Design of Experiments Screening Design Used to Optimize the Punching Process of Cable Ducts Made of Polymer Blend PC/ABS

Sebastian F. Noller, Roland Heiler, and Anja Pfennig
University of Applied Science (HTW) Berlin, Faculty 2: Technology and Life, 12459 Berlin, Germany
Email: {sebastian.noller, roland.heiler, anja.pfennig}@htw-berlin.de

***Abstract*—When punching cable ducts made of polycarbonate/acrylonitrile-butadiene-styrene (PC/ABS), burr and film often occur. These make additional deburring processes necessary, which are reflected in the product price. In the following study, the punching process is examined by means of Design of Experiments in order to highlight the relationship between the input variables (factors) and the output variables (quality characteristics). The punching process was analyzed and the key factors were identified and subsequently rated by means of a Failure Mode and Effects Analysis (FMEA). The rated factors were then selected using the Pareto principle. Factor levels and a D-optimal screening test plan were defined with the Software Modde. The resulting quality characteristics were categorically evaluated using illustrated evaluation catalogs. The mathematical models of the quality characteristics were then optimized and evaluated. The results indicate that the clearance is the decisive variable for all five quality characteristics considered. It is interesting to note that for some quality characteristics a reduction of the clearance would be positive, whereas for some a reduction would be positive. It is assumed that an ideal clearance size exists in between these limits.**

***Index Terms*—Polymer blend PC/ABS, Design of Experiment (DoE), punching process, cable duct**

I. Introduction

During the punching process of polycarbonate/acrylonitrile-butadiene-styrene (PC/ABS) polymer blend cable ducts, burr and film formation occurs. This reduces the quality of the end product and therefore must be avoided (Fig. 1). Furthermore, the resulting burr could possibly injure cables and workers [1]. Damage to cables endangers the operational safety of the electrical system. Film, for example, can clog tools or bearings, causing problems in production, packaging etc. Without an adequate solution to these problems, an additional deburring process step is still necessary. However, it increases the product price. The University of Applied Sciences (HTW) Berlin is aiming at improvement in cooperation with Stanova Stanztechnik GmbH, Berlin.

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

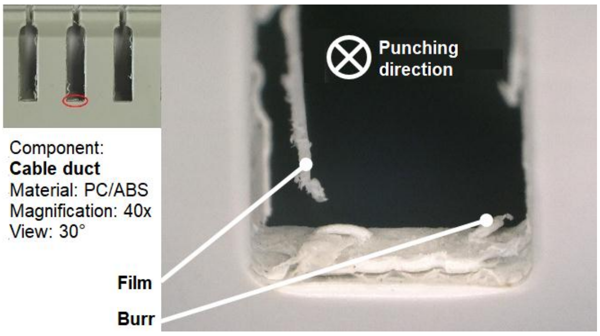

Figure 1. Burr and film formation on a punched-out section of a cable duct made of PC/ABS [4].

Most studies on this topic focus on the optimization and analysis of the material properties of PC/ABS. The 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 the optionally used additives [5-9]. So far, an analysis and/or optimization of the manufacturing process has not been described. In the following study, it is therefore attempted to avoid the formation of burrs and film by varying tool and process parameters. In addition, the relationships between the influencing variables (factors) and the output variables (quality characteristics) are to be highlighted. For this purpose, the Design of Experiments (also called DoE) is used.

II. Materials and Methods

The material behavior of PC/ABS during punching is investigated using the "FlexSpee" punching unit from Stanova Stanztechnik GmbH, Berlin. Punches generally based on ISO 8020, die and guide bushes generally based

Manuscript received December 7, 2019; revised August 1, 2020.

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doi: 10.18178/ijmerr.9.9.1226-1232

on ISO 8977 with a rectangular cross-section (7x7 mm) are used as active parts of the tool (Fig. 2). These were selected as an economical and yet meaningful alternative to the tools used in practice [10]. The active parts are mounted in a punching tool, which is operated by the “FlexSpee” punching unit with a rack and pinion drive. Punching speeds of up to 500 mm/s are possible.

