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TOOL WEAR PERFORMANCE EVALUATION IN MDF MACHINING WITH ANTHROPOMORPHIC ROBOT

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Professional paper
Recent progress in robotics makes robots suitable for many different applications. Beside manipulative and installation applications, which are the most common for robot manipulator, milling can be performed as well. In the near future, robot manipulators, integrated with spindle, proper cutting tool and milling parameters could replace conventional CNC middle toleranced machining, especially for soft material end products. In general, tool life behaviour in milling with robots is not available or studied. Therefore, this work presents the analysis of HSS tool wear in milling MDF (medium density fibreboard) with an anthropomorphic robot. The focus is on the correlation of the tool wear and the workpiece position in the robot operation area. To analyse this, tests were performed in four different positions according to the distance between robot base and test milling position. Results show that increasing distance significantly affects tool wear, on account of vibrations, what shows completely different behaviour than stiff conventional CNC machine tools.

Keywords: *anthropomorphic robot, machining, medium density fibreboard (MDF), tool wear*

Evaluacija trošenja alata kod obrade MDF s antropomorfnim robotom

Stručni članak
Najnoviji napredak u robotici čini robote pogodne za različite potrebe. Osim manipulativnih i instalacijskih aplikacija, koje su najčešće za robotske manipulatore, može se obavljati i glodanje. U bliskoj budućnosti robotski manipulatori s integriranim vretenom, pravilnim reznim alatom i pravilno odabranima parametrima glodanja, mogli bi zamijeniti konvencionalne CNC strojeve kod srednjih tolerantnih strojnih obrada, pogotovo kod upotrebe mekanih materijala krajnjih proizvoda. U principu, trajanje alata i trošenje tijekom glodanja s robotima nije dostupno ili istraživano. Stoga, ovaj rad predstavlja analizu HSS trošenja alata tijekom obrade MDF (ploče srednje gustoće) materijala s antropomorfnim robotom. Težište je na međuodnosu trošenja alata i položaja izratka u području rada robota. Za tu analizu, ispitivanja su provedena u četiri različita položaja prema udaljenosti između baze robota i ispitivanog položaja glodanja. Rezultati pokazuju da porast udaljenosti značajno utječe na trošenje alata, zbog vibracija, što pokazuje sasvim drugačije ponašanje od krutih konvencionalnih CNC strojeva.

Ključne riječi: *antropomorfni robot, ploče vlaknatice srednje gustoće (MDF), strojna obrada, trošenje alata*

1 Introduction

In the time of constant progress and search of new sustainable and economically justified technologies, the question is raised how to cut costs and find at least partial replacement for large and very expensive conventional CNC machining centres. This is emphasized especially when multiaxis machining is needed and the tolerances are not crucial. Machining with industrial anthropomorphic robots is one of the promising new solutions for those applications.

Recent progress in offline programing software made complex large workpieces possible to be machined with robotic manipulators. Modern CAM (computer aided manufacturing) softwares, with additional modules for robot machining, offer new perspective in usage of robotic manipulators. Development of software in recent years enabled the robots to be used not only for conventional purposes of manipulative operations, but also for multi-axis simultaneous machining [1]. That opened a new horizon of possibilities, including the use of an anthropomorphic robot as a CNC machine, for larger machining areas, especially if rail system is integrated for translational movement of the whole robot. According to Abele et al. [2], the major fields of application for industrial robots are prototyping, pre-machining, cleaning, etc., while in case of middle tolerance parts even end-machining operations should be added. Such conditions are facing the wood processing industry, what can be therefore a proper field to implement robot machining technology.

High adaptivity and low investment made robots suitable to machine very large and complex workpieces, such as pre-fabricated building walls or large scale moulds, variety of soft material prototypes, etc. Medium density fibreboard (MDF) is one of the most commonly used materials in wood processing, prototyping and house building industry.

Medium density fibreboard (MDF), as said before, is one of the most widely spread materials in furniture industry. It is an industrial wood product made out of wood fibres, glued together with resin, by pressure and heat. Because of numerous advantages, such as: high smoothness of face layers, good machinability, homogeneity in comparison with some other wood composites (particle board, OSB boards, etc.), etc., MDF is a preferred material over solid wood in many applications. In machining of MDF, generally the same cutting tools are used as for particle board or other wood composites. Since raw (unfinished) MDF boards contain less abrasive materials, like some other secondary wood products (example: particle boards), it is not necessary to use very expensive and hard cutting tools (diamond tools) in machining operations [3, 4, 5]. Therefore, in this work economical HSS cutting tools are applied to experiments. HSS cutting tool edge is predicted to deteriorate quite fast, but still could provide useful data on tool wear and robot structure influence on it.

