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Incremental micro-forming for surface finishing with piezoelectrically actuated hammering tool with coupling unit

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Abstract
Machine hammer peening can be referred as an incremental mechanical surface treatment procedure, which can be realized by using various tools being based on various actuator principles. For the purpose of high productivity, a high-performance drive for generating vibrations in the tool of a high frequency is desired. Therefore, this paper presents a new hammer peening tool with a piezoelectric actuator. In order to facilitate this actuator principle for practical applications, a coupling unit is necessary being installed between the tool and the machine. This coupling unit insulates the process vibration at the machine (e.g. a machine tool or an industrial robot) and changes the operating mode of the hammer peening process from position controlled to force controlled. In such way, the accuracy of the positioning movement as well as the accuracy of the workpiece are not the issue anymore and the piezoelectrically actuated tool with a low stroke of 120 µm can be deployed for practical applications. This tool together with the coupling unit can reach hammering frequencies in the range from 800 to 1300 Hz. These frequencies enable higher feed rates and productivity of the hammer peening process than tools with pneumatic or electromagnetic actuators being available on the market. For the purpose of demonstration of the tool potential, some experimental tests are presented in this paper. Here, workpiece being milled like in die making were treated by the hammer peening process with the new tool. The surface were smoothed from Ra 1.18 µm to Ra 0.10 µm.

Machine hammer peening, piezo peening, surface smoothing, Incremental micro-forming, manufacturing

1. Introduction and motivation

The hammer peening is a technology for surface finishing, with which values of Rz = 1 µm can be reached [1]. In principle, it consists in incremental plastic deformations of peaks in the surface profile. The tip of a hammer peening tool having the shape of a ball makes a periodical movement in normal direction to the surface. This hammering movement is combined with a feed for smoothing the surface along a line. Repeating the feed along a shifted line, a surface can be machined with hammer peening [2]. The effect of smoothing depends on the impact distance s_e, i.e. the distance between two neighbouring ball prints on the surface measured in the feed direction, and the shifting distance between the two lines. The impact distance and the shifting distance are often set to the same value to reach a consistent smoothing effect over the surface. Since the feed rate v_f results from the impact distance s_e and the frequency of the hammering movement f_H according to $v_f = s_e f_H$, it is obvious that a high hammering frequency leads to a high feed rate and, therefore, to a short time for hammer peening of a surface. Considering the large surfaces of forming dies, which are often treated with the hammer peening, the importance of the hammering frequency becomes significant. The existing tools for hammer peening are based on a pneumatic exciting principle with f_H less than 250 Hz [3] or electromagnetic driving principle with f_H less than 500 Hz [4].

In this paper, a new hammer peening tool is presented. This tool deploys a piezoelectric actuator for generating the hammering movement. In general, a piezoelectric actuator cannot reach a similar stroke like the two exiting principle mentioned above. Despite this drawback, a special design of the tool allows the use of the piezoelectrically actuated tool for hammer peening of three-dimensional surfaces with high deviations from the nominal geometry in the range of 2 mm are not an exception. This is highly relevant for treatment of deep drawing dies, since these are often manually adjusted in order to compensate deviations in a forming press.

2. Design of tool and coupling unit

The structure of the hammer peening tool with a piezoelectric actuator is shown in Figure 1. It is a simple design consisting of the piezoelectric actuator, a punch with the ball at its end, a guiding system for the punch, the base together with connecting flange and a housing pipe. The piezoelectric actuator features the maximal stroke of 120 µm, the blocking press force of 12500 N, maximal tensile force of 2000 N due to the static preloading of the piezoelectric actuator and maximal voltage of 1000 V. It is obvious that this design on its own would not be able to compensate the deviations in the range of 2 mm, as mentioned above. In order to do this, the tool is supplemented with a coupling unit. This unit is installed between the tool and machine (e.g. a machine tool or an industrial robot). The goal of the coupling unit is to generate a static preload with that the tool is pressed against the surface and the value of the static preload is almost constant, i.e. independent on the deviations in the surface geometry. The coupling unit has been developed in two versions. The first version (so called mechanical coupling unit) features a spring with a low stiffness so that the movement caused by the deviations from the nominal surface geometry induces a low change in the static preload (see Figure 1). The second version of the coupling unit (so called pneumatic coupling unit) is designed with a pneumatic bellows cylinder (see

Figure 2). The pneumatic bellows cylinder is combined with a pressure control valve. The coupling unit can move only with one degree of freedom in fact in the direction of the stroke. The remaining five degrees of freedoms are bounded by three sliding guiding rods. The stroke of both coupling units amounts to 4 mm.