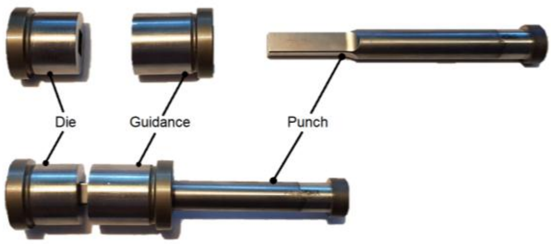

Figure 2. Active tool elements used in the experiments.

The experiments examine the quality characteristics of burr and film formation. In addition to these primary quality characteristics, the quality of the cut surface, the shear droop, and a plastic deformation that partially occurs on the underside of the punched-out area were also investigated (Table I). An extruded PC/ABS material provided by Covestro AG, Leverkusen was used as test material. This was purchased in the geometry of a cable duct and converted into flat material by machining. This PC/ABS fulfils the necessary requirements for cable ducts with regard to extrudability and flame-retardant properties according to UL94: "v-0". The material thickness is 1.2 mm. Furthermore, the material has already been used for the production of cable ducts.

Before the actual experimental design could begin a selection of the factors to be investigated was chosen in a structured brainstorming using an Ishikawa- (also called Herringbone-) diagram. Subsequently, a derivative of the Failure Mode and Effects Analysis (FMEA) was carried out, in which the individual factors or their respective negative effects on the formation of burrs and film were evaluated depending on the strength of the effect and the probability of occurrence and of detection. This step must be carried out extremely conscientiously.
Influential factors that have been wrongly excluded will have a negative effect on the later results of the other factors.

The factors were then listed according to their importance and selected according to the Pareto principle, 80 % of work in 20 % of the time. The advantage of this is the exclusion of factors with little or no influence and thus a reduction of the experimental effort. Besides the actual factor selection, the factor levels play a decisive role. If they are not defined correctly, an incorrect parameter space is investigated, which may not contain the results we are looking for. The factor levels listed below were defined on the basis of experience from preliminary investigations [10, 11].

A D-optimal screening design was generated with the "MODDE V 12.1" software from Sartorius Stedim Data Analytics AB, Umeå, to investigate the influencing variables (screening) that are decisive for the quality characteristics and their interrelationships (Fig. 3). This was chosen on the basis of the different mathematical nature of the factors and the different number of factor levels.

Modde does not only support the generation of the experimental design. The user is forced to deal with the factors in detail already during the definition step (Table II). In the next step an experimental design is chosen. The possible selection of experimental designs is determined by the combination of the amount of factors, the number of factor levels, the mathematical characteristics of the factors and, above all, the combination of the aforementioned properties. Simplified, the more the factors differ, the fewer designs are available. The experimental design itself is selected according to the type of test (e.g. screening), the result desired (e.g. effect plot) and the number of tests to be carried out. Modde recommends two of the possible experimental designs. In addition, the experimental design can be randomized and blocked during its creation.

	1	2	3	4	5	6	7	8	9	10
	Exp No	Exp Name	Run Order	Incl/Excl	Punching speed	Roughness	Coating	Clearance	Spring constant	$BlockV
1	1	N1	1	Incl	500	0,022	CrCN	0,067	25,1	B1
2	2	N2	2	Incl	500	0,077	CrCN	0,069	25,1	B1
3	9	N9	3	Incl	300	0,077	None	0,223	81,7	B1
4	10	N10	4	Incl	300	0,077	None	0,223	81,7	B1
5	7	N7	5	Incl	500	0,015	Carbon X	0,407	81,7	B1
6	11	N11	6	Incl	300	0,077	None	0,223	81,7	B1
7	3	N3	7	Incl	100	0,016	TiCN	0,408	25,1	B1
8	5	N5	8	Incl	100	0,038	None	0,064	81,7	B1
9	4	N4	9	Incl	100	0,095	TiCN	0,407	25,1	B1
10	8	N8	10	Incl	500	0,091	Carbon X	0,414	81,7	B1
11	6	N6	11	Incl	100	0,077	None	0,061	81,7	B1
12	22	N22	12	Incl	300	0,077	None	0,223	81,7	B2
13	17	N17	13	Incl	500	0,095	TiCN	0,065	81,7	B2
14	13	N13	14	Incl	100	0,091	Carbon X	0,072	25,1	B2
15	19	N19	15	Incl	100	0,077	CrCN	0,412	81,7	B2
16	20	N20	16	Incl	300	0,077	None	0,223	81,7	B2
17	14	N14	17	Incl	500	0,038	None	0,407	25,1	B2
18	16	N16	18	Incl	500	0,016	TiCN	0,065	81,7	B2
19	18	N18	19	Incl	100	0,022	CrCN	0,409	81,7	B2
20	12	N12	20	Incl	100	0,015	Carbon X	0,064	25,1	B2
21	21	N21	21	Incl	300	0,077	None	0,223	81,7	B2
22	15	N15	22	Incl	500	0,077	None	0,404	25,1	B2