In many cases, there are large MDF or some other wooden composite workpieces, which need to be machined with 3-axis or even multi-axis machines (prototypes, mould tools, prefabricated house walls, etc.) to form a final product. Because of middle tolerance wood and wood composite end-products, potential needed post machining operations (sanding) and high flexibility, machining with robots is appropriate application for wood processing industry.

There was a lot of research work made on tool wear in machining of MDF. However, all the researches were focused on conventional woodworking machines. In general, they show that MDF machining parameters, tool material and applied tool angles had a significant influence on tool life [6, 7, 8]. In machining with anthropomorphic robots, very little is known about the behaviour of the milling tool during the process.

It is estimated that results of this work will show that the tool wear in machining with robot is going to be greater in comparison to conventional CNC machines. The reason lies in lower robot stiffness, which can result in the higher attained vibrations during milling processes.

Abele et al. [2] in their work discuss different stiffness models and static displacement of the robot during milling processes. Stiffness models showed lowering of stiffness with increasing distance of cutting tool from the robot base. Higher vibrations in comparison with conventional CNC machines can so be mainly the result of lower stiffness of the robot, which varies according to the robot position, i.e. decreases with the robot base distance [2, 9, 10].

Milling with robots is quite appropriate for wood processing industry because it is topical and due to its numerous advantages, especially high adaptivity that is very interesting for the industry. There is a lack of knowledge in the field of tool wear and machining wood and wood based materials with robots, so that is why the aim of this work is to gather new knowledge through investigations and studies.

2 Materials and methods

Milling tests with industrial robot and CNC machine were conducted using the same machining parameters on MDF material. Material was chosen due to its broad application in woodworking and house building industries.

Non-laminated industrial MDF board with thickness of 19 mm ± 0,1 mm was used as a machining material. Large board was sawn into test pieces for the experiments: 1000 × 250 mm for the robot and for the experiments on CNC machine: 500 × 270 mm.

The average measured moisture content of prepared test workpieces, according to ISO 16979 [11], was 7 % and the mean measured density of the test pieces according to ISO 9427 [12] was 700 kg/m^3, for all of the tests.

Cutting tools used for the experiments were made out of high-speed steel (HSS), with an edge angle of 38° and dimensions of 30 × 5,5 × 1,2 mm, as shown in Fig. 1. Blade knives were mounted on LEITZ 1-blade shank wood cutting tool holder with diameter of 12 mm. All parameters used for conducted tests were recommended by the manufacturer. The tool rotation speed was 8000 rev/min and the feed rate was set to 2400 mm/min. The calculated feed per tooth was 0,3 mm. In all the milling experiments the "zig zag" milling (down and up milling, Fig. 2) strategy was used, with constant 2 mm overlap (a_e = 2 mm). Because of milling with the side of the tool, cutting depth was 19 mm (a_p = 19 mm) with the corresponding tool tip breakthrough of 2 mm.

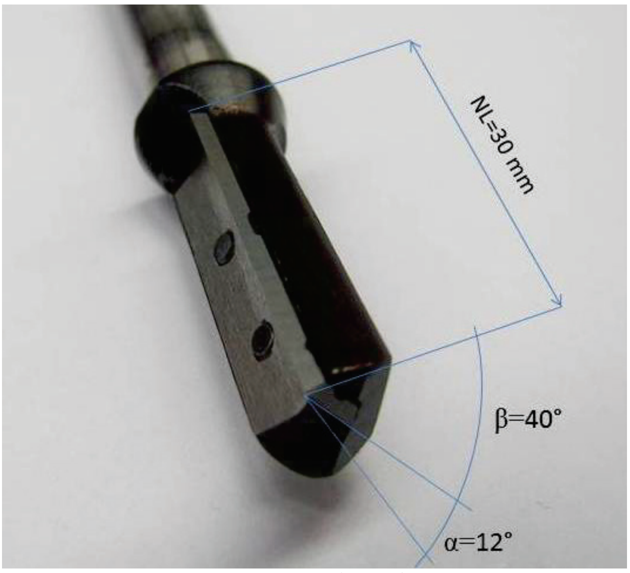

Figure 1 Cutting tool.

Tool wear tests were performed on KUKA KR 150 L110 industrial anthropomorphic robot and compared to conventional 3-axis CNC milling machine Mori Seiki. Robot was equipped with water cooled 6,3 kW HSTec motor spindle and dust evacuation system. Tool attached to the robot flange has a maximum reach of 3600 mm, and is capable of carrying 110 kg of load attached to the robot sixth axis flange [13].