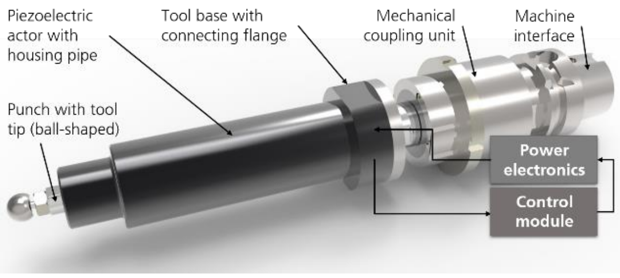

Figure 1: Design of the piezo actuated peening tool with the mechanical coupling unit

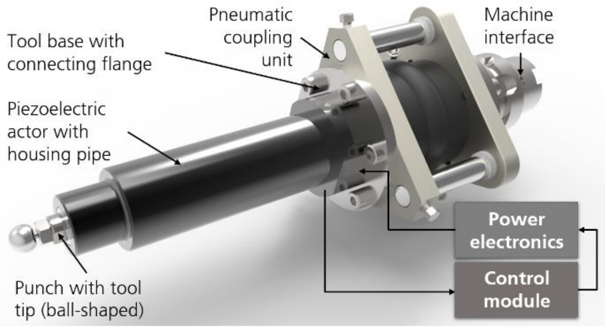

Figure 2. Design of the piezo actuated peening tool with the pneumatic coupling unit

3. Functional principle

The goal of the coupling unit is to compensate the deviations in the geometry as depicted in Figure 3. For this purpose, the tool is operated under static preload. In such case the relatively position of the tool to the surface is not the issue anymore. Instead of this, the static preload has to be kept constant regardless the deviations in the geometry of the surface, in Figure 3 labelled as g. The technical solution for the constant static preload could be the force-controlled movement of the tool or a mechanical solution with zero stiffness. In the second case, the movement of the tool caused by the deviations from the nominal geometry would not cause any change in the static preload. Therefore, two versions of the coupling unit has been developed, as mentioned above. The first one deploys a spring of very low stiffness. This leads to negligible changes in the static preload caused by the deviations of the surface. The second one consists in the combination of the pneumatic bellows and the pressure control valve. This valve ensures a constant pressure (in Figure 3 labelled as p_{const}) in the pneumatic bellows, thus, a constant static preload (in Figure 3 labelled as $F_{preload}$). Figure 3 shows the principle of keeping the constant static preload for the pneumatic version of the coupling unit. Here, the tool is depicted at two different time instances t_1 and t_2. At the first time instance, there is a large difference between the real surface geometry and the surface from CAD, for which the tool path is actually programmed. In this case, the coupling unit is pulled out. At the second time instance, the coupling unit is compressed. The pressure-controlled valve ensures the constant pressure in the pneumatic bellows. Therefore, the static preload is also constant at both time instances.

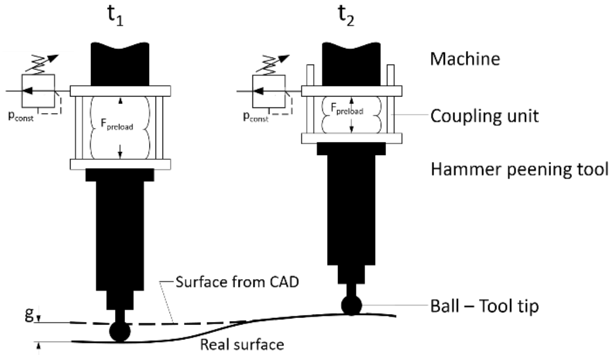

Figure 3. The principle for compensating the deviations in the geometry of the surface

The static preload force presses the hammer peening tool against the workpiece. When the piezoelectric actuator is excited with a certain hammering frequency and this frequency is high enough, the tool tip lifts off the workpiece due to inertial forces and the elasticity of the whole system. If the effect of lifting off is sufficient, i.e. the mean value of the periodical hammering movement lies above the surface of the workpiece, the feed of the tool is possible with a negligible resistance, therefore, without impacts on the surface quality.

When hammer peening is going to be performed, the tool is positioned to the workpiece until contact between the tool tip and the workpiece exists. Afterwards, the static preload is exerted and run-up of the piezoelectric actuator is started, i.e. the maximal voltage value of the piezoelectric actuator for a selected hammering frequency is increased in accordance with a smooth function (see Figure 4) to avoid a step load of the piezoelectric actuator, thus, to avoid its overload by an unforeseen dynamic load.

