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Modelling of Cutting Force and Robot Load During Machining

Grzegorz Gołda[1], Adrian Kampa [1*]

[1]Silesian University of Technology, Faculty of Mechanical Engineering, Institute of Engineering Processes Automation and Integrated Manufacturing Systems,

Konarskiego 18A, 44-100 Gliwice, Poland

grzegorz.golda@polsl.pl, *adrian.kampa@polsl.pl

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Abstract. Industrial robots are used for many tasks, mainly for material handling, welding and cutting. Robots can be also equipped with other tools, for example drill or mill cutter and used for machining. Nowadays small numbers of robots are used mainly for machining of soft materials, such as plastic, wood, foam and aluminium. Robots can be used also for machining of hard materials and steel, but that is related with greater cutting force. An example of deburring and chamfering of sharp edges were analysed. The first problem is prediction of cutting force and selection of proper robot with adequate payload. A mechanistic model of cutting force during milling a chamfer on the edge is presented in the article. Afterwards a methodology for robot selection is explained. Some problems that are possible during robot machining are discussed, and some solutions are proposed. Results obtained with developed model can be used for design of robotic cell for robotic machining.

Introduction

Industrial robots are primarily used for welding, painting, transporting and for operating some machinery. Robots can be also equipped with other tools, for example drill or mill cutter and used for machining. Such examples are relatively few because there are a lot of machine tools including automated CNC machines, which are characterized by a very good functionality and provide high accuracy machining. Described in literature are some instances of the application of robots for working soft and easily-to-machine materials like wood, plastics (styrodur, XPS), gypsum, marble and aluminium [13].

In most cases this is applied to rapid prototyping and rapid tooling, which is the manufacture of spatial models and prototypes of large size and complex shape. The resulting prototypes can be used to test and improve the product, or to complete forms for the finished products [9]. There are also some application of robots for polishing, grinding, deburring and chamfering the edges of finished products [2].

The burrs and sharp edges that remain after some machining operations must be removed. In most cases that is done by chamfering the edges with hand tools. These tasks require skilled workers and are physically exhausting and due to the considerable diversity they are hard to mechanization, therefore industrial robots can be used to perform that work.

Compared to conventional machine tools, robots have some advantages, which are [13, 15]: large range, flexibility, high speed, and are easily programmable. On the other hand the greater disadvantage is small stiffness of robotic arms and limited payload. Also the precision of robot positioning is smaller than modern CNC machines and there are problems with robot calibration.

Researches related with robot machining can be categorized into a few groups [15]: robot machining system development, robot machining path planning, machining force prediction, dynamic or stiffness modelling, vibration/chatter analysis, calibration and error compensation.

Also at the STU we have performed some experiments with robot machining (Fig. 1).

Fig. 1. Example of robot machining

The primary aim of this study was to examine a possibility of using an industrial robot FANUC ArcMate100iB to rapid prototype processes by machining a plate of styrodur (XPS) was used, because of it is easy to machining.

The main problem, during programming of robotized milling process, was a selection of correct parameters of realized trajectories (linear and circular interpolation, feed - tool center point speed and acceleration/deceleration, precision and accuracy of movements, additional parameters of instruction). During researches we examined the impact of processing parameters on accuracy and quality of the surfaces. The parameters like feed, cutting speed, depth of cutting layer, number of tool paths were controlled by the industrial robot control system.

The goal of future studies will be investigate the effect of cutting forces for hard and difficult machining materials (like steel), on the surface quality of the prototype and examine the impact on the tools. Machining of hard materials is related with greater force that causes additional load on the robot and can results with a deflection of the arm. Therefore, it requires a method for prediction of cutting force and thorough verification of the robot load. Also the stiffness of robot arm must be taken under consideration.

Machining forces

The case of milling the chamfer on the edge was taken into consideration. Chamfer parameters are shown in Figure 2. Typical parameters are dependent on the size of the element and are approximately a= 0,1-2 mm, α = 30-60 °, usually α = 45°.