Figure 3. D-Optimal experimental design for screening experiments generated using Modde V 12.1.

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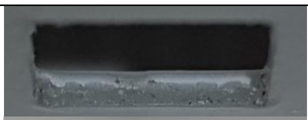
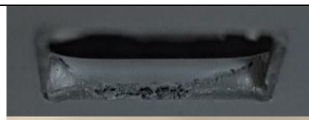
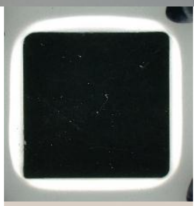
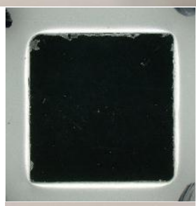
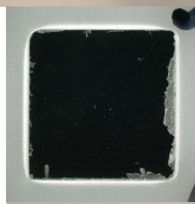
TABLE I. SELECTION FROM THE EVALUATION CATALOG FOR QUALITY CHARACTERISTICS

Quality characteristics	+	+-	-
Cut surface quality			
Burr			
Film			
Plastic deformation at the bottom			
Shear droop			

This means that the experiments are carried out randomly, and the program can determine differences between e.g. two experiment days by means of the blocks. Randomization is particularly important when carrying out experiments, as each factor level has to be set for every new test, even if it has already been used in the previous setting. This minimizes the probability of errors since an incorrect setting may only be accidental. On the contrary if the setting is made only once, it may accidentally be incorrect falsifying the entire experimental results. After the experimental design has been created, the actual tests are run. A total of 22 runs were carried out over two days, each with 3 cut-outs.

TABLE II. FACTORS SELECTED FOR SCREENING EXPERIMENT

Factor	Factor levels	Unit	Mathematical characteristics
Punching speed	100 - 500	mm/s	continuous
Roughness	0,023; 0,085	µm	discrete
Coating (Punch)	CrCN; TiCN; a-C:H; None	---	categorically
Clearance	0,066; 0,277; 0,408	Mm	discrete
Spring constant (blank holder)	25,1 ; 81,7	N/mm	discrete
Block	B1; B2	day	categorically

After the experiment the punched material was evaluated in terms of its quality characteristics. Since no quantitative measurement with justifiable effort and justifiable accuracy could be realized, a categorical evaluation was made using whole numbers. For this purpose, (after an initial examination of the punched-out areas) illustrated evaluation catalogues were used, which are presented in extracts in the following (Table II). Only the quality characteristics described in each case may be considered. A magnifying glass and different lighting conditions were used for the evaluation.

III. RESULTS

After the experiment was performed and evaluated, the results were implemented in the Modde experimental design. Modde then calculates the correlation between the factors and the quality characteristics. This involves generating an independent mathematical model for each quality characteristic. However, since outliers may exist, for example, these models must be controlled and optimized. Modde offers an analysis aid for this purpose:

- Assessment of repeatability by comparing the evaluations of tests with identical factor settings. Of course, small deviations are indicative of a good model. If the deviations are relatively large, this may be due to faulty measurements or an uncontrolled experiment.
- Representation of the distribution of the results. A normal distribution is ideal here. If the distribution of the results deviates too much from the bell shape, a mathematical transformation may be necessary.
- Effect plot with standard deviations. Statistically insignificant effects where the standard deviation is

larger than the actual effect are excluded from the respective model. It is assumed here that these have no or a relatively small effect on the respective quality characteristic.