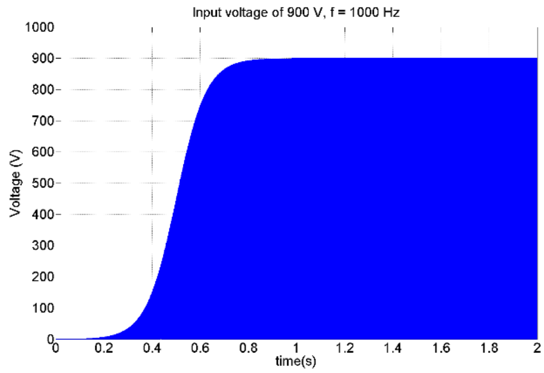

Figure 4. Run-up of the tool according to a smooth function

The hammering frequency f_H plays an important role in the process of hammer peening with piezoelectric actuator. It is crucially for the productivity and for the lift off effect. The aim is to set the hammering frequency as high as possible. This is linked with some challenges like the effect of jumping tool on the surface as well as resonances of the machine, the workpiece and the workpiece fixation, which are source of noise and which can reduce the surface quality during the hammer peening process. When the effect of jumping tool on the surface occurs, the hammering movement is not determined by the movement of the actuator but by the dynamic properties of the whole system including the tool, the coupling unit, the machine and the workpiece. In this case, the hammering frequency is significantly lower than the frequency of the piezoelectric actuator. Therefore, this effect has to be avoid. The simulation of this effect is presented in [5], though for the previous design of the hammer peening tool.

If the hammering frequency is a priori not known, it can be determined within a simple experiment. The tool is positioned to a location on the workpiece without any functionality, e.g. in a peripheral area. At this location, the hammer peening tool is pressed against the workpiece with the desired value of the static preload. Afterwards, the actuator of the hammer peening tool is excited with a sinus swept signal with linearly changing frequency and with a constant voltage amplitude. While this, the acceleration on the tool base is measured with an accelerometer. A possible set-up for the simple experiment is depicted in Figure 5. Here, the hammer peening tool together with the mechanical coupling unit is clamped in the spindle of a horizontal nc milling machine. The test workpiece is fixated on the table of the machine. One accelerometer is mounted on the tool base. This acceleration is evaluated for determining the hammering frequency. In Figure 5, there is also another accelerometer mounted at the coupling unit. This accelerometer measures the vibration at the machine spindle in order to assess the insulating function of the coupling unit, i.e. reduced vibration at the machine spindle. The insulating factor amounts to 10, i.e. the amplitude of accelerations measured at the spindle are ten times lower than acceleration amplitudes measured at the tool base.

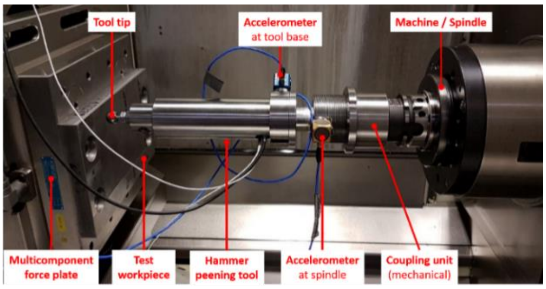

Figure 5. The experimental set-up for testing the hammer peening tool with a mechanical coupling unit

Figure 6 shows the measured acceleration at the tool base in the direction of the stroke during the excitation with the sinus swept signal. The tool (mounted with the pneumatic coupling unit) was operated under static preload of 300 N. The voltage amplitude of the sinus swept signal amounts to 900 V and the frequency was linearly changed from 950 Hz to 1300 Hz. The actuator presented in this paper has an upper frequency limit for operation at 1300 Hz. Due to the linear change of the frequency, a unique relation between the time axis and the frequency axis exists. Thus, the time instances can be replaced by frequency values as in Figure 6. In such way, an appropriate hammering frequency can be chosen.

