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COMPARISON BETWEEN CONVENTIONAL MILLING AND CLIMB MILLING IN ROBOTIC DEBURRING OF PLASTIC PARTS

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Abstract: *This article presents the work performed by the authors in the field of the robotic deburring. The scope of the research is limited to applications in which an articulated arm, low payload robot manipulates the milling-type deburring tool around a plastic workpiece, which is clamped on a fixture. The main objective of the research was to conduct some experimental procedures in order to develop a comparative analysis between conventional milling and climb milling approaches in robotic deburring. The experimental equipment consisted of an articulated arm, 6 DOF Kawasaki FS10E industrial robot with 10 kg payload. The robot was equipped with an ATI RC-340 radially compliant deburring tool. The experimental procedure was conducted by creating two deburring programs around the outer edges of the workpiece (one program corresponding to the conventional milling approach and the other program corresponding to the climb milling approach). The programs were developed using the point-to-point block teaching method on the teach-pendant. Each program was then run several times, with gradually increased radial contact force of the tool (by increasing the compliance pressure) and the results after each program run were observed by visual inspection. Based on these observations, the conclusions were drawn regarding the efficiency and applicability of each feed direction approach.*

Key words: *robotic deburring, climb milling, conventional milling, radial compliance, radial contact force.*

1. INTRODUCTION

In the extremely dynamic field of industrial robotics there are currently technical solutions to be found for almost every application category. The flexibility and programmability of industrial robots greatly improve the ability of these equipments to adapt even in the most challenging conditions. Even in the machining field, where machine-tools have the advantage regarding most of the aspects, there are certain areas where industrial robots have well established roles.

The most widely implemented robotic application in the machining field is robotic deburring. Traditionally, deburring was performed manually. In the last few decades, various methods for mechanized deburring were developed, including brushing, abrasive finishing and mass finishing. Nevertheless, these approaches are only efficient for parts of relatively simple shape or, in some cases, with small dimensions. In order to ensure a flexible solution that is suitable for any part shape or dimension, robotic deburring cells were developed [1].

There are currently two main approaches in robotic deburring: the robot can manipulate the deburring tool around the workpiece, which is clamped on a fixture (as shown in Fig. 1) or the deburring tool can be mounted on a fixed support and the robot can manipulate the workpiece around it (as shown in Fig. 2) [2]. Furthermore, the deburring tool can be brush-type, abrasive-type and mill-type, as shown in Fig. 3.

Taking into account the above context, the scope of the research described in this paper is limited to applications in which the robot manipulates the milling-type deburring tool around a plastic workpiece, which is clamped on a fixture. Being a milling application, the optimization of such a deburring process must be done by analyzing the specific parameters. In order to achieve the best results, the research will be split in three stages: feed direction analysis, feeds and speeds analysis and chatter suppression analysis. The work presented in this paper represents the first stage of the research and focuses on a comparative analysis between conventional milling and climb milling approaches [3].

2. EXPERIMENTAL EQUIPMENT

The analysis of conventional milling and climb milling methods was done using an experimental approach. The deburring operations were performed by a Kawasaki FS10E articulated-arm robot with 6 degrees of freedom, including a Kawasaki D controller, as shown in Figure 4. The front and side views of the robot, together with the working space, are shown in Fig. 5 [4]. The functional parameters of the robot are shown in Table 1.

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Fig. 1. Deburring application with the robot manipulating the tool.

Fig. 2. Deburring application with the robot manipulating the workpiece.

a

b

c

Fig. 3. Deburring tool types: *a* – mill-type tool (end-effector); *b* – brush-type tool (end-effector); *c* – abrasive-type tool (fixed tool).

The robot was equipped with an ATI QC41 automatic tool changer and an ATI RC-340 deburring tool (shown in Fig. 6). The front and side views of the deburring tool together with functional and assembly dimensions are shown in Fig. 7 [5]. The functional parameters of the end-effector are shown in Table 2. It should be noted that the deburring tool has radial compliance in order to provide a passive force control function and to ensure good contact between the tool and the part. Both the spindle and the compliance system are pneumatically actuated.

Fig. 4. Kawasaki FS10E articulated-arm robot and Kawasaki D controller.

