euspen's 25th International Conference & Exhibition, Zaragoza, ES, June 2025
www.euspen.eu

Productive surface smoothening of free-shaped surfaces through coupled process design for milling and hammer peening

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Abstract
Hammer peening is a partial forming process for smoothening free-shaped surfaces, which are commonly used in forming tools. The roughness value Rz of the surface after hammer peening are in the range of a few microns down to one micron. The resulting roughness depends on a few process parameters and the initial roughness after milling. At present, a major disadvantage is the long machining time when the state-of-the-art peeing tools and the belonging peening technology is deployed. Thus, in this paper an approach to significantly increase performance of peening technology using a new hammer peening tool with a piezoelectric actuator and a high hammering frequency of 1.3 kHz is presented. The productivity has been further increased through implementation of a coupled process planning for milling and hammer peening. The potential for surface smoothening of the hammer peening with the piezo-actuated tool is fully utilised and the milling path distance can be increased to reduce the total machining time. A new plugin for CAM has been developed that contains a process model for hammer peening and milling, so that the process parameters can be optimally set depending on the desired roughness value after hammer peening. The current process models consider two materials a cold working steel 1.2379 and a die and mold steel 1.2312. Finally, the machining results of a work piece with free-shaped surface in a five-axes milling machine, are presented and discussed.

Surface, Finishing, Productivity, CAM

1. Introduction

The hammer peening is a technology for finishing operations of free-shaped surfaces, which are very common in the die making industry. In general, a surface roughness of about Rz = 1 µm is possible [1]. The hammer peening technology consists in vibrating movement of a ball-shaped tool tip that hits the surface repeatedly. Thus, the roughness peaks are deformed and the overall roughness value is reduced. Beside the roughness value, the wear resistance is also improved due to the strain hardening in a layer at the surface. The finishing process for large surfaces is however time consuming – hammer peening of a surface of 1 m^2 can take many hours depending on the set process parameters. One of the significant factors influencing the peening time is the frequency of the tool tip movement (hammering frequency). It is clear that the greater the hammering frequency the lower time needed for hammer peening is. There are various tools for hammer peening. They can be distinguished from each other by the actuator principle; like hammer peening tool with pneumatic (tool frequency up to 250 Hz) [2] or electromagnetic actuator (tool frequency up to 500 Hz) [3].

In this paper, a hammer peening tool with a frequency up to 1.3 kHz is presented. A significant increase in productivity by factor up to 5 is expected. Furthermore, this tool is able to finish surfaces of higher roughness value than the pneumatic tool can do due to process force, which is higher by factor nearly 3 with respect to the pneumatic tool. The roughness value after milling is usually about Rz = 10 µm when pneumatic tool is used. This fact implies that the milling process can be adjusted in manner higher productivity as well. Through the coupled planning for milling and piezo hammer peening the overall productivity of machining of free-shaped surfaces can be increased further. For this purpose, a plugin for a CAM software has been developed.

In the paper, the current piezo-actuated hammer peening tool is introduced. In the next section the coupled process planning for milling and hammer peening is explained. The implementation is realised by a plugin for a CAM software in which the path planning for milling and hammer peening is computed. This plugin generates NC-code for milling and hammer peening as well. The results are demonstrated through milling and hammer peening of a free-shaped workpiece. The discussion wraps up the paper.

2. Piezo peening

The working principle of the hammer peening tool with a piezo-electric actuator was presented in the previous paper [1]. The tool presented here has been redesigned to reduce the large length, which causes low tilting stiffness, makes difficult handling, and limits the working space of machines being used for hammer peening. However, the principle remains the same. This means that the whole tool is pressed against the work piece with a constant force. This force is exerted by a unit that couples the tool and the milling machine with zero stiffness in the longitudinal direction. Thus, this unit can eliminate the influence of deviations resulting from the machine, workpiece, and the process. The piezo-electric actuator is just used for the excitation that lifts up the tool despite the constant force. In such way, the hammer peening process can be conducted very stable with respect to the hammering frequency and the process force. The reduction of the tool length is possible due to the integral design, i.e. the coupling unit is integrated in the tool, see Figure 1. The constant force is exerted by a pneumatic muscle, which is the part of the couple unit. The zero stiffness is achieved by deployment of a pressure reduction valve, which is connected upstream of the pneumatic muscle. The piezo-electric actuator is realized by using a high voltage piezo-stack (1000 V) with the maximal displacement of 120 µm and the maximal force of 12 kN. The allowed force in tension, which is particularly important parameter when used in the hammer peening tool, amounts to 4.8 kN. The ball at the tool tip can be changed and various diameters between 16 and 20 mm are available.