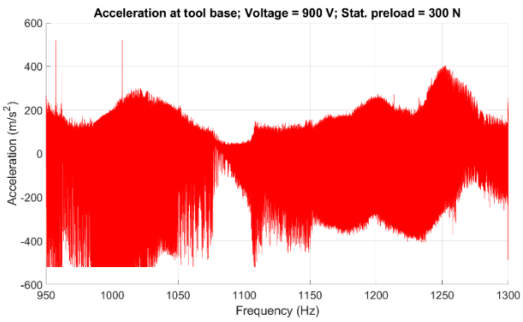

Figure 6. Effect of jumping tool on the surface, recognisable in the range from 950 Hz to 1150 Hz, depicted by acceleration of the tool base for sinus swept input signal

In Figure 6, the effect of jumping tool on the surface can be seen in the range from 950 Hz to 1150 Hz. Furthermore, the appropriate frequency range for the hammer peening could be selected in the range from 1150 Hz to 1250 Hz. In this case, the mean value of the measured acceleration should lie below the zero line in order to facilitate the feed movement of the tool with a low resistance, as mentioned above.

4. Setting technological parameters

The choice of technological parameters for hammer peening aiming at maximal efficiency always represents a challenge. Some technological parameters like the impact distance, the shifting distance, the angles of the tool orientation related to the workpiece as well as the angle between the feed direction for hammer peening and for milling are common for all actuator principles (pneumatic, electromagnetic or piezoelectric) being used for a hammer peening tool. Therefore, some findings have been made in studies for other hammer peening principles can be reused in case of the piezoelectrically actuated hammer peening tool. For instance, such a study can be found in [6], where the above mentioned parameters were investigated experimentally as well as computationally using the finite element method for the pneumatic hammer peening tool. Here, mathematical models for design of the hammer peening process were developed. The goal of the current research work is to adopt, extend or modify these process models for the piezoelectrically actuated tool with other limits regarding the hammering frequency.

The hammer peening is performed with a set of technological parameters, which take an influence on the machining results, especially on the surface quality. Comparing the pneumatic principle, the technological parameters being special for a hammer peening tool with a piezoelectric actuator are the static preload $F_{preload}$, the actuator voltage U_{Act} and the hammering frequency f_H. In order to gain experiences with setting these technological parameters, machining tests has been performed. The assessing criterion in these tests is the roughness of the machined surface.

The static preload is varied in the range from 350 to 800 N. The lift off effect and the effect of jumping tool are crucial when the static preload is set. A high value of the static preload presses the tool against the workpiece too much so that the lift off effect cannot occur and the feed movement is not possible. On the other hand, a very low value of the static preload let the effect of jumping tool arise, as described above.

The hammering frequency were set in a frequency range from 800 Hz to 1300 Hz. The upper limit of the frequency range results from the used piezoelectric actuator, as already mentioned above. A further limiting factuator for the maximal frequency is the maximal tensile force acting on the piezoelectric actuator. The higher frequency the higher is the tensile force caused by the inertial forces. The maximal frequency value resulting from the maximal tensile force was found out by using simulation. The frequency value of 1300 Hz ensures a safety load case for the piezoelectric actuator. The lower limit is not critical for the actuator but leads to a lower productivity. In the experimental set-up, the lower frequency limit was set to 800 Hz, since there are some resonances in the machine bellow this value, which affect the process.

The actuator voltage is a free programmable value, which can be theoretically set in the range from 0 to 1000 V. In this paper, experiments with three values for the voltage of 300, 600 and 900 V were performed. The voltage correlates with the force of the piezoelectric actuator, i.e. excitation force in the whole system. The excitation signal in the experiments was set according to a sine function with a mean value being higher than the amplitude in order to avoid an excitation in tension. The signal was always run-up as shown in Figure 4.

All hammer peening tests presented in this paper were performed with the same shifting distance of 0.2 mm.

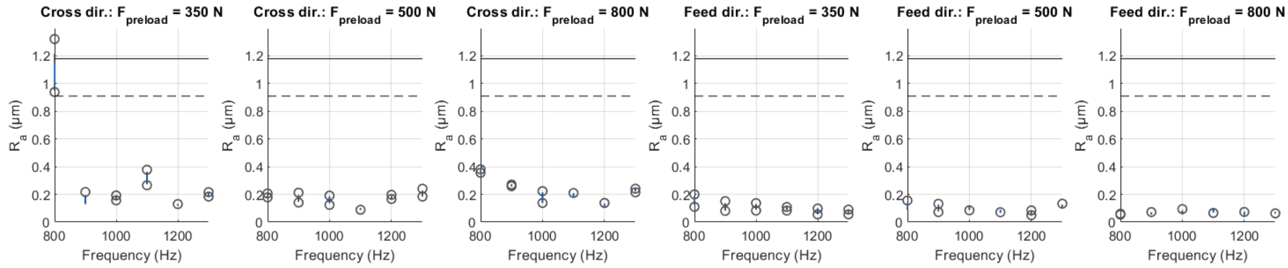

Figure 7. Box plot of results of hammer peening tests for excitation of 300 V; dots represent the outlieres and lines depict the variance; horizontal line and horizontal dashed line stand for the roughness after milling in the cross and the feed direction, respectively.