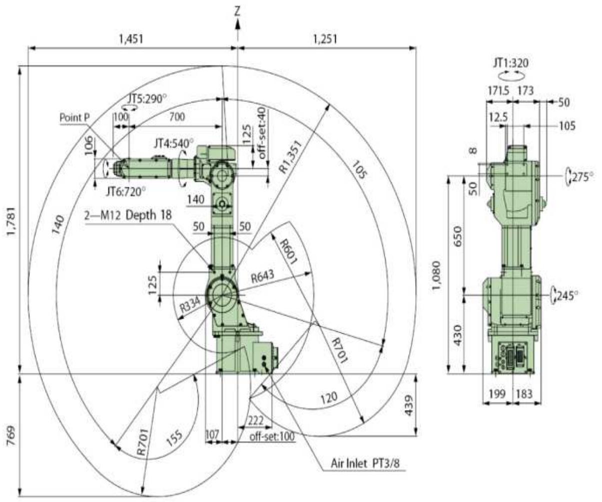

Fig. 5. Front and side views of Kawasaki FS10e robot.

Table 1

Kawasaki FS10E robot parameters

Architecture	Articulated arm		
DOF	6		
Joint limits and speeds	Joint	Limits	Speed
	1	±160°	200 °/s
	2	−105° – 140°	140 °/s
	3	−155° – 120°	200 °/s
	4	±270°	360 °/s
	5	±145°	360 °/s
	6	±360°	600 °/s
Payload	10 kg		
Wrist load	Joint	Torque	Inertia
	4	21.5 N·m	0.63 kg·m^2
	5	21.5 N·m	0.63 kg·m^2
	6	9.8 N·m	0.15 kg·m^2
Repeatability	±0.1 mm		
Weight	170 kg		
Acoustic level	< 70 db		

Fig. 6. Robot tooling: *a* – ATI QC41 automatic tool changer; *b* – ATI RC-340 deburring tool.

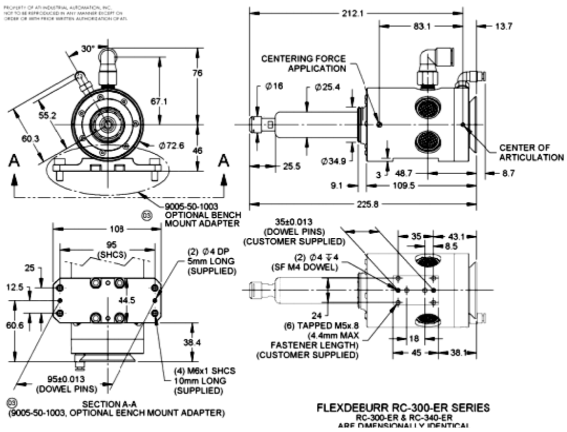

Fig. 7. ATI RC-340 functional and assembly dimensions.

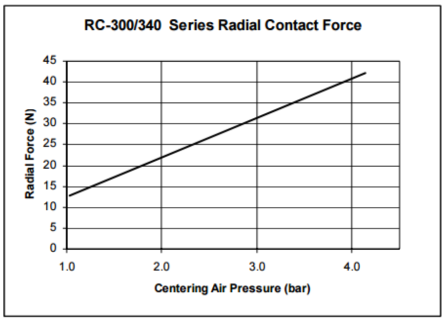

Fig. 8. ATI RC-340 radial contact force diagram.

Table 2

ATI RC-340 deburring tool parameters

Motor type	air turbine
Idle speed	40 000 rpm
Max. Torque	0,08 Nm
Power	340 W
Weight	1.2 kg
Compensation	max. ±7.5 mm, recommended ±3 mm
Compliance force	12.7–42 N at 1–4.1 bar
Spindle air speed	6.2–6.5 bari
Air consumption (idle)	2.8 l/s
Air consumption (stall)	10.2 l/s
Acoustic level	< 70 dB
Collet size	6 mm

The spindle of the deburring tool requires a pneumatic pressure of 6.2–6.5 bar, while the compliance requires a separate pneumatic circuit with a regulator that can be used to vary the pressure up to 4.1 bar (in order to control the compliance force). The diagram that shows the dependence between the radial contact force and the pressure in the compliance pneumatic circuit is shown in Fig. 8.

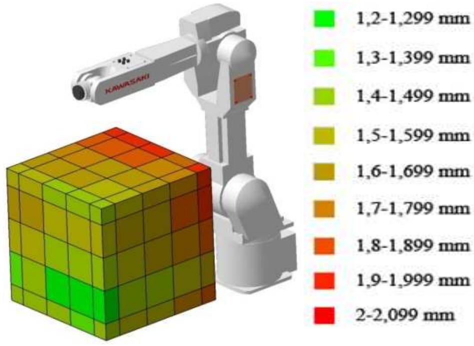

Fig. 9. Accuracy map of the Kawasaki FS10E robot.

Fig. 10. The T-slot plate mounted on the two axis manual positioning system.

