ROBOT BASED MACHINE HAMMER PEENING USING AN ELECTROMAGNETIC DRIVEN HAMMERING DEVICE

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Abstract

The usability of a component and in particular its functional performance is highly dependent on the properties of its surface and subsurface region. Machine hammer peening is a manufacturing process for the mechanical surface treatment of workpieces, with the aim to induce compressive residual stresses in near surface layers. This comes along with strain hardening effects and increased surface hardness of the edge layer. By the use of adequate process parameters, it is even possible to modify the surface topography. In order to implement machine hammer peening processes, NC-guided machine tools have to be used to generate single deterministic tool contact marks. In the course of this work an electromagnetic actuator system will be implemented on a 6-axes industrial robot KUKA KR30-3 and the static and dynamic behaviour of the robot during the hammer peening process will be investigated in order to evaluate the applicability to generate deterministic patterns.

Keywords: machine hammer peening; electromagnetic hammer system; industrial robot; static and dynamic behaviour; NC-guided system; deterministic surface pattern

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1. Introduction

Machine hammer peening (MHP) is a novel and innovative surface treatment technology, which is gaining importance for several industrial applications. Nowadays, this process, which is based on the oscillating movement of an axially guided tool with mostly a spherical cemented carbide tip, is increasingly used for the die and mould making industry [1,2] as well as in the automotive sector [3]. In particular, manual tasks like surface smoothing can be substituted. In general, classical kinematics of machining systems, like serially linked linear axis machine tools, are used to machine surfaces [4,5]. Furthermore, for smoothing tasks articulated robot systems with high payloads, based on pneumatic hammer peening actuators, are already established [3]. It is probable that pneumatic working systems induce lower process forces than electromagnetic driven systems, which are based on a completely different working principle. In the course of this work, an electromagnetic hammer peening system will be used with a small payload articulated 6-axis robot to assess, among others, the effects on machining a plain surface of a 1.2379 tool steel. The engaged robot is a KUKA KR 30-3 with a nominal payload of 30 kg and is commonly used for handling tasks. In contrast to a flexible 5-axis milling machine, lower initial costs and machine hour rates affirm the implementation of the MHP process on this kind of industrial robots. Furthermore, a high flexibility and a big work space related to the required physical footprint of the machine are the main advantages. Apart from the investment cost of smaller processing machines, less expenses for a safety system are needed. This cost efficient use of the technology, as well as the high flexibility is particularly attractive for small and medium sized enterprises.

2. Machining system

As part of this study, an articulated-arm robot by the company KUKA with the type KR30-3 equipped with an electromagnetic actuator system of the company accurapul was used. The application of such a MHP-device on a robot with a low payload is shown in Figure 1. Compared to a classical machine tool, one main distinguishing factor are the kinematics of the robot. Instead of linear axis, the articulated robot consists of six linked elements which are connected by rotary joints with corresponding rotary axis.

Fig. 1. Working area of the KUKA KR30-3 Robot for machine hammer peening

Axis one to three (A1-A3) are called main axis, whereas axis four to six (A4-A6) are known as wrist axis and are serially linked to the preceding axis. The end of axis number 6, called a robot flange, is where the actuator is mounted. With a mounted actuator system, the end of the hammer tip is representing the Tool Center Point (TCP) and marks the center of rotation for the machining process. Due to that, it is possible to define the trajectory of the robot in joint coordinates as well as in Cartesian coordinates. In the joint coordinates system each position of the robot flange in space is defined by the angles of rotation of the six joints of the arm. In opposite, the world coordinate system is defined by the Cartesian coordinates X, Y and Z. In the case of the KUKA KR30-3, the world coordinate system with corresponding directions of these axes, is fixed in space. It is possible to convert the joint angles, for instance by the use of the Denavit-

Hartenberg transformation, in the Cartesian space and vice versa. The machining setup is described in the following section.

Due to an undefined position of the robot in the work area, a transformation of the world coordinate system is necessary to produce a prescribed trajectory in the base coordinate system. Thus, a translation and a rotation of the base coordinate system, referring to the world coordinate system, have to be performed. The position of the robot and the machining table with their coordinate systems is shown in Figure 1. The Machining table is equipped with a zero clamp mechanism. The end-effector of the robot, which is indicated as the last element of the kinematic chain, is defined by the electromagnetic actuator system.