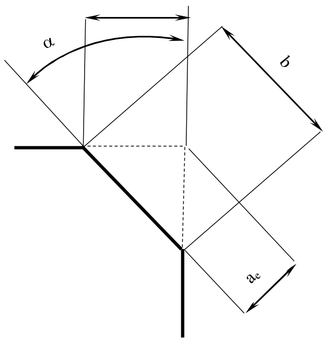


Fig. 2. Chamfer parameters a-α

Milling is a machining with tool with multiple blades. There are some analytical models which allow calculating the cutting forces during the milling (Altintas, 2012). Schema of milling forces is shown in Figure 3. There are three forces on the cutting edge: tangential force Ft, radial force Fr, and axial force Fa. Cutting forces from edges are added up and the resultant forces acting on the tool Fx, Fy, Fz can be obtained.

Mechanistic model of cutting forces

In the mechanistic model, cutting force depends on the geometrical dimensions of cut, tools geometry, tool trajectory in relation to the workpiece, workpiece material and other phenomena that occur during machining [3,4]:

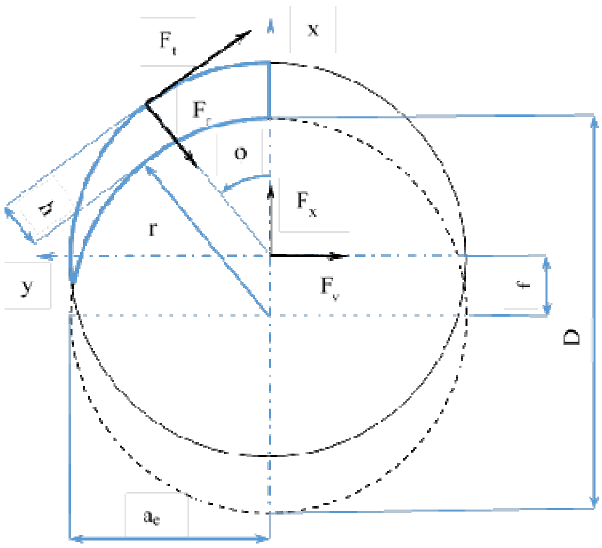
$$Fi = Ki\ A(\varphi) \quad (1)$$

Where : Fi – cutting force on the edge [N], A – cross sectional area of cutting layer [mm^2], Ki – cutting resistance index [N/mm^2], φ – cutting angle, i = {t, r, a}

Cross-section cut layer is variable and depends on the thickness of the cut layer *h(φ)* and height of machined layer *b(φ),* which are a function of the instantaneous position of the cutting edge *φ*.

$$A(\varphi) = b(\varphi)\ h(\varphi) \quad (2)$$

The geometry of the machining process is presented in Figure 3 and chip parameters are shown in Figure 4



D – diameter of milling cutter,
f – feed,
a_e – width of cut,
φ – cutting edge angle,
r – milling cutter radius,
h – chip thickness,
F_t – tangential cutting force,
F_r – radial cutting force,
F_x, F_y – cutting forces in tool coordinates.

Fig. 3. Schema of milling geometry

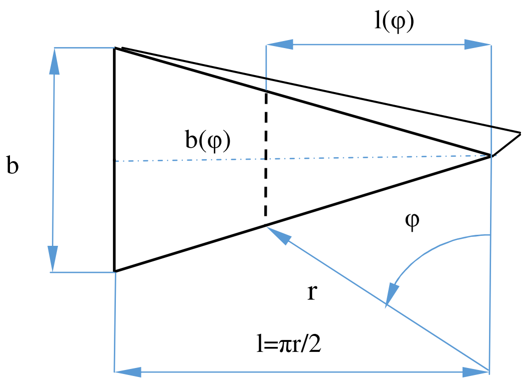


Fig. 4. Schema of chip parameters (after linear extension)

Assuming orthogonal milling and that the maximum milling width a_e = ½ D, where D is tool diameter. When tool have 4 blades z=4, then at any time, only one blade is in contact with material and cutting conditions are advantageous. Depending on formula (1) the coefficients of cutting resistivity (specific cutting force) Kt, Kr, Ka are modelled as a nonlinear function of the instantaneous cutting layer thickness h(φ) and the exponent m.