In order to provide support for the plastic part and the corresponding fixture, a T-slot plate was used. As shown in previous works, the accuracy of the robot varies inside it's working space (for the Kawasaki FS10E robot, the accuracy map is shown in Fig. 9) [6]. In order to ensure that the workpiece is placed inside the workspace area which benefits from the best accuracy of the robot, the plate was mounted on a two axis manual positioning system, as shown in Fig. 10.

3. EXPERIMENTAL SETUP AND PROCEDURE

The T-slot plate, together with the 2-axis manual positioning system, was mounted on a metal frame fixed in front of the robot. The part being used as an experimental workpiece was a plastic dustpan with burred edges, as shown in Fig. 11. The dustpan was mounted on the T-slot plate using clamp straps, screws and T-slot nuts. The edge of the T-slot plate was aligned with robot's base coordinate system. Finally, using the positioning axes of the support system, the workpiece was positioned inside robot's workspace area with the highest accuracy. The final experimental setup is shown in Fig. 12.

The part was chosen taking into account several aspects. First of all, it should have had significant burrs, so that the efficiency of burr removal could be evaluated. Secondly, the part should have been sturdy enough so that its structure could withstand the machining forces generated during deburring and maintain structural integrity. Finally, the plastic should have been thin and soft enough so that any variation of machining condition would have visible consequences.

As recommended by ATI, the experimental procedure was divided into the following steps:

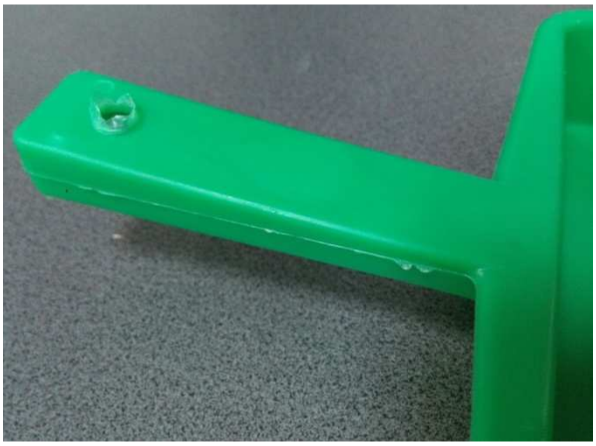

Fig. 11. Burred edges on the dustpan.

Fig. 12. Experimental setup for robotic deburring.

1. The clamp straps were placed in the middle of the part, between the front of the dustpan and the handle, as it can be seen in Fig. 12.
2. As the burrs are of similar size on the entire outer edge of the dustpan, both milling approaches (conventional milling and climb milling) will be applied on the same setup: the front of the part will be deburred using conventional milling and the handle will be deburred using climb milling.
3. In order to program the robot for both deburring operations, a dowel pin used as a teaching tool was mounted on the tip of the RC-340 deburring end-effector. The diameter of the dowel pin should be lower than the diameter of the actual cutting tool (but the difference should not exceed the compliance of the deburring end-effector). Taking into account that, in this case, the diameter of the cutting tool was 9.5 mm and the compliance of the deburring end-effector was 7.5 mm, a dowel pin with the diameter of 7.5 mm was used.

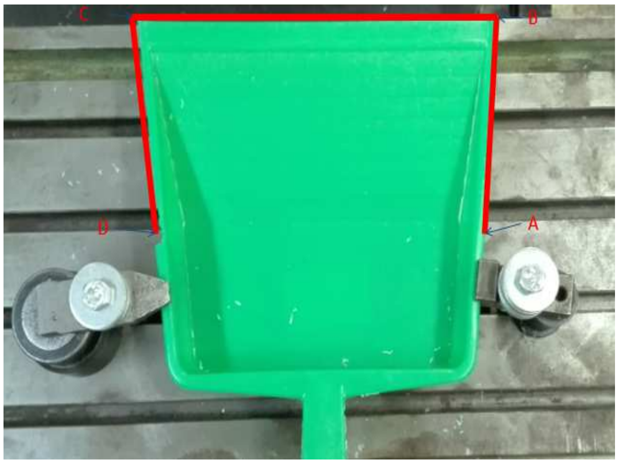

Fig. 13. Deburring the front part of the dustpan – conventional milling trajectory.