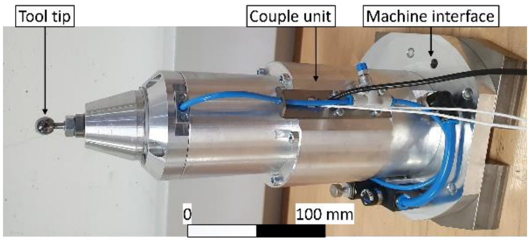

Figure 1. Hammer peening tool with piezo actuator and couple unit

In this paper, the roughness Rz is tactilely measured with the device by Mahr MarSurf PS10. The cutoff wavelength of the L filter was set to 2.5 mm and the evaluation length to 12.5 mm to consider the periodic profile after milling with the ball-end cutter. The measuring of the surface profile curve was performed five times along a new path in the feed direction for hammer peening and again in the cross direction. The mean value for each direction was computed and the higher one was always considered for further evaluation.

3. Coupled process planning for milling and piezo peening

To increase the productivity by means of coupled process planning, a process model is developed. The process model computes the estimated roughness after the hammer peening in dependence of the roughness after milling and the hammer peening process parameters. The process model has been implemented for two steels 1.2379 and 1.2312. Hammer peening experiments for various process parameters and roughness after milling were conducted to gather the required empirical data. The roughness after milling Rz_f was set by the path distance of milling tool for values of 0.7, 1.0 and 2.0 mm, which lead to roughness values Rz in the range of 10 to 84 µm. The process parameters of hammer peening are the impact distance s_e, the tool path distance s_b, the tool tip diameter d and the angle between the hammer peening tool path and the milling tool path φ. The experiments were designed for varied hammer peening process parameters according to the D-optimal method. The method suggests 21 experiments to cover the parameter space. This set of experiments was carried out for each material and the roughness value after milling. This results in 126 experiments in total to fit the process model. The process model is a quadratic model with interactions of first order. The model parameters are identified by a regression analysis. The box-cox diagrams showed that logarithmic and square root transformation are meaningful. Thus, the process models are of following form:

- Steel 1.2312: $\log(Rz_{1.2312}) = f_{1.2312}\,(Rz_f, d, s_e, s_b, \varphi)$
- Steel 1.2379: $Rz_{1.2379}^{0.5} = f_{1.2379}\,(Rz_f, d, s_e, s_b, \varphi)$

The results of the regression analysis for steel 1.2312 are depicted in Figure 2. It is obvious that the most significant parameters are the roughness after milling Rz_f, the tool path distance s_b and the tool tip diameter d. The adjusted coefficient of the determination amounts to 0.91 which is a satisfying value. Figure 3 depicts the results of the regression analysis for steel 1.2379. Here, the adjusted coefficient of determination amounts to 0.919. The significant parameters are all the process parameters and the roughness value after milling although the angle φ is only significant in interaction with Rz_f.

	Coefficient	Significance
Term	log ($Rz_{1.2312}$)	
Constant	-0,676936	0,119
Rz_f	-0,0406130	1,00E-07
s_e	-0,438882	0,654
s_b	3,81164	1,00E-04
φ	-0,00129732	0,832
Rz_f^2	0,000767523	0
$Rz_f\ s_e$	0,00151683	0,745
$Rz_f\ s_b$	0,00556002	0,239
$\varphi\ Rz_f$	-0,000122237	0,001
s_e^2	1,78848	0,376
$s_b\ s_e$	-1,38733	0,155
$\varphi\ s_e$	0,0118916	0,122
s_b^2	-5,45277	0,007
$\varphi\ s_b$	-0,00616300	0,424
φ^2	9,54548e-05	0,409
d	0,177201	4,00E-04
	R^2	0,915
	Adj R^2	0,91
	RMS Error	0,372
	Pure Error	0,159
	Residual df	234

