euspen's 24th International Conference & Exhibition, Dublin, IE, June 2024
www.euspen.eu

Micro deburring of high-precision injection moulded parts using thermal energy machining

E. Uhlmann[1, 2], T. Hocke[2], C. Schmiedel[1], M. Casel[3], A. Ghani[3], C. Lahoda[2]

[1]*Fraunhofer Institute for Production Systems and Design Technology IPK, Germany*
[2]*Institute for Machine Tools and Factory Management IWF, Technische Universität Berlin, Germany*
[3]*Data Analysis and Modeling of Turbulent Flows DMF, Technische Universität Berlin, Germany*

christian.lahoda@iwf.tu-berlin.de

Abstract

Injection moulding is a widely used process in modern manufacturing, offering an economically efficient production of high-precision components in various economic sectors, e.g. for medical applications. However, an inherent challenge in injection moulding is the formation of small burrs, particularly in the regions of the mould parting line. These represent a significant risk in fluid technology applications such as cardiac support systems, where patient safety may be compromised by damage to vital blood components. Conventional deburring techniques like disc finishing or brushing prove ineffective in eliminating these microscopic burrs due to the complex and sensitive geometries. In this context, thermal energy machining represents a promising post-processing approach for deburring of high-precision injection-moulded components. Using controlled thermal energies to precisely shape and smooth the edges of these components, this technique offers a viable solution. This study includes a comparison of conventionally used edge deburring methodologies such as disc finishing, abrasive flow machining as well as thermal energy machining. These techniques were analysed to identify their efficiency in achieving edge deburring on high-precision injection moulded thermoplastic polyurethane elastomer components. Based on the results, it could be proven that only thermal energy machining enables a complete and homogeneous removal of the initial burr, whereby the edge rounding could be increased by a factor of 20 compared to the initial state. These results provide a fundamental basis for refining and optimising post-processing strategies with a particular focus on safety and performance within critical domains such as medical devices and fluid technology applications. The use of the thermal process leads to an increase in efficiency in the edge deburring process and contributes to the overall goal of improving patient safety and the overall functionality of equipment used in medical and fluid-related contexts.

Keywords: thermal energy machining, injection moulding, micro deburring

1. Introduction

The demographic change with it's increasing life expectancy of the population leads to a growing demand for medical supplies, instruments and implants [1, 2]. Technical plastics are an important factor in the manufacturing of these products as they offer significant freedom of design and fulfil the high requirements of mechanical, chemical and physical properties.

With regard to the processing of these high-performance polymers, injection moulding is one of the most economic solutions for the manufacturing of high-precision components across diverse sectors, particularly in medical applications [3]. Nevertheless, the manufacturing of high-precision polymer parts using injection moulding is limited regarding the formation of small burrs, especially along parting lines. In critical applications like fluid technologies such as cardiac support systems, these microscopic burrs result in significant risks to patient safety [4]. Conventional deburring methods like disc finishing or brushing prove inadequate due to the intricate geometries involved. As a result, the need for reliable and cost-effective post-processing technologies in this area is growing.

For this purpose, this study adresses the research regarding the capability of thermal energy machining (TEM) as a post-processing technology for deburring complex high-precision injection-moulded components. By employing controlled thermal energies E_{th} to precisely shape and smooth component edges, this method presents a promising solution for the deburring of complex parts. Through a comparative analysis of conventional deburring methodologies including abrasive disc finishing and abrasive flow machining, the investigation aims to identify the efficiency of thermal energy machining in achieving complete and homogeneous burr removal as well as edge rounding. The results contribute to refining post-processing strategies, particularly in critical domains such as medical devices with a focus on enhancing patient safety and performance.

2. Experimental Setup

The TEM process belongs to the subgroup of chemical ablation and can effectively remove burrs and improve specific geometric parameters of the components such as edge rounding r_β, surface roughness as well as the K-factor k. It is a versatile and cost-effective method that can be used on a wide range of metallic and polymer-based materials, even in geometric hard-to-reach areas. The combustion can be as short as a few milliseconds and can reach combustion temperatures up to $\vartheta_C \leq 3{,}000$ °C, depending on the chamber filling pressure p_C, gas type and equivalence ratio φ. Areas of the part with a large surface-to-volume-ratio ψ, such as burrs, can overheat and melt [4].