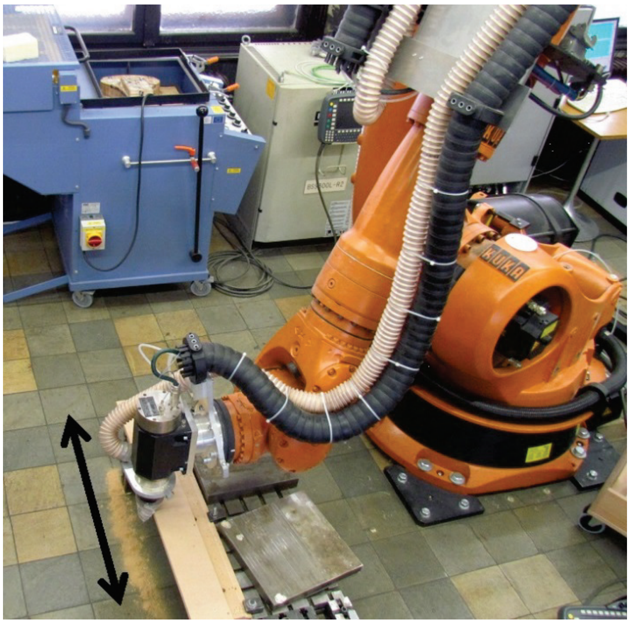
Figure 2 Up and down milling strategy used in tool wear tests (pose D)

To provide results of the tool wear in one of the chosen robot working planes, the robot working space has been divided into four different test distances (robot poses) as shown in Tab. 1 and Fig. 3. Different robot poses present different distances of cutting tool from the robot base. Planar tests were chosen because those are the most common forms and layouts of the milling material in wood processing industry (board-planar).

Test distances were divided into 600 mm intervals at constant vertical robot position (Z = 400 mm), according to the robot base. The nearest test distance in selected robot configuration, has been positioned at the distance of 1400 mm from the robot base. This corresponds to the nearest test pose that the robot still reaches under the selected configuration.

Table 1 Distances from cutting tool to robot base

Test position (pose)	A	B	C	D
Robot base-test position (pose) distance, mm	3200	2600	2000	1400

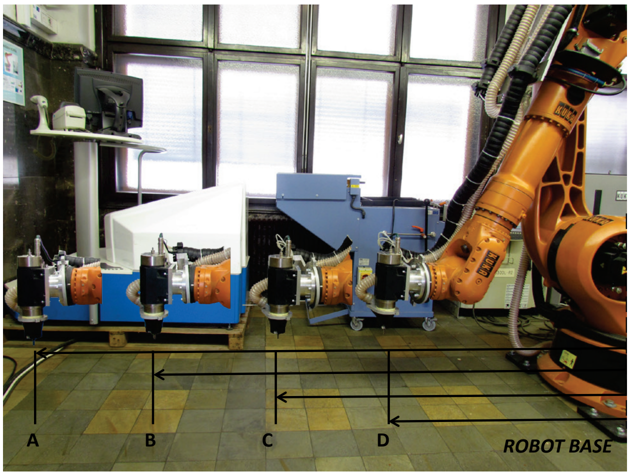

Figure 3 Attained positions (poses) of the robot in the tool wear tests

All the robot poses were oriented in the same direction (in front of the robot, elbow up configuration and rotation about tool axis 0°) as can be seen in Fig. 3.

Comparable tests made on CNC machine (Fig. 4) were done for the reference thus evaluating the difference between robot and CNC machine tool wear during MDF board milling. Smaller MDF test boards were used in CNC machine experiments due to limited machine workspace area. Strategy and cutting length were, for the intention of transparent comparison, identical for booth machine tools.

Figure 4 Mori Seiki CNC machine

Total cutting edge tool path in machined material has been determined to be 1750 m. Tool edge path in machined material (L) is given by the tool path of single cut (l) multiplied by the total number of cuts taken per tooth (C):

$$L = C \times l, \tag{1}$$

Total number of cuts per tooth (C) is defined as follows:

$$C = \frac{l_B}{f_t} = \frac{l_B n}{v_f z}, \tag{2}$$

where l_B is milled specimen length, f_t feed per tooth, z number of teeth, v_f feed and n rotating speed.

Single cut length (l) is given by the following equations;

$$\sin\alpha = \frac{\frac{f_t}{2}}{r}, \quad \cos\beta = \frac{r - a_e}{r}, \tag{3}$$

$$\theta = \arcsin\left(\frac{f_t}{2r}\right) + \arccos\left(\frac{r - a_e}{r}\right), \tag{4}$$

where r is the diameter of the cutter and a_e is overlap of the cut. Contact angle θ was measured in radians (Fig. 5).