Figure 2. Results of the regression analysis for steel 1.2312

	Coefficient	Significance
Term	$Rz_{1.2379}^{0.5}$	
Constant	3,23464	0
Rz_f	-0,015502	0,044
s_e	4,84193	7E-07
s_b	4,98111	4E-07
φ	0,001916	0,74
Rz_f^2	0,000666	1E-11
$Rz_f\ s_e$	0,01668	0,003
$Rz_f\ s_b$	0,0422	0
$\varphi\ Rz_f$	-0,00026	3E-08
s_e^2	-11,1333	4E-08
$s_b\ s_e$	1,30555	0,167
$\varphi\ s_e$	0,008756	0,239
s_b^2	-10,1942	3E-07
$\varphi\ s_b$	-0,00208	0,708
φ^2	1,43E-05	0,898
d	-0,30644	7E-10
	R^2	0,924
	Adj R^2	0,919
	RMS Error	0,36
	Pure Error	0,118
	Residual df	234

Figure 3. Results of the regression analysis for steel 1.2379

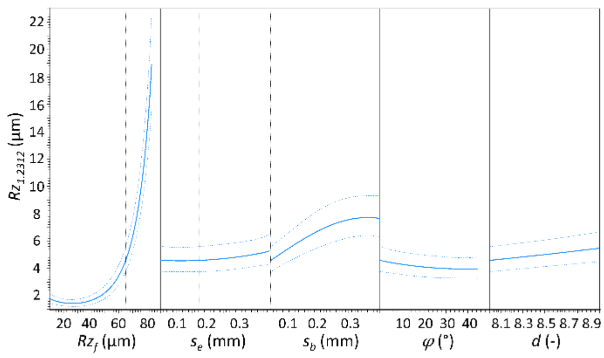

Figure 4. Section of response surface of the process model for steel 1.2312 being defined by the vertical dashed lines

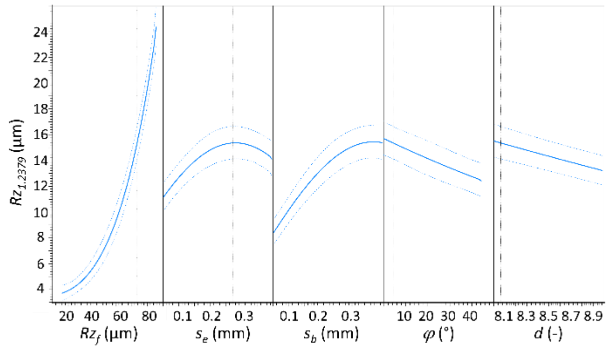

Figure 5. Section Response surface of the process model for steel 1.2379 being defined by the vertical dashed lines

The response surface of the process model for steel 1.2312 is shown in Figure 4. Since the process model consists of 5 parameters just one section of the response surface is depicted. The parameter values defining the section is depicted by the vertical dashed lines. The bold blue line depicts the process model and the thin blue lines determines the confidence interval. It is obvious that the roughness after milling is the most influencing parameter. The parameter d is defined by number 8 and 9 instead of 16 and 20 mm, respectively. The angle φ is defined in the range from 0 to 45° here. The value of 0° means that the path of the hammer peening tool is perpendicular to the path of the milling tool. By changing the position of the dashed lines, the influence of the process parameters and the roughness after milling can be investigated. In analogy, the response surface of the process model for steel 1.2379 is shown in Figure 5. The process model enables the optimal setting of milling parameters and hammer peening parameters when the tool path is planned. The optimization can be formulated in two ways: (i) for maximal productivity or (ii) for minimal final roughness. The first formulation requires process model of the form $s_e = f_{se}\ (Rz_{steel}, Rz_f, d, s_b, \varphi)$, $s_b = f_{sb}\ (Rz_{steel}, Rz_f, d, s_e, \varphi)$ and $Rz_f = f_{Rzf}\ (Rz_{steel}, d, s_e, s_b, \varphi)$. The second formulation is based on the process model being presented so far.