The used workpieces were high-precision injection moulded parts made of the thermoplastic polyurethane Tecobax (TPU) by the company The Lubrizol Corporation, Wickliffe, USA.

TPU is a thermoplastic polyurethane and is characterised by high elasticity, making it suitable for applications that require excellent rebound resilience. For that reasons, the selected TPU ensures that the components maintain dimensional stability and structural integrity under varying conditions even after compression and expanding. The workpieces are characterised by a cylindrical structure with inlets providing a maximal blood flow. These consist of several small struts with a minimal geometrical width of $a_S = 0.5$ mm. The workpieces are further characterised by complex geometries, which results in challenging deburring. The use of these specific high-precision components aimed to provide a representative and practical application for evaluating the efficiency of thermal energy machining in addressing micro-burrs and sharp edges on injection moulded polymer parts.

The high-precision injection-moulded components underwent the post-processing deburring using the TEM machine type iTem Plastics by the company ATL Anlagentechnik Luhden GmbH, Luhden, Germany. The schematic layout of the machine is shown in Figure 1.

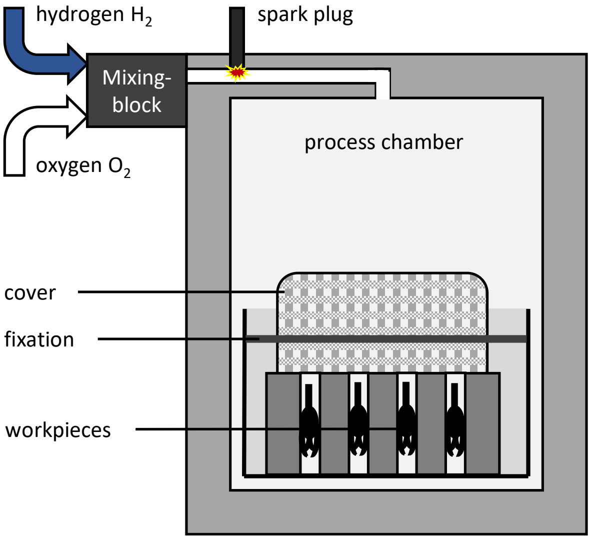

Figure 1. Schematic Layout of the TEM machine iTem Plastics

The configuration of the process chamber encompasses several critical components. The centrepiece of this system is the process chamber, which positions the parts to be deburred. This chamber is fortified with a hydraulically sealable door, which has to withstand the forming pressures p_D generated during the deburring operation. Preceding their placement within the process chamber, the components are loaded into a carrier basket. This basket supports loading and unloading processes as well as optimising efficiency in the operation of the deburring chamber. The total deburring time of $t_D = 5$ min includes the application of the vacuum and the injection of the gas. For this reason, the carrier basket is important for the economical operation, as new components can be already loaded during the deburring process.

Recognising the potential destructive force by the deflagration, precautions are taken to shield the small structures of the components from the unrestrained impact of the deflagration front. Diverse protective geometries are employed to protect the parts against inadvertent damage. The structural integrity of the chamber is complemented by the installation of a mixing block. This component enables both homogeneous mixing of the process gases and their controlled introduction into the process chamber. The various gases used in this process include natural gas, hydrogen and oxygen. For reasons of ecological sustainability, hydrogen and oxygen are now primarily used as combustion gases. The ignition of the explosive mixture is initiated through strategically positioned spark plugs, installed both atop and along the sidewall of the process chamber.

In this research, the deburring process was carried out using hydrogen and oxygen as the process gases. Therefore, a controlled mixture of oxygen and hydrogen gases with a volumetric ratio of $\psi_G = 3{:}1$ was employed. The deburring process was conducted under a vacuum pressure of $P_V = 200$ mbar. Following the establishment of the vacuum, the processing chamber was filled with the process gases at a pressure ranging of $350 \text{ mbar} \leq P_I \leq 600$ mbar. Furthermore, the ignition of the deflagration was initiated from the top of the process chamber. The parts were positioned within a metal plate made of stainless steel type 1.4301 featuring holes with a diameter of $D_H = 10$ mm and a height of $h_H = 40$ mm. This arrangement ensured that the resulting deflagration was directed toward the inner geometry of the components. In addition, parts of the combustion energy E_C could be dissipated to keep the precise strut structures intact. The protective geometry is shown in Figure 2.