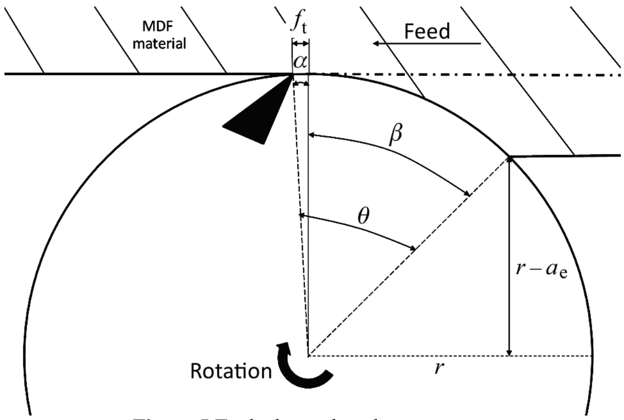

Figure 5 Tool edge path and contact zone

Single cut (l) is calculated by:

$$l = r\theta = r\left(\arcsin\left(\frac{f_t}{2r}\right) + \arccos\left(\frac{r - a_e}{r}\right)\right). \tag{5}$$

Complete tool path is then defined as follows:

$$L = \frac{l_B n r}{v_f z}\left(\arcsin\left(\frac{f_t}{2r}\right) + \arccos\left(\frac{r - a_e}{r}\right)\right). \tag{6}$$

Tool wear measuring method was performed according to Kowaluk et al. [3], where average tool wear in three measured points was defined. Measuring points were always taken at the same position of the tool blade and then averaged. All the measurements were carried out by Mitutoyo microscope with 30× magnification. Example can be seen in Fig. 6.

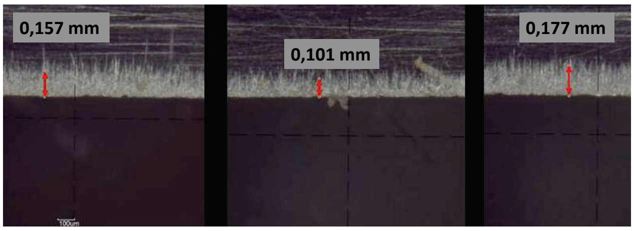

Figure 6 Tool wear measurement examples

Tool wear measurements were first conducted after 17 m of the tool edge path. The following four measurements were performed in approximately 60 m intervals, for better tool wear survey. In the first five measurements, the most vigorous tool wear was expected, so it was continued with shorter periods of conducted tool wear measurements.

After 240 m of the tool path, tool wear was expected to be more moderate, so measurements were done on approximately every 200 m intervals, until total 1750 m of the tool edge path. Altogether 12 measurements for each cutting tool, in the specific robot pose and milling on the CNC machine, were gathered. For every test position and milling with CNC machine, the wear tests were conducted on two blade knives, to statistically confirm gathered measurements.

3 Results and discussion

The results of milling tests and tool wear are presented in Fig. 7, Tab. 2 and Tab. 3. As shown, the most drastic tool edge wear rate is noticed in the interval from 0 m to 400 m in milling with robot (in all poses) as well as in case of milling with CNC machine tool. From approximately 400 m up to 1750 m of tool path, more moderate and regular tool wear trend can be noticed (Fig. 7).

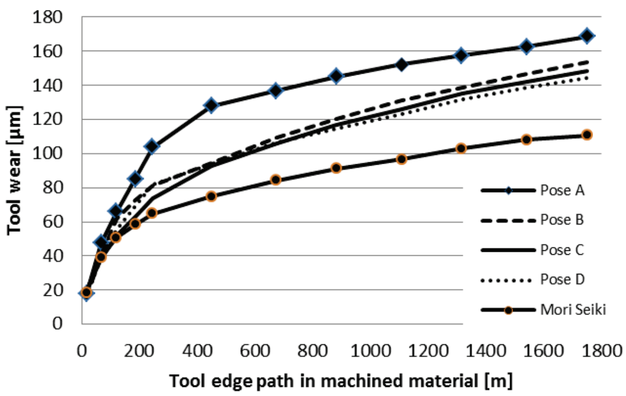

Figure 7 Average tool wear progress for different robot poses and tool wear in case of CNC machine usage

Considering the robot milling tests, tool wear varies significantly in correlation with the attained robot position (pose). The largest average tool wear was noticed in the farthest position A (3200 mm from the robot base). Following positions (B, C and D) had minor deviations but still show the same trend of tool wear decrease, if the distance from the robot base is decreased.