- Presentation of the fit of the models on the basis of the key figures R2, Q2, Model Validity and Reproducibility, as explained below. These key figures show to what extent interventions in the model also optimize it.
- Finally, the measured or evaluated results are compared to the predictions of the model for exactly these values in the form of a diagram (observed value over predicted value). Minor deviations only indicate a good model.

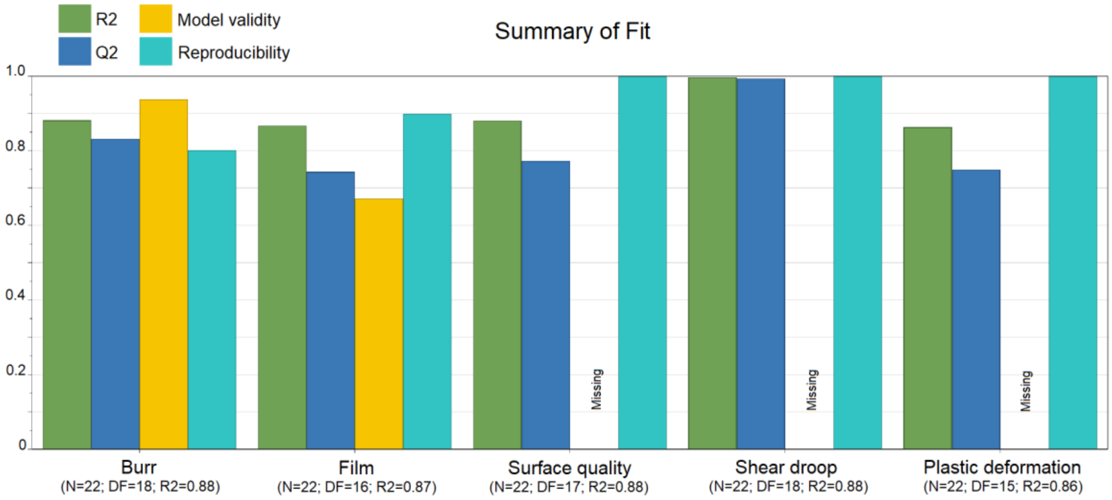


Figure 4. Summary of Fit (representation of the fit of the mathematical models).

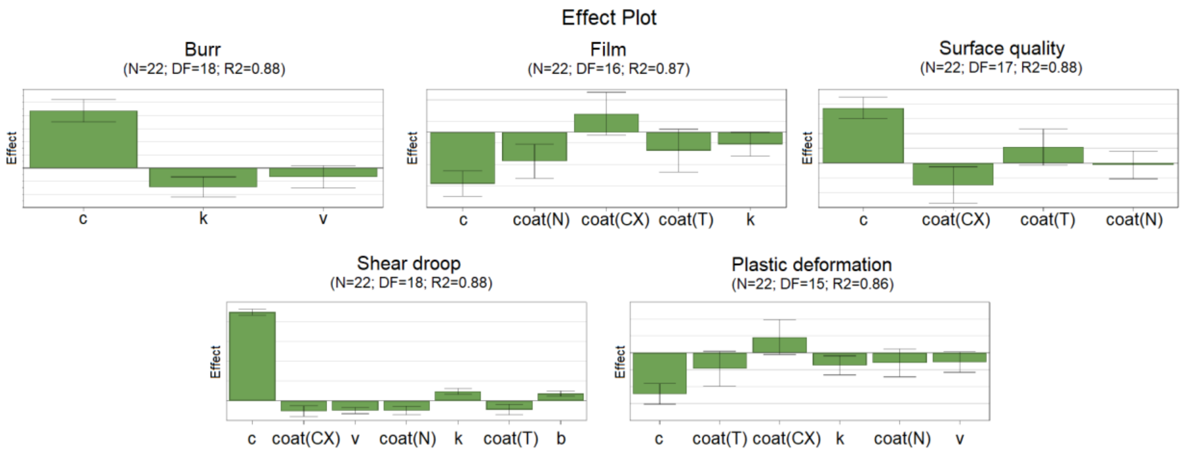


Figure 5. Effect plot of the results: Effects represent the change in the quality characteristics when the respective factor varies over its factor range.