3. System properties

In the present study, an electromagnetic hammer peening device is applied on an industrial robot to generate defined surface properties, primarily on metallic materials. Due to the static and dynamic behavior of the robot and the actuator, the surface modification process will be affected by the entire mechanical system. By understanding the system behavior of the robot, the influence on tool path can be improved by using appropriate planning strategies. In addition to the static and the dynamic behavior of a robot, the backlash, particularly for the first axis, is influencing the path accuracy of the deterministic peening process. In addition to the occurring forces, which are described for the electromagnetic system in [2, 3], a deflection due to the low stiffness takes place and induces a deviation in the stroke of the hammer tip. Thus, depending on the system behavior, an undefined contact might be the result. Besides the varying process forces, the stroke of the hammer tip has to operate in a defined field to guarantee a stable machining process [4]. For these reasons, investigations on the system behavior, by applying an electromagnetic hammer system have been carried out.

3.1. Static behavior of the system

In general terms, the static behavior of an open kinematic chain, like a robot system, has a lower stiffness as comparable serially linked machine designs. While the kinematic error of serial connected links is composed of all single faults, a classical kinematic chain of a 5-axis machine tool is only affected by three links as presented in [5]. Performance features like path accuracies and stiffness are strongly depended on the build and the geometry of a mechanism. The measuring setup, to determine the static stiffness of the KUKA KR30-3 in the local predefined workspace, consists of a uniaxial load cell and inductive position sensors. The static system behavior was measured with and without the actuator system. In order to associate the stiffness values to the work area (four points on the zero clamping system – see Figure 1), the results of the measurements are shown in Figure 2.

Fig. 2. Static stiffness in the base coordinate system

In general, the indication of the stiffness values is depending on the direction of loading and measuring. Against this background, the stiffness values k are presented in Table 1, whereas the first index indicates the load direction, the second indicates the direction of measurement and the third characterizes the test point. As the results show, the stiffness values of the combined system, are below 1,1 N/μm for both, with and without MHP-actuator. As presented in [6], the occurring forces of the electromagnetic actuator are depending on the MHP-parameters I, f, h , where I is the intensity of the system, which is proportional to the current, f is the working frequency of the system and the so called stroke h represents the distance between the hammer tip and the treated surface. A consequence of the low stiffness of the robot

and the acting process forces of the electromagnetic system is an increase of the distance between the tip and the surface. More specifically, the stroke h is influenced. This effect will be discussed in more detail in the next chapter.

	$k_{zz1} [N/\mu m]$	$k_{zz2} [N/\mu m]$	$k_{zz3} [N/\mu m]$	$k_{zz4} [N/\mu m]$
Without MHP-tool	0,95	0,75	0,80	1,10
With MHP-tool*	0,70	0,75	0,70	0,78
Coordinates X/Y/Z [mm]	1195,46/- 461,44/1319,04/1219,04*	1297,94/- 633,19/1319,04/1219,04*	1126,17- 735,67/1319,04/1219,04*	1023,74/- 563,89/1319,04/1219,04*

Table 1. Results of the stiffness measurements

3.2. Dynamic behaviour of the system

As already mentioned, the MHP-surface treatment process can be classified as a deterministic process. Along with NC-controlled machine system, a predictable contact between the tool and the workpiece can be achieved. Therefore, it is possible, among others, to create deterministic patterns on the surfaces of workpieces and influence their characteristics [4]. In order to achieve this, the robot system has to move with a constant feed rate while machining. On this account, measurements of the running speed in the work area were conducted using a laser interferometer. The direction of motion was in the direction of the X and Y-axis of the base coordinate system as presented in Figure 1. Thus, different target values for movement speed were set and the minimum, maximum and mean (current speed) values were calculated. The results of these measurements can be seen in Table 2. The evaluation of the data of the investigation demonstrates clearly that there is a difference in speed, which influences the deterministic contact. If the hammer peening frequency f for the electromagnetic device is set to 200 Hz, a deviation of 31 μm occurs if there is a difference in speed of about 372 mm/min at a target feed rate of 1200 mm/min (Table 2 first row). In turn, this means that with an unstable feed rate a deterministic machining process cannot be achieved. Instead, a constant hammer frequency with a differing feed rate leads to a stochastic contact of the tool and the workpiece surface. The effect of such an unstable feed rate is schematically shown in Figure 3

feed rate [mm/min]	current speed [mm/min]	minimum speed [mm/min]	maximum speed [mm/min]	speed variation [mm/min]
1200	1200	1008	1380	372
2400	2400	2160	2622	462
3600	3600	3384	3792	408
4800	4800	4590	5034	444