They are selected on the basis of cutting tests for specific materials. And cutting force coefficient is determined from the relationship:

$$Ki = Ci\ h(\varphi)^{-m} \quad (3)$$

For the assumed conditions of milling the cross-sectional area of cutting layer is the product of a growing function b (φ) and decreasing function h(φ)

$$A(\varphi) = b(\varphi)\ h(\varphi) = 2b\ \varphi\ f \cos(\varphi)/\pi \quad (4)$$

After substituting with formulas 3 and 4 tangential cutting force Ft is equal:

$$Ft(\varphi) = Kt\ A(\varphi) = Ct\ h(\varphi)^{-m}\ 2b\ \varphi\ f \cos(\varphi)/\pi \quad (5)$$

On the basis of [3], it was found that for the orthogonal milling, there is a relationship between the tangent force Ft and the radial Fr, and the axial force Fa is close to zero.

Determination of the resultant force acting on the tool requires a transformation of the coordinate system with the coordinate system of the blade to the centre of the tool coordinate system.

$$\begin{cases} Fx = Ft \sin\varphi - Fr \cos\varphi \\ Fy = Ft \cos\varphi + Fr \sin\varphi \\ Fz = Fa \end{cases} \quad (6)$$

Resultant cutting force Fw:

$$F_w = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (7)$$

Example of cutting force prediction

Typical machining parameters were assumed: chamfer a=1,4 x45°, feed f=0,05mm/z, b=2 mm, mill tool - finger cutter from cemented carbides VHM HPC, diameter D=10 mm, blades z=4, κ=90°, n=9550 rev/min, cutting speed V=300 m/min, feed rate vf= 477 mm/min. Material: mild steel C35, C=1516 N/mm^2, m=0,27, Kr=0,5.

Using the previously mentioned formulas and assumed machining parameters a numerical simulation of the cutting forces was performed. Calculated cutting forces for one edge, based on this model, are shown in Figure 5.

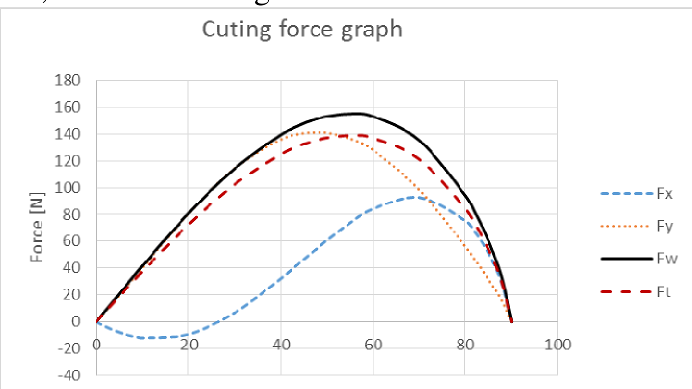


Fig. 5. Cutting forces for one edge of tool

For fixed cutting parameters, the maximum cross-sectional area there is for cutting angle φ ≈ 49 °, while due to the strengthening of material and increase of the specific cutting force the cutting force Ft reaches the maximum value at the angle φ ≈ 55°.

Obtained results are similar with other experimental results that are described in the analysed bibliography [4, 11].

Value of force Fx is negative in a certain angular range as a result of machining geometry. Since the force Fx change the direction this may be source of vibrations and chatter. The resultant force Fw acts on the tip of the tool and causes the tool deflection and the deflection of the robot arm.

Simulations of machining other materials were also done, and the cutting forces obtained for machining different materials is shown in Figure 6.