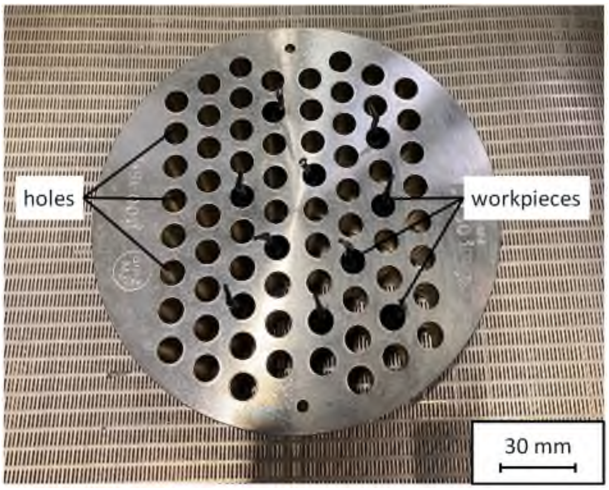

Figure 2. Protective geometry and workpiece holder

In addition to the holes in the thick steel plate, the components were enclosed by a perforated cover. This additional layer of protection served to further dampen and evenly distribute the deflagration. To prevent any displacements of this cover due to the deflagration pressure p_D, the cover was attached to the carrier basket using rods. For a visual representation of this setup, please refer to Figure 3.

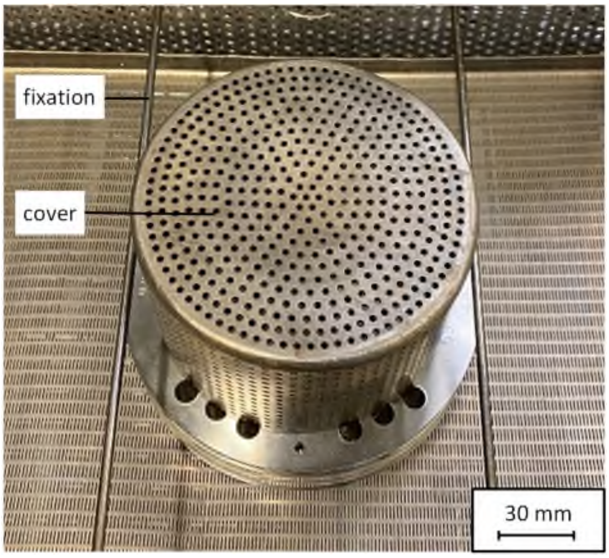

Figure 3. Final protective cover on top of the workpiece holder

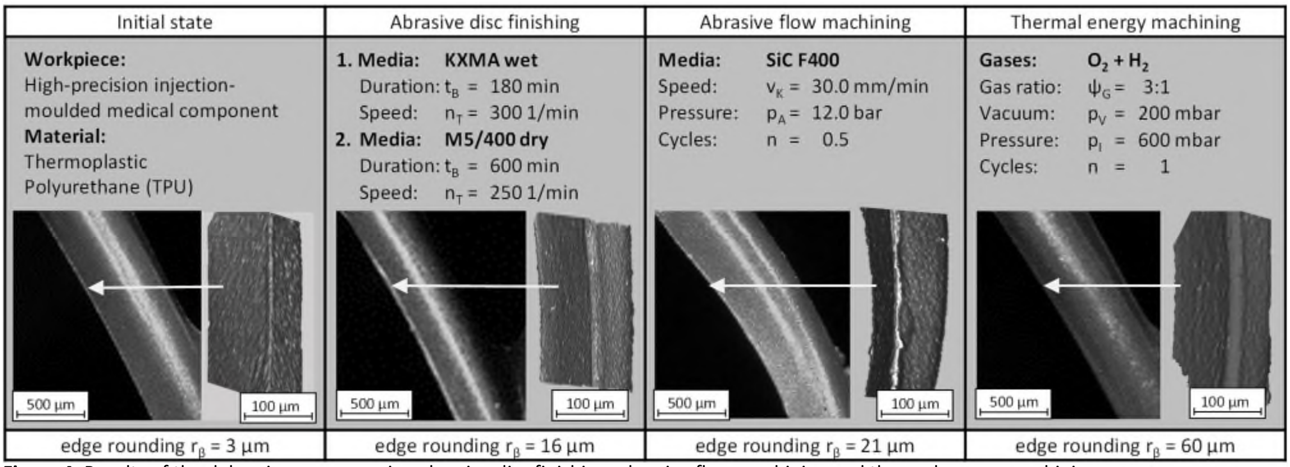

Figure 4. Results of the deburring process using abrasive disc finishing, abrasive flow machining and thermal energy machining