Table 2. Measurements of the velocity of the robot

Fig. 3. Effect of unstable feed rate during MHP-machining

As well as looking at the influence of the feed rate on the processing results, additionally the dynamic behaviour of the robot system while machining was investigated. As presented by Bleicher in [6], the velocity and therefore the kinetic energy of the impact are dependent on the stroke of the hammer tip. For this purpose, the distance between the robot flange, where the electromagnetic system is mounted, and the treated surface was measured using a non-contact eddy current displacement sensor. Due to the low static stiffness of the robot, each impact of the hammer tip causes a displacement of the robot flange. Additionally, each single impact can be seen as a single impulse which causes a broadband excitation in the frequency area by an approximate Dirac delta function [10]. This means, that each impact excites, in the investigated frequency range, different eigenfrequencies and other associated modal parameters. A typical time displacement diagram and a calculated frequency spectrum of a single area of an MHP-process are depicted in Figure 4. The appropriate process parameter settings may also be taken from the figure. For this special purpose, an exact path planning, by the use of linear interpolation, was done.

This measurement shows, that within a single path, a maximum deflection of about 166 μm of the robot flange with respect to the workpiece surface occurs. Furthermore, a detailed look at the frequency spectrum shows significant values at excitement frequency of 200 Hz and a high peak at about 12,2 Hz. Previously performed measurements indicate a resonance frequency in the range of 10,4-12,2 Hz of the robot for this position. As described before, a broad band excitation due to each single impact takes place and the system starts to oscillate with its eigenfrequencies. The processing of a single line of 30 mm requires about 1,83 seconds. At a feed rate of $v_f=1200$ mm/min a distance of 30 mm should be managed within 1,5 seconds. The difference between the target and the actual value is due to acceleration and breaking effects at each single point on the trajectory.

Fig. 4. Time and frequency domain analysis of MHP-processing

4. MHP-Robot-Machining

To examine the system behaviour of an electromagnetic driven machine hammer peening system on the KUKA KR-30-3, machining of a two dimensional area in the XY-plane of the base coordinate system was performed. In particular, two different machining strategies were applied. It was necessary for the robot to be able to move the hammer tip of the actuator system with an appropriate machining speed v_f and stroke h relative to the surface of the workpiece. The ability of a robot to achieve a precise processing of a programmed machining program can be divided in two aspects. While the position accuracy only describes the ability of repeatable positioning of the system to a single point, the path accuracy of the system can have a substantial impact on the HMP-process with a predefined trajectory speed.

4.1. 2D-Machining

In the programming of the movement of an articulated robot, a distinction between *On-* and *Off-line* programming is made [11]. When using *Off-line* programming to generate machining programs, a more precisely defined tool path can be achieved. To this end, *Off-line* programming was used to create appropriate tool paths for MHP-machining. To estimate the effects of MHP-machining with a 6-axis robot, rectangle fields of 16x30 mm on a 1.2379 (X155CrVMo12-1) steel sample were machined with different strategies. The initial surface roughness of the treated area was generated by a predefined milling process. The mean roughness depth R_z of the initial surface was 50 μm . The machining program was generated using Cartesian coordinates in the base coordinate system and by the employing linear interpolation between each point on the trajectory.

Fig. 5. Path planning strategies.

Additionally, a second rectangle field was treated with an approximation of the tool path. To obtain a continuous, steady velocity profile, each point on the trajectory is approximated by a sphere with a defined radius. The *TCP* is guided within the sphere boundaries, whereas a minimal deflection of the preset feed rate is targeted to the detriment of the tool paths accuracy (see Figure 5 right). Compared to an exact tool path strategy (Figure 5 left), a smoother, more steady velocity profile can be expected.