The quality of the models is assessed using the four statistical indicators R2, Q2, Model Validity and Reproducibility (Fig. 4). These indicators allow conclusions about the fit of the current mathematical model (Summary of Fit) to the physical reality. During the optimization steps mentioned above the key figures show whether an improvement of the model is achieved or not.

- Here R2 stands for the ability of the mathematical models to fit the existing physical relationships of the results. R2 should always be above 0.5. [12]
- Q2 shows an estimate of the prediction accuracy of the future model. This should definitely be above 0.1, better above 0.5. Furthermore, the difference between the parameters R2 and Q2 should be less than 0.3. [12]
- The model validity should be above 0.25. A low value for example indicates existing outliers, a wrong model or existing but undiscovered quadratic relationships. [12]
- The fourth indicator is the reproducibility, which is the variation of the response under the same conditions as the total variation of the response. This value should always be above 0.5. [12]

The key figures are satisfactory and indicate relative good models. However, the lack of model validity in some cases is striking. This is due to the categorical valuation carried out. Because the same numerical values were used to calculate the reproducibility subsequently the reproducibility is either 1 or 100 %. This hinders the calculation of the model validity. [12]

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Once factors are determined to have no influence on the quality characteristic and are excluded from the respective mathematical model of the distinct quality characteristic, the actual evaluation can begin. The results can be presented clearly as an effect plot (Fig. 5). Previously excluded factors are no longer present in the respective effect plot. The effects of the factors on the respective quality characteristics are arranged in descending order according to the respective influence or effect intensity. The height of the individual bar represents the size or intensity of the effect. The algebraic sign stands for the respective effect direction. The error bar of the effects describes the standard deviation of the effect intensity. If the standard deviation is larger than the actual effect intensity, the results are statistically not significant. During the optimization of the models, however, it was observed that the exclusion of some of these factors sometimes led to weakened models or a lower model validity value. Therefore, these factors were not excluded from the models. Possible reason is the categorical evaluation of the quality characteristics. In this case, integer categories are used instead of measured values. Thus, as long as there is a difference, the minimum difference between two "measured values" is always at least 1 or higher. If measured values were available, their difference would probably be significantly smaller than 1. As a result, the standard deviations given tend to be overestimated. This leads to the assumption that effects can be excluded because they are apparently statistically not significant – although they are.

A negative effect direction is representative for an improvement of the respective quality characteristic at a change of the factor level from low to high.

- Punching speed *v*: Only minor effects on burr formation, shear droop and plastic deformation on the underside can be seen as a function of punching speed. Note, the continuous negative algebraic sign of the effects.
- Roughness *R*: The roughness of the punch mantle surfaces has no effect in the parameter space.
- Coating *Coat*: The coatings show no effect on the burr formation, but influence all other quality characteristics to a minor extent.
- Clearance *c*: The clearance has the greatest influence on all quality characteristics. The effect of the clearance has a different algebraic sign for burr formation, cut surface quality and shear droop than for film formation and plastic deformation on the bottom.
- Spring constant *k*: In addition to the clearance, the spring constant or the resulting blank holder force is an important variable. It can be found in almost every quality characteristic.
- Blocks *b*: The blocks or the day of the test only influences the shear droop.

Table II shows the type and extent to which the respective factors influence the punching process. Table III summarizes the individual effects. However, no statement is made about the direction or intensity of the effect.

TABLE III. EFFECTS OF THE FACTORS ON THE RESPECTIVE QUALITY CHARACTERISTICS FOUND USING DOE

Factor	Effect on the following quality characteristics
Punching speed	Burr, shear droop, plastic deformation at the bottom
Roughness	None
Coating (punch)	Film, cut surface quality, shear droop, plastic deformation at the bottom
Clearance	Burr, Film, cut surface quality, shear droop, plastic deformation at the bottom
Spring constant (blank holder)	Burr, Film, shear droop, plastic deformation at the bottom
Block	Shear droop