In the comparative assessment of post-processing, additional experiments were conducted using abrasive disc finishing. Therefore, the machine tool CF 2x18 by OTEC Präzisionstechnik GmbH, Straubenhardt, Germany, was applied. The initial processing step involved wet processing for a duration time of t_P = 180 min using fine-grained ceramic particles composed of sintered ceramic type KXMA. Subsequently, a polishing procedure in corn granulate with attached diamond particles classified as media M5/400 was used for a duration time of t_P = 600 min. In addition, the injection-moulded components underwent post-processing through abrasive flow machining, whereby a non-Newtonian fluid containing silicon carbide particles type F400 were pressurised through the components using a hydraulic piston. This procedure was carried out with the machine tool Delta Towers 100D IPC by Micro Technica Technologies GmbH, Kornwestheim, Germany.

To assess the deburring results, the edges of the components were measured using the focus variation microscope InfiniteFocus by Alicona Imaging GmbH, Graz, Austria. The measured data were used to analyse the edge rounding r_β of the machined parts.

3. Experimental Results

Within the investigation of high precision injection-moulded polymer components, three deburring processes in form of abrasive disc finishing, abrasive flow machining and thermal energy machining were applied. The results of the experiments are shown in Figure 4. In their initial state, the components showed an edge rounding of r_β = 3 µm. In the context of a cardiac support system application, this represent a potential risk of damage to blood components or cardiac tissue. Through abrasive disc finishing, the edge rounding could be improved to r_β = 16 µm. However, noticeable inhomogeneities and breakouts were observed along the edges of the machined parts. Due to geometric limitations, only isolated edges could be reached by the processing medium, preventing a homogeneous treatment of all edges. Similar challenges were encountered using the abrasive flow machining, whereby an improvement in edge rounding to r_β = 21 µm was achieved. Nevertheless, the processing results also showed inhomogeneities concerning the machined surfaces and edges. Additionally, the high machining pressure of P_A = 12 bar led to a permanent component deformation, thus compromising the high-precision geometry. By using the thermal energy machining, a homogeneous maximum edge rounding of r_β = 60 µm could be obtained, without any observable breakouts or other irregularities along the edges. To gain extensive knowledge about the influence of the pressure P_I of the used processing gases hydrogen and oxygen, a pressure ranging of 350 mbar ≤ P_I ≤ 600 mbar was analysed. The results are shown in Figure 5.

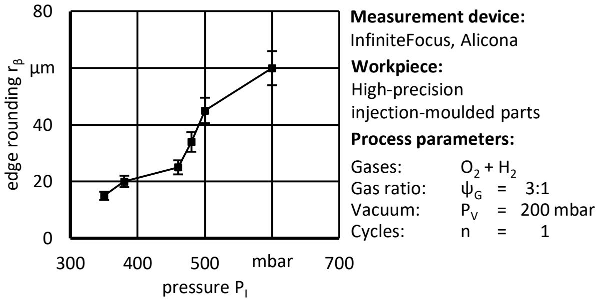

Figure 5. Edge rounding r_β in dependency of the pressure P_I using TEM

As a result of the investigations, an almost linear correlation between the pressure P_I of the gases and the edge rounding r_β could be identified. The application of increased pressures P_I facilitated a greater induction of thermal energies E_T into the component, leading to an increased edge rounding r_β. However, structural damages to the components could be observed at pressures P_I > 600 mbar. Therefore, this also represents the process limitations for the TEM process for the material TPU and the specific component geometry.