Positions B, C and D also lay in the robot optimal working area. Tool wear in those tests poses decreases by approximately 3 % according to the decreasing test distance. As expected, test position D (the closest to the robot base) had the lowest tool wear among all performed tests made with anthropomorphic robot. It is shown to be 17 % lower than the farthest test position A.

Average tool wear after 1750 m of the tool path, according to robot position, is presented in Tab. 2.

Table 2 Average tool wear comparison

Machine	Robot			
Test position (pose)	A	B	C	D
Average tool wear, µm	169	153	149	145
Increase of the tool wear according to test pose D	1,17	1,06	1,03	1,00

As predicted in the introduction, the tool wear decreases in proximity of the robot base. Average tool wear comparison (tool wear index, Tab. 2) is graphically shown in Fig. 8.

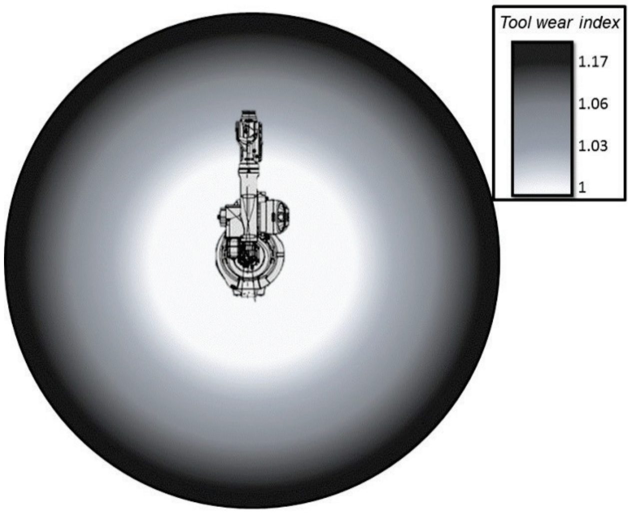

Figure 8 Graphical display of the HSS tool wear in robot working area

Milling tests performed on the CNC machine showed that the tool wear was lower than in robot machining case, most probably due to higher stiffness and consequently reduced vibration during milling process (Tab. 3 and Fig. 7). Average robot machining tool wear, after 1750 m of tool path, was compared with average tool wear of CNC machine Mori Seiki, under identical milling parameters and tool path length (Tab. 3 and Fig. 7).

Table 3 Average tool wear comparison: robot vs. CNC machining

Machine	Robot				CNC machine
Test position (pose)	A	B	C	D	Mori Seiki
Average tool wear, µm	169	153	149	145	111
Tool wear robot/Mori Seiki comparison	1,52	1,38	1,34	1,31	1,00

It can be seen that tool wear of tests performed by robot machining, was 31 to 50 % higher than tool wear during milling with CNC machine tool.

4 Conclusion

The presented work shows the analysis of tool wear (HSS blade), comparing robot machining with conventional CNC machining. Tool wear was in case of robot machining further segmented to progressing distance between robot base and milling position. Results for all varied milling positions were compared, under identical machining parameters, with conventional CNC machine experiments.

As expected, on account of the robot lower rigidity, the tool wear was the biggest in most distant position according to the robot base and then lowered within attaining position. Tool wear, after performed 1750 m of tool edge path, between maximal and minimal robot distance attained in tests, was varied up to ~17 %. Besides this, the robot area of minimal difference of the tool wear was determined. It corresponds to approximately 1000 mm wide planar area at the height of 400 mm, spread out from 1400 mm to 2600 mm from the robot base. In practice, it also corresponds to the area with maximal robot milling reachability and most appropriate area for robot milling. Recognised and proposed area can be used to determine the most favourable workpiece position in the robot working sphere, from the tool life aspect of view. Tool life can now also be predicted not just with the contact path progress, but also according to the tool trajectory and robot milling position, when milling MDF board.

Tool wear was also compared with conventional CNC milling machine tool operation. As expected, the tool wear trends were milder in CNC, while milling with robot is superimposed with low stiffness and so presence of vibrations. That has been even further confirmed with the observation that robot position during milling significantly influences the tool wear. This effect goes on account of attained vibrations in milling process and diverse stiffness characteristics of the robot according to its position in the workspace.

Since the evolution in robotics, especially in machining applications, is far from being over, more and more applications of milling with robots in woodworking industry can be expected. And for sure, one of the most important data will be tool wear and tool life. Therefore, the results of this paper, related to tool wear in incoming machining strategies/technologies, can contribute to the progress in development of robot machining technologies.

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