IV. DISCUSSION

- Clearance: As already mentioned, the clearance is the decisive variable for all quality characteristics. It is particularly interesting that the effects on burr and film formation triggered by the clearance show a different algebraic sign. Thus the burr and film formation can be optimized by opposite dimensional changes of the clearance. In order to reduce film formation, the clearance must be increased and vice versa in order to reduce burr formation, the clearance must be reduced. That is: if it is chosen too large, burr is formed, if it is chosen too small, film is formed. Results appoint that a sheared optimum of both, burr and film formation exists.
- Punching speed: When increasing the punching speed, it is noticeable that all the effects highlighted have a negative algebraic sign. Thus, a further increase of the punching speed probably leads to further improvements.
- Roughness: The roughness of the punch does not seem to have any influence on the quality characteristics. However, this is only valid for the distinct parameter space. Preliminary investigations have shown differences between polished and unworked punches. In the present tests, however, polished punches were compared in two different polishing grades. No significant differences are detectable.
- Coating: In most cases the coatings show only minor influences. However, the effect on film formation is interesting. Derived from the different algebraic signs the CarbonX coating shows different effects than no coating or TiCN. However, the causes of the differences in particular remain unknown.
- Spring constant: According to the evaluation, the blank holder force is significant but of minor magnitude. These findings are therefore contrary to earlier evaluations [11]. The lower significance of the blank holder force from the DoE tests can be explained by the fact that the parametric space was not defined meaningfully enough. Therefore, the lower factor level was numerically chosen too high. As a consequence, the positive influences of the blank holder could not be shown completely. However, exactly these effects are demonstrated

experimentally using a transparent tool and a high-speed camera.
- Blocks: The blocks associated with the trial days hardly show any influence. This demonstrates that the external influences on both test days were nearly identical and that the experimental procedure is reliable. Therefore, blocks can be neglected.

In addition to the experimental results above, the utility of the approach is demonstrated. DoE is applicable for the optimization of manufacturing processes even if no quantitative measurements of quality characteristics are possible. In this case, however, the evaluation must be carried out extremely conscientiously. Note that mixing of physical effects to define quality characteristics is risky. If, for example, the shear droop is classified as part of the surface quality, false results are most likely. The mathematics behind the DoE may not recognize this physical error and calculate incorrect results.

V. Conclusion

The correlations of quality characteristics and selected factors were determined with the aid of Design of Experiments – more precisely a D-Optimal screening design. For this purpose, the process was analyzed, decisive factors were identified and quality characteristics were defined. After punching tests had experimentally been carried out, the results were evaluated categorically using illustrated evaluation catalogues. After entering the results into the software Modde, the effects of the factors on the corresponding quality characteristics were calculated.

- The clearance is the decisive factor. If it is chosen too large, burr is formed, if it is chosen too small, film is formed. Thus the burr and film formation can be optimized by opposite dimensional changes of the clearance. It is possible that an ideal clearance exists with which both a minimum of film and burr can be achieved.
- In addition to the clearance, a holding-down of the material, in the close vicinity of the punch-out, during the punching of PC/ABS is essential for good results. In the present work this could only be shown partially due to the fact that the factor levels chosen were too large.

Using the example of the blank holder prior knowledge about the process to be analyzed is necessary. Preliminary testing offers first reliable insights. This is the only way to ensure that the results are interpreted correctly and that any uncertainties are uncovered. Process knowledge is also indispensable when defining factors and quality characteristics. Falsely chosen factors or factor levels will directly be reflected in the results. If quality characteristics are misinterpreted, mixed or not detected, they cannot be evaluated correctly or optimized. The accuracy of the results can be significantly improved if the quality characteristics are measured quantitatively.

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.

Acknowledgment

The authors would like to acknowledge bachelor candidate K. Knoblich for his support in conducting the experiment and our cooperation partner Stanova Stanztechnik GmbH for their support and helpful information.

Supported by:

Federal Ministry
for Economic Affairs
and Energy

on the basis of a decision
by the German Bundestag

References

[1] Hellermanntyton. [Online]. Available: https://www.hellermanntyton.de, retrieved May 01, 2020.

[2] H. Sze On Chan, "Measurement of hydrochloric acid emission from burning PVC compounds," *Journal of Fire Sciences*, pp. 106-122, vol. 2, 1984.