4. Simulation

The results presented show the fundamental suitability of the TEM process for deburring high-precision injection molded parts. In addition, TEM is a very experience-based process that requires iterative adjustments to identify the right operating conditions or the need for additional equipment such as flame guide geometries or absorber materials to achieve high-quality deburring results. To avoid these iterative adjustments, numerical simulations are proposed in this study as they provide reliable and condensed spatio-temporal data of chemically reacting flows and conjugate heat transfer challenges between solid and gaseous phases. Therefore, two different transient 2D simulations of the TEM process were performed in this study to demonstrate the ability of high-fidelity simulations to analyze the TEM process:

One combustion simulation within the process chamber (Figure 6a - d) and one simulation of the heat transfer from burnt gases into the cold workpiece (Figure 6e - h). Both simulations are based on a simplified generic process chamber with a dimension of 60 mm x 60 mm that confines two different generic workpieces featuring generic burrs.

The simulation of the combustion process within the chamber was performed with the reactingFoam-solver by the company OpenCFD Ltd, Bracknell, UK, that solves the compressible Navier-Stokes equations as well as the governing reaction chemistry. The walls of the process chamber and the boundaries of the workpieces were set as isothermal with ϑ_B = 20°C and no-slip

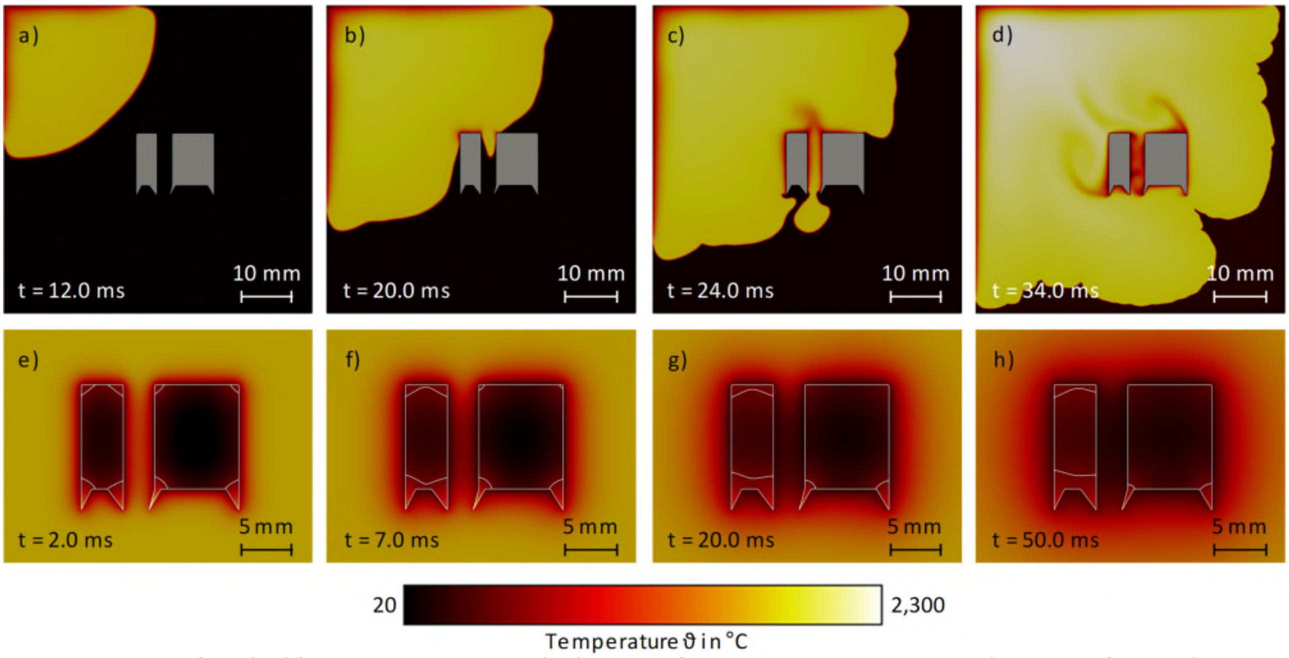

Figure 6. Simulation of the a) - d) flame propagation and the e) - h) heat transfer into the workpiece and the burr (contour line ϑ = 230 °C)