Furthermore, the tool was perpendicular oriented to the workpiece and the feed direction for hammer peening was perpendicular to the feed direction for milling (see Figure 8). The feed rate v_f was set to 5 m/min. The constant feed rate leads to a change in the impact distance s_e depending on the hammering frequency f_H, i.e. a higher hammering frequency results in smaller impact distance. The static force was measured with the multicomponent force platform (see Figure 5). The tests consist in hammer peening of rectangle areas with dimensions of 25 x 10 mm (see Figure 8) on a workpiece (Mat.-No. 1.2379 X155CrVMo12-1) being milled with a ball cutter. Such milling process is typical for die making. The arithmetic average roughness Ra of the milled surface amounts to 0.91 µm in feed direction for milling and 1.18 µm in the cross direction.

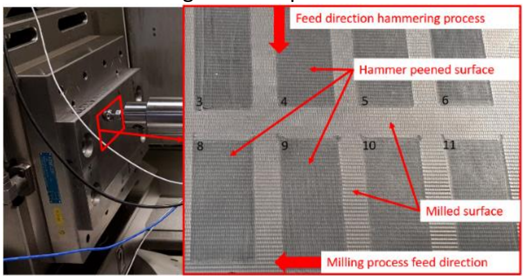

Figure 8. The experimental set-up for testing the hammer peening and the feed directions of the machining processes

The roughness of the surface before and after the hammer peening was tactilely measured with the device by Mahr MarSurf PS10. The measuring of the surface profile curve were performed in the feed direction for hammer peening as well as in the cross direction (i.e. in the feed direction for milling). The mean roughness value Ra is used for the evaluation, as this is common in the targeted industries.

The measurement was performed five times, each time along a new path. The cut-off wavelength of 0.8 mm filtered through the device software. This setting is recommended for aperiodic surface profiles with an expected surface roughness value Ra of 0.1 µm to 2.0 µm. In this paper, the mean value from the five measurement is evaluated.

The results of the hammer peening tests are shown in Figure 7. It can be seen that the roughness value Ra in the feed direction for hammer peening shows lower deviations than the roughness value in the cross direction. In the feed direction, Ra values of 0.10 µm were reached. In the cross direction, the same Ra values could be only reached with the static preload of 500 N and at frequency of 1100 Hz. Furthermore, there is an outlier in roughness in the cross direction for static preload of 350 N and hammering frequency of 800 Hz. In this case, the effect of tool jumping obviously occurs (see Figure 6) and the roughness could not be smoothed properly. The impact of the voltage on the smoothing the roughness seems to be negligible, at least for the static preload of 500 N and the hammering frequency of 1300 Hz. In this case, a lightly decreasing function of the roughness and the voltage can be noticed. The maximal roughness value Ra amounts to 0.10 µm at 300 V and Ra of 0.07 µm at 900 V.

5. Summary, conclusion and future work

The paper presents a new tool for hammer peening with a piezoelectric actuator. The presented tool can be deployed for hammer peening of a workpiece with deviations from the nominal surface in the range of 2 mm. This is only possible due to special coupling unit being installed between the tool and the machine. The hammer peening tool with the coupling unit is operated under a static preload. In such way, the new tool is moved over the workpiece with constant static preload and the relative position between the tool and the workpiece does not play a role anymore. The coupling unit is designed in two versions. The first one is a pure mechanical design with a spring of very low stiffness so that the deviations cause a very low change of the static preload. The second one uses a pneumatic bellows cylinder together with a pressure control valve to realize zero stiffness. Therefore, a force-controlled movement is not necessary for hammer peening with the new tool.

In the paper, some aspects related to operating the new tool like the run-up of the tool and the effect of jumping tool are explained. Furthermore, machine hammer peening tests were performed with the new tool in order to demonstrate the functionality as well as a first study of technological parameters like hammering frequency, the static preload and the voltage of the piezoelectric actuator were presented. The results show that the new tool is able to reduce the Ra values of the roughness from 1 µm to 0.1 µm at hammering frequency of 1300 Hz. This shows the big potential for productivity increasing when the new tool is used.

The research work in the future focuses on the further improvement of the design of the tool and the coupling unit. Beside this, a process model is developed with that the reliable technological parameters for high productivity can be selected. Moreover, this new technology for hammer peening will be considered in a CAM software.

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