The parameters for the MHP-machining can be taken from Figure 4. The parameter for the sphere radius was set to 0,1 mm. An evaluation of the resulting surface topography was performed by 3D-surface measurements using a Alicona Infinite Focus measurement device and is presented in the following section.

4.2. Results

Figure 6 is illustrating the results of the surface topography measurements. A closer look at the topography of the field machined with the approximated tool path shows a periodic waviness of the surface in the ZX- and the XY-plane. When measuring the distance between the peaks of the waves, a value of about $dis=1.866$ mm can be obtained. At a feed rate of $v_f=1200$ mm/min (20 mm/sec), a frequency of about 10,7 Hz can be calculated by equation 1, which suggests that the dynamic behavior of the robot in this position is affected by the machining process and a resonance frequency of the system is excited.

$$f_{sys} = \frac{1}{T} = \frac{1}{dis/v_f} = \frac{1}{1,866 [mm] / 20 [mm/s]} = 10,7 Hz \quad (1)$$

This characteristic of the robot occurs in the reversal point of the tool path while braking and accelerating and is caused by inertial masses and the resulting attenuation because of acceleration processes. It must be ensured, that a deviation of the target contour is within defined tolerance limits of the workpiece. In order to solve the problem, different types of strategies need to be studied. However, an exact tool path planning without the interpolation method *\$C_DIS* (KUKA syntax) has been performed on a second field. The results of this process do not show a waviness of the surface as observed before (see Figure 6 right). In contrast to that, a uniform deflection of the machined surface was achieved. In both cases, the last tool path as well as the material banking can be clearly seen. In the case of the exact tool path, it is possible to determine the surface roughness in X- and Y-direction (see Figure 6 right) by using a tactile surface roughness measuring device. The impact on the surface hardness was determined using a hardness testing device, according to Vickers, which works on the principle of TIV-Method (Through Indenter Viewing). The used test probe (HV1) is working with a testing force of 1 kp (1kp $\equiv$ 9,80665 N). The results of the roughness and hardness measurements are summarized in Table 3 (surface roughness) and Table 4 (surface hardness).

Fig. 6. Evaluation of MHP-treated surfaces.

These data indicates that the potential for reducing the surface roughness for the treated surface by using an exact tool path strategy for tool steel 1.2379 is very high for X- as well as for Y-direction. The smoothing potential for both is above 97 percent regarding to the initial surface roughness R_z of about 50 μm . Taking into account the result of the hardness measurements of the treated surface, the improvement is as high as 47 percent. The achieved surface hardness as well as the surface roughness is strongly affected by the stroke h and the impact angle β_i of the tool tip [12].

	Surface roughness X-direction R_a [μm]	Surface roughness X-direction R_z [μm]	Surface roughness Y-direction R_a [μm]	Surface roughness Y-direction R_z [μm]
Mean value	1,2	0,21	6,00	1,48
Standard deviation	$\pm 0,08$	$\pm 0,03$	$\pm 0,16$	$\pm 0,01$

Table 3. Roughness measurements of the machined field (Figure 6 right) according to ISO 4288

	Initial surface hardness [HV]	Surface hardness after hammer peening [HV]
Mean value	255	375
Standard deviation	± 15	± 20

Table 4. Hardness measurements of the machined field (Figure 6 right) according to Vickers

5. Summary and Outlook

It has been shown, that a 6-axis articulated robot system of the type KUKA KR30-3 is capable to apply the electromagnetic hammer peening system for smoothing processes and to increase the surface hardness of a 1.2379 steel. Moreover, the static and dynamic behavior and their effects on the hammer peening process were discussed and the impact of a broad band excitation of the robot due to each single impact has been shown. Furthermore, it should be pointed out that the advantages, that a trajectory planning by the use of an approximated tool path can bring, are to the detriment of the path accuracy and the stability of the robot system. An exact tool path causes problems with the velocity behavior and result in multiple impacts of the hammer tip due to a stochastic hammer peening process. The question rises whether a deviation of the planed trajectory or a multiple peening of the surface is acceptable. Further investigation, relating to optimized trajectory planning, are one of the key issues to produce parts under stable and capable conditions.

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7. References

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