boundary conditions. The resting gasous phase was initialised as a suitable premixed mixture of methane and air with a stochiometric equivalence gas ratio ψ_G at atmospheric pressure p_A and room temperature ϑ_R, which was ignited by a spark in the upper left corner. Figure 6a - d depicts the subsequently ignited mixture that forms a flame front that causes a steep temperature rise, propagating towards the unburnt mixture. While this propagation mostly unperturbed at first (Figure 6a), the flame interacts with the workpieces that cause deflections of the flame front (Figure 6b - c). After a time of t = 34.0 ms, the flame further propagated confining both workpieces with hot burnt gases (Figure 6d). The temperature field that encloses the workpieces exhibits strong inhomogeneities in the vicinity of the workpieces. The temperature ϑ between the workpieces is significantly lower than on the other workpiece surfaces.

The second simulation utilizes the chtmultiregionFoam solver by the company OpenCFD Ltd, Bracknell, UK, and governs the heat transfer between the gasous phase and the workpieces. For this purpose, the workpieces were discretised in addition to the gasous phase. While the workpieces were initialised with a temperature of ϑ_{WP} = 20 °C, the gasous phase was set with an average hot gas temperature of ϑ_G = 1.800 °C. Furthermore, the gasous phase was set to the species composition of completely combusted gases corresponding to a stoichiometric methane-air mixture, whereas the workpieces feature the material properties of TPU. After the start of the simulation, the large temperature gradient ϑΔ causes a heat flux from burnt gases into workpieces as shown in Figure 6 e-h, leading to an overall rise of the temperature ϑ in the workpieces, where the burrs display significantly larger temperatures ϑ compared to the remaining parts due to the different surface-to-volume ratios ψ of the burrs. Based on this, the figures with contour lines of ϑ = 230 °C as the melting temperature ϑ_M of TPU show that the smaller workpiece heats up significantly more than the larger one. This indicates that the surface-to-volume ratio ψ is a decisive parameter for the deburring quality. Overall, both simulations depict a high complexity of the TEM process, featuring large spatio-temporal inhomogeneities. While the first simulation indicates a strong interaction between workpiece geometry, flame propagation and the resulting temperature field, the latter highlights the importance of the surface-to-volume ratio ψ for the spatial temperature evolution within the workpiece. However, it is noted that both flame propagation and heat exchange between gasous and solid phase occur simultaneously in reality. This results in further complexities of the TEM process, which will be further addressed in future studies.

5. Conclusion and further investigations

This study adressed post-processing techniques for deburring complex high-precision injection-moulded components. Using TPU workpieces, the TEM process demonstrated superior edge rounding of r_β = 60 µm without irregularities at the surfaces and edges. In contrast, abrasive disc finishing and abrasive flow machining showed uneven results and several deformations. The use of TEM enables an almost linear relationship between the edge rounding r_β and the pressure p of the applied gases hydrogen and oxygen. In addition, initial simulations of flame propagation and heat transfer during the TEM process were carried out. It was found that the TEM process is a highly transient process. Overall, TEM represents a promising post-processing method for deburring of high-precision injection-moulded components made of TPU, demonstrating superior efficiency in achieving homogenous edge rounding r_β. While traditional methods show significantly limitations, TEM is a suitable solution and shows its potential for enhancing safety and performance in critical applications such as cardiac support systems. Future research work will address the more detailed simulation of the TEM process. This will primarily involve a more precise simulation and detailed analysis of the interaction between the flame propagation and the burr geometry in order to achieve a comprehensive model of the TEM process. The fundamental aim is to significantly reduce iterative process adaptations and to develop a detailed scientific knowledge of the TEM process.

References

[1] Wintermantel, E.; Suk-Woo, H.: Medizintechnik - Life Science Engineering. Berlin, Heidelberg: Springer, 2009.

[2] Seul, T.; Roth, S.: Kunststoffe in der Medizintechnik. München: Hanser, 2020.

[3] Uhlmann, E.; Mullany, B.; Biermann, D.; Rajurkar, K.P.; Hausotte, T.; Brinksmeier E.: Process chains for high-precision components with micro-scale features. CIRP Annals – Manufacturing Technology, Volume 65, Issue 2 (2016), p. 549 – 572.

[4] Thilow, A. et. al.: Entgrattechnik – Entwicklungsstand und Problemlösungen. Kontakt & Studium Band 392. Expert, 2017. p. 122 – 135.