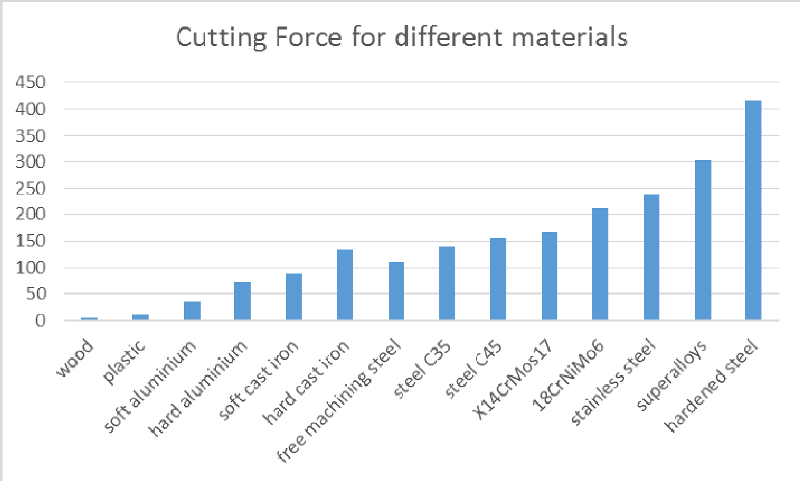


Fig. 6. Comparison of cutting force Ft for different materials (a=1.4x45º, b=2 mm, f=0,05mm)

It follows that the cutting forces for different materials may vary considerably and that must be taken into account during robot load verification.

Robot arm load

In the case of machining untypical load of robot arm occurs. The load consists of the weight of equipment (high power electrospindle can be very heavy) and cutting forces that can operate in different directions. Manipulator kinematics can be described using Denativ-Hartenberg convention [6] and each frame of manipulator can be described as homogeneous transformation matrix. The overall transformation between the base coordinate and the 6-stage manipulator end point can be described as shown in [14].

Electrospindle can be considered as next frame of robot and described similarly. To calculate the effect of cutting forces on the robot arm the moments of these forces must be determined. During machining the tool can be set at different angles relative to the robot arm. The weight of the equipment G and the payload capacity Gmax, and the machining forces Fx, Fy, Fz must be taken into account. Calculated machining forces and bending moments over robot arm axis Mx, My, Mz must be smaller than the forces and torques limits specified in robot specification [10].

Taking into account the calculated forces acting on the robot arm it should also pay attention to the stiffness of the robot arm and possibility of displacement.

Articulated manipulator can be treated as a combination of rigid arms with resilient joints. The stiffness of the joints is about 10^5 - 10^6 Nm/rad [8]. Empirically determined coefficients of rigidity for heavy duty robots are about Kx,z = 1000 N/mm, and Ky = 500 N/mm [1]. The displacement of the robot end-point Pi can be approximated as a linear dependence of the force Fi and stiffness Ki.

Some examples of machining configuration were analysed. Possible are six main processing cases as the cutting direction relative to the axis of the robot arm and a plurality of intermediate cases. In some cases, moments of cutting force and the moments of gravity forces are cumulative and that results in adverse robot load. Taking into consideration the calculated load during adverse machining conditions of hard materials an arm displacement under the influence of cutting forces can be significant (greater than 1 mm), which is unacceptable in the case of precise machining. Temperature changes and the thermal expansion of the robot arm may also have adverse effect on machining accuracy [5].

Conclusions

Because machining force is not constant and can still changes value and direction, it can be the source of vibration and chatter. Small stiffness of robot arm combined with vibrations can caused losing of robot position and improper surface after machining.

Therefore, in a further stage of work the experimental verification of real cutting force is planned. Also the dynamic load model of robot and a verification of real robot rigidity should be taken into consideration. In connection with possible problems during machining the real-time monitoring system [7] for machining forces and compensation devices is needed. Possible processing strategies include [12]:

- selection of robots with greater stiffness,
- offline program generation with force compensation,
- online control with force compensation,
- online contour tracking,
- adaptive deflection compensation,
- additional actuation mechanism for error compensation.

Despite of some problems robot machining technology has great possibilities and results obtained with developed model can be used for design of robotic cell for machining.

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