[3] Obo. [Online]. Available: https://www.obo.de, retrieved May 01, 202

[4] S. F. Noller, R. Heiler, and A. Pfennig, "Process development: Burr and film formation during high speed punching of extruded PC based polymers," *Materials Science Forum*, pp. 135-142, vol. 982, 2019.

[5] G. Weber and J. Schoeps, "Morphologie und technologische Eigenschaften von Polycarbonat/ ABS-Mischungen," *Die Angewandte Makromolekulare Chemie*, pp. 45-64, vol. 136, 1985.

[6] R. Greco, M. F. Astarita, L. Dong, and A. Sorrentino, "Polycarbonate/ABS Blends: Processability, thermal properties, and mechanical and impact behavior," *Advances in Polymer Technology*, pp. 259-274, vol. 12, 1994.

[7] R. Krache and I. Debbah, "Some mechanical and thermal properties of PC/ABS blends," *Materials Science and Applications*, pp. 404-410, vol. 2, 2011.

[8] M. Notomi, K. Kishimoto, T. Wang and T. Shibuya, "Tensile and fracture behaviors of PC/ABS polymer alloy," *Key Engineering Materials*, pp. 779-784, vols. 103-187, 2000.

[9] M. Rafizadeh, J. Morshedian, I. Ghasemi, and A. Bolouri, "Experimental relationship for impact strength of PC/ABS blend based on the Taguchi method," *Iranian Polymer Journal*, pp. 881-889, vol. 14, 2005.

[10] S. F. Noller, A. Pfennig and R. Heiler, "Process development for punching extruded PC based materials in cable duct production," *E3S Web of Conferences*, pp. 06015, vol. 97, 2019.

[11] S. F. Noller, R. Heiler, and A. Pfennig, "Adjusting the punching process of PVC and PC/ABS cable ducts using high-speed video recordings," *to be published*, 2020.

[12] Sartorius Stedim Data Analytics: *User Guide to MODDE*, vol. 12, 2017.

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S. F. Noller was born in Söflingen, Germany in 1990. He studied mechanical engineering at the University of Applied Science (HS) Ulm, Germany and at the University of Applied Science (HTW) Berlin, Germany, where he graduated in 2018. Parallel he completed an apprenticeship as industrial mechanic. During his Master's Degree was responsible for minimum quantity lubrication systems at SKF, Berlin. Parallel to his bachelor studies including the aforementioned apprenticeship, he worked for Hans Lingl Anlagenbau GmbH, Germany on brick manufacturing machines. Currently Sebastian Noller is research fellow at the University of Applied Science (HTW) Berlin, Germany in the field of manufacturing process optimization.

R. Heiler was born in Frankfurt a. M., Germany in 1965. He studied Mechanical engineering at the Technical University in Darmstadt, were he graduated in 1992. His Ph.D. in the field of thermal drilling and thread forming was earned in 1999 from the University of Kassel, Germany. From 1998 until his appointment as full professor at the University of Applied Sciences Berlin, he was responsible as head of the department and product manager for the development, production and marketing of threading tools in companies of the Sandvik Group. At the HTW-Berlin he´s teaching manufacturing and production technologies for engineering students. Roland Heiler's research focus is in the area of machining solutions of high-performance materials with precision cutting tools.

A. Pfennig was born in Büdelsdorf, Germany in 1970. She studied Minerology at the Rheinische Friedrich Wilhelms University Bonn, Germany, where she graduated in 1997. Her Ph.-D. in the field of ceramic moulds for liquid metal casting was earned in 2001 from the Friedrich Alexander University of Erlangen, Germany. She then worked for Siemens Energy in charge of ceramic shields for stationary gas turbines and transferred to Berlin in 2008 where she conducted scientific research on the oxidation of high temperature materials and corrosion behavior of steels used in Carbon Capture Techniques. 2009 she became full professor at the Applied University Berlin, HTW where she currently teaches material science for engineering students. Anja Pfennigs research interest and expertise is in the field of corrosion fatigue of materials at high temperature and high pressure simulating geothermal environments.

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