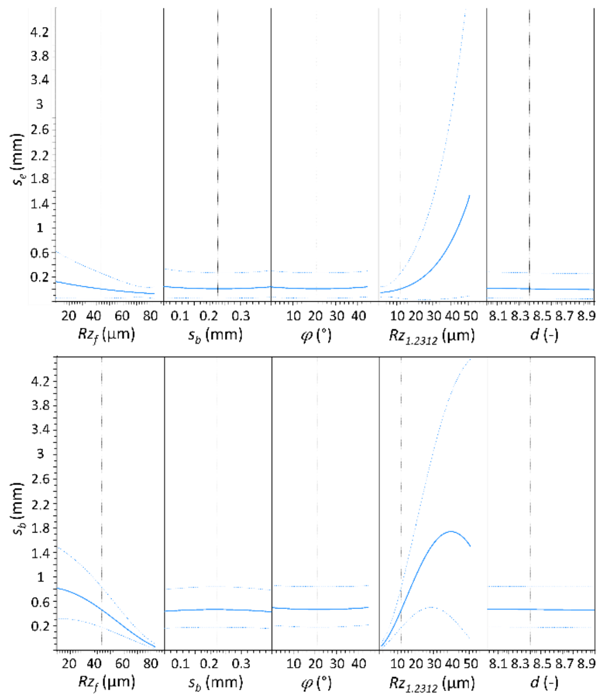

Figure 6. Response surface of the process model for steel 1.2312

The models of the form f_{se}, f_{sb} and f_{Rzf} unfortunately do not yield usable results since the confidence interval is too large, as depicted in Figure 6. Therefore, the second formulation is pursuit in this paper to optimize the productivity. The optimization is performed for parameters, which can be specified in the parameter space $10 \le Rz_f \le 84$, $0.05 \le s_e \le 0.4$, $0.05 \le s_b \le 0.4$, $45 \le \varphi \le 90$ and $16 \le d \le 20$. The goal is to choose the Rz_f, s_e and s_b as high as possible. For each parameter selection, the optimization task is computed according to Figure 7.

$$
\begin{gathered}
\nabla f_{1.2312}(p) + \sum_{i=1}^{I} \lambda_i \nabla g_i(p) + \sum_{j=1}^{J} \mu_j \nabla h_j(p) = 0 \\
g_i(p) = 0 \quad \forall\ i = 1, \dots, I \\
h_j(p) \le 0 \quad \forall\ j = 1, \dots, J \\
\mu_j \ge 0 \quad \forall\ j = 1, \dots, J \\
\mu_j h_j(p) = 0 \quad \forall\ j = 1, \dots, J
\end{gathered}
$$

Figure 7. Optimization task exemplary for steel 1.2312

In Figure 7, p is the vector of parameters being optimized, functions and h are equations and inequations of boundary conditions. The inequations are transferred to equations by using the multiplier μ. λ represents the Lagrangian multiplier. This optimization tasks leads to a system of non-linear equations. Each parameter selection reduces the number of equations in this system.

4. Path planning with CAM

Enhanced toolpath generation strategies combining milling and peening to improve target geometry roughness values were implemented and integrated in ModuleWorks Rhino plugin, which was further used for CAM path planning. Figure 8 shows the GUI of the ModuleWorks Rhino plugin consisting of elements dedicated for toolpath planning of different machining operations, simulation options, and visualization of the workpiece geometry with toolpaths.

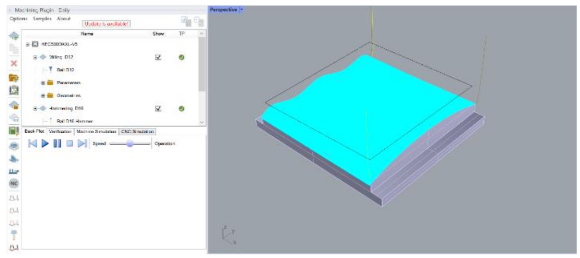

Figure 8. ModuleWorks Rhino-Plugin for milling and hammering toolpaths planning

A Heckert HEC 630 machine tool was modelled and used for machine simulation. The machine model included 3D elements along with machine's kinematic structure. The CAM setup is shown in Figure 9.

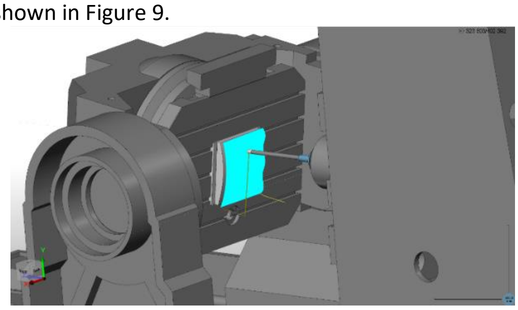

Figure 9. Screenshot of the CAM machine simulation for milling and hammering processes (Heckert HEC 630)

