of the characteristics of PVC and PC/ABS while punching.

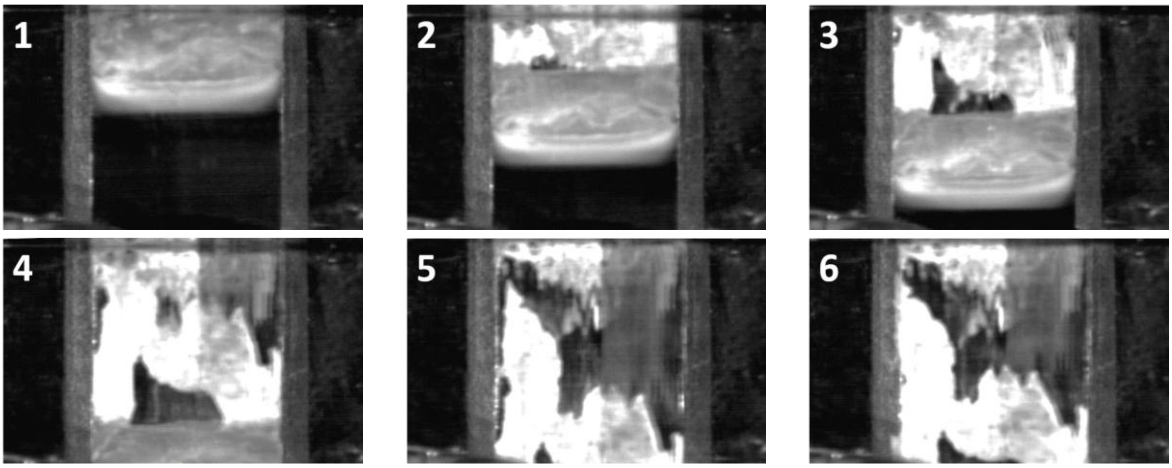

Figure 7. High-speed recordings of the stamping process with transparent insert show film formation and propagation.

• PC/ABS: For PC/ABS initial loading compresses the polymer (step 3) followed by crack initiation at the cutting edges of the punch and the die. The upper punch-sided crack propagates nearly horizontally, while the lower crack propagates almost vertically. Visually, the impression is created that the lower crack continues to propagate until the material is separated. The upper horizontal crack on the other hand, appears to rotate is propagation by approximately 180°, thus resulting in the concave cross-section of the cut surface. Until immediately before the material separation (step 8) the component and slug are still conjunct. They are then separated by the cutting edges of the punch and the die sliding past each other. Therefore, there is no fracture as detected for the conventional punching process. After separation, the aforementioned connection between the slug and the component can be interpreted as a burr on the upper side of the slug and the lower side of the cut surface. This indicates plastic elongation of the material until material failure. Insufficient material separation could possibly indicate that the selected cutting edge rounding is too large. Sharp cutting edges cut, rounded edges are more likely to press.

• Blank holder: The blank holder is temporarily without function, because it oscillates in punching direction after first being placed on the material. This seems to have no or only slight negative effects on the punching of PVC. For PC/ABS, on the other hand, it can be assumed that the blank holder is essential. This is possibly due to the higher elongation at rupture of PC/ABS materials compared to PVC materials. In addition, the high-speed recordings reveal that the PVC material nearly remains deformation-free during punching until fracture despite being held-down only temporarily.

In contrary PC/ABS deforms during the punching process most likely resulting in the almost horizontal propagation of the punch-sided crack. As the crack propagates, the deflection also changes [11], probably causing the concave shape of the cut surface cross-section. The concave shape may be minimized by increasing the blank holder force respectively the spring stiffness and by reducing the mass of the blank holder. Both measures increase the Eigenfrequency of the blank holder system and of the moving parts which cause the oscillation to run with a higher frequency and a lower amplitude. This would shorten the time periods in which no hold-down force is applied. In addition, the integration of damping elements inside the tool would be advantageous. Damping can accelerate the decay of the oscillation. Furthermore, in some recordings, regardless of the oscillation, a pushing up of the blank holder by the PC/ABS material or more precisely its deflection was seen. This means that the blank holder force is at least temporarily lower than the force resulting from the deflection of the material on the blank holder. Therefore, PC/ABS does not have a continuous hold-down and no defined boundary or cutting conditions. In addition, in some videos a lateral sliding of the (held-down) material was observed. This is also due to the insufficiently adjusted blank holder force. No smooth cut surface is created, because the material to be punched moves while being punched. This also has a negative effect on the shape and position of the punch-out. The lift-off and deformation of the material observed in step 11 is rated negatively, because the component can suffer both cosmetic and mechanical damage. All of these phenomena can be prevented by creating a hold-down in the close vicinity of the punch-out.

• Film: Film formation is caused by reducing the clearance as a function of material thickness. The film is initially conjunct to both the slug as well as the component. The downward movement of the punch increases the distance between component and slug. Here, material separation occurs after an elongation that is approximately 2.5 times the material thickness. Note, the film is directly formed in the clearance. Presumably, the film is drawn from the material residue between slug and component. However, at step 5 the film is separated from the component and, in the example considered here, removed with the slug. Whether the film is separated at the punch, at the slug or in between seems to be a coincidence. Regardless, the presence of film usually leads to negative consequences such as plugging of the die or bearings.

V. Conclusion

The punching process of PC/ABS and PVC cable ducts was visualized by means of a transparent tool and a high-speed camera. Adjusting steps were developed to reduce burr and film formation:

• PVC: PVC does not require any or only slight hold-down. The material fails after a minimal plastic deformation or before a hold-down becomes necessary. This is probably due to little elongation at rupture compared to PC/ABS. Overall, PVC can already be processed with satisfactory results.

• PC/ABS: No classic punching process applies when processing PC/ABS. The material is strongly deformed and then shear-cut. Poor cut surfaces and possibly burr and film formation are caused by connecting component and slug until separated by the punch. This insufficient material separation could possibly indicate that the selected cutting edge rounding is too large. Therefore, for punching PC/ABS it is recommended to use a blank holder and as sharp as possible but slightly chamfered cutting edges on the punch and the die to guarantee high wear resistance. Also the hold-down force should be sufficiently high. Note, the entire magnitude of the material needs to be cut.

• Blank holder: There is no effective hold-down. Besides the oscillation an insufficiently adjusted blank holder force and a missing blank holder in the close vicinity of the punch-out negatively influence the punching process. All of the issues should be improved by increasing the blank holder force.

• Film: With reducing the clearance as function of material thickness film formation was activated if the slug is not separated from the component completely. Additional thermal processes (such as the heat resulting from friction in the clearance) may affect film formation. However, the film is probably caused mainly by plastic deformation of the material within the clearance. It is assumed that film formation can be prevented widely by a clearance adjustment. Furthermore, a relatively sharp-edged tool is recommended.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

S. F. Noller and R Heiler conducted the research and analyzed the data; S. F. Noller and A. Pfennig wrote the paper: all authors had approved the final version.

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