5. Application to a free-shaped work piece

A free-shaped work piece is machined: In the first step the shape is milled with a ball-end cutter with a diameter of 12 mm and two teeth. The process parameters for milling are the tool velocity n_T = 5000 1/min and a feed per tooth of f_z = 0.15 mm. The tool path distance during milling is 1 mm. The characteristic milling rows are clearly visible in Figure 10. The roughness Rz of the milled surface was measured and vary in the range 15 to 22 µm. After the tool had been exchanged, the hammer peening process was conducted with the piezo actuated tool being presented in section 2. The hammering frequency was set to 1250 Hz and the actuator was excited by 300 V. The process parameters were chosen for low value of the final roughness, thus, $s_e = s_b$ = 0.05 mm, φ = 90° and d = 16 mm. The goal was to achieve the roughness Rz of 1 µm.

Figure 10. The work piece after milling

Figure 11. The work piece after hammer peening

For the assessment of the surface quality after machining, the surface of the workpiece can be divided into a few areas with various characteristics. The roughness value Rz after hammer peening varies over the whole surface in the range 0.7 to 1.9 µm. There are areas with expected results or better. However, some areas feature annealing colour (in Figure 11 highlighted by red lines), which can be identified as dark straw. Such colours correspond to temperatures up to 240 °C. Annealing only occurs in those temperature regimes. Such elevated temperature result from friction heating. The process itself can be excluded since the annealing colour would be visible over the whole surface. The areas with the annealing colours match areas where the tool is not positioned perpendicular to the surface. This was validated in the CAM environment. The tool path planning algorithm allows small angle deviations from the perpendicular position of the hammer peening tool to optimize the rotary movements of the machine. The tool is however not able to guide the movement of the tool tip perfectly rigid. Thus, an additional sliding movement of the tool tip on the surface occurs. Such movement is linked with friction. The heat generated by friction causes the high temperature on the surface.

6. Results and Discussion

In the paper, a new prototype of the piezo-actuated hammer peening tool is introduced. This tool can perform hammer peening with hammering frequency up to 1.3 kHz which is reflected in a higher productivity comparing to the state-of-the-art tools by a factor up to five.

Since the new hammer peening tool is capable of smoothing higher roughness than competing hammer peening tools, the productivity of existing processes can be further increased by the means of coupled process optimization of the milling and hammer peening. For this purpose, a process model has been developed that can express the roughness after hammer peening in dependence on the milling roughness and hammer peening parameters with coefficient of determination higher than 0.9. The direct optimization of the hammer peening parameters for high productivity is not possible due to too large confidence intervals of the transformed process models. Thus, a successive optimization is suggested. In the path planning CAM plugin, the technological settings for milling and hammer peening can be conducted and the plugin generates NC-code for both processes (milling and hammer peening). The presented developments were tested during machining of a free-shaped surface. The milling had resulted to surface roughness values Rz reaching up to 22 µm. After milling, the machined surface was smoothed by hammer peening to roughness values varying between 0.7 and 1.9 µm. The hammer peening process was designed for the utmost roughness value of 1 µm, which was eventually not achieved. Two explanations are given to explain the difference between the simulation and experimental data: insufficient stiffness of the tool in the lateral direction and no perfect perpendicularity of the hammer peening tool to the surface. These deviations are the likely reason for the areas with annealing colours being visible on the surface of the workpiece after hammer peening.

Concluding, the hammer peening tool with a piezo-electric actuator is capable to machine a very smooth, free-shaped surface with a high frequency. However, there is still work to do, to avoid the annealing colours and to improve the model prediction. Thus, the future work will focus on the improvement of the lateral stiffness of the tool. Furthermore, the influence of the hammer tilting angle (deviation from the perpendicular position) on the surface quality will be considered during tool path planning.

References

[1] Fiedler S and Kolouch M 2021 Incremental micro-forming for surface finishing with piezoelectrically actuated hammering tool with coupling unit *In Proc.: euspen's 21st International Conference & Exhibition, Copenhagen, DK, June 2021*

[2] Wied J 2010 Oberflächenbehandlung von Umformwerkzeugen durch Festklopfen *PhD-Thesis of University of Technology Darmstadt*

[3] Bleicher F, Lechner C, Habersohn C, Kozeschnik E, Adjassoho B and Kaminski H 2012 Mechanism of surface modification using machine hammer peening technology *CIRP-Annals Manufacturing Technology* **61** 375-378