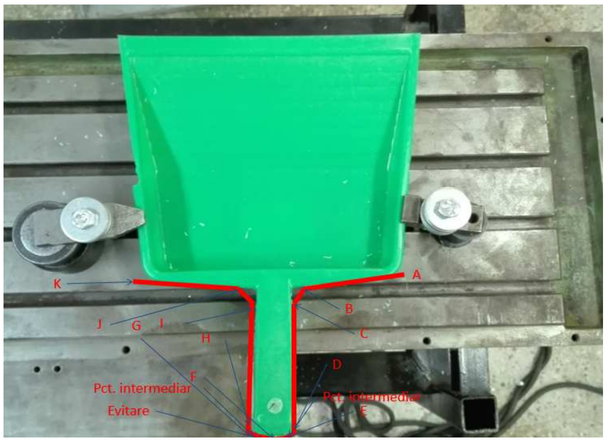

Fig. 14. Deburring the handle of the dustpan – climb milling trajectory.

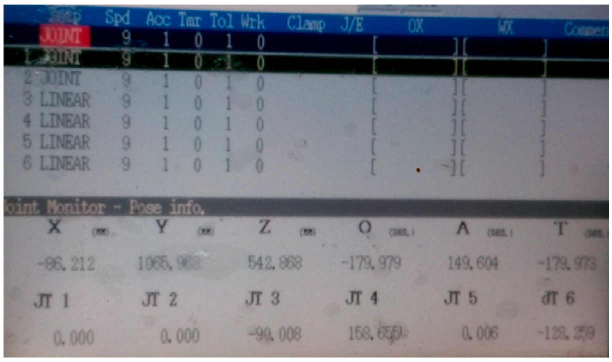

Fig. 15. The point-to-point block teaching program.

4. The programming of the robot was done using the dowel pin so that it remained tangent to the outer edge of the dustpan. For comparison purposes, two programs were created: deburring the front of the workpiece using conventional milling (trajectory shown in Fig. 13) and deburring the handle of the workpiece using climb milling (trajectory shown in Fig. 14).
5. The programs were created using the block-teaching approach, so that each program line corresponded to one trajectory segment, as shown in Fig. 15.
6. After both programs were developed, the dowel pin was replaced by the cutting tool and the pressure in

the compliance circuit was reduced to a very low value – about 0.3 bar. Using this setting, each of the programs was run (without the spindle rotating) to ensure that no programming errors occurred and the tool was in permanent contact with the workpiece along the trajectory. After this verification was done, the pressure in the compliance circuit was increased by a small step (0.1–0.2 bar, due to the softness of the material) and each program was run again, this time with the spindle on. This procedure must be repeated until all the burrs are removed, thus setting the corresponding compliance value for the application. For experimental purposes, in this case, the pressure in the compliance circuit was further increased after burrs removal, in order to observe the behavior of the material.

7. In order to analyze the impact of the lead in and lead out strategies with respect to feed direction, the conventional milling trajectory was configured so that the tool engages the part on a direction perpendicular to the milling path, while the climb milling trajectory was configured so that the tool engages the part on a direction tangent to the milling path.

4. EXPERIMENTAL RESULTS

By following the above steps, both programs were repeatedly run with increased radial contact force until significant damage of the workpiece occurred. It should be taken into account that, being a dedicated deburring tool, the ATI RC-340 end-effector runs the spindle at a speed of 40000 RPM, which is not adjustable. Thus, the robot must follow the programmed path using high feed values in order to avoid local melding of the plastic. During the experiments the following aspects were observed:

1. At very low compliance pressure (about 0.3–0.5 bar) there is almost no effect on the burrs in both cases. The tool is pushed outwards from the part and a few burrs are flattened.
2. By increasing the compliance pressure above 0.5 bar for the climb milling trajectory, almost all the burrs are flattened against the outer edge of the part, as shown in Fig. 16. In some places, local melding of the material can be observed. Because the radial contact force is still too low, no milling occurs and no burrs are removed. For the conventional milling trajectory, these effects occur at a higher compliance pressure – about 0.6 bar. Also, for the conventional milling trajectory there are more areas with local melding of the material.
3. By increasing the compliance pressure above 0.7 bar for the climb milling trajectory, almost all the burrs are removed. Due to the thin and soft material, there are a few burrs remained on the part outer edge. For the conventional milling trajectory, this effect occurs above 0.8 bar.
4. When increasing the compliance pressure above 1 bar for the conventional milling trajectory, the tool starts to mill the outer edge of the workpiece. Furthermore, as the tool moves forward along the path, the depth of cut increases. For the climb milling trajectory, above 1.1 bar pressure, the tool also affects the outer edge of the part, but, in this case, mostly in the form of chipping the material (shown in Fig. 17).
5. For the conventional milling trajectory, when increasing the compliance pressure above 0.7 bar, there was a chipping of the part edge at the point where the tool engages the workpiece (as shown in Fig. 18) – the teaching point B (see Fig. 13).
6. Also, for the conventional milling trajectory, when increasing the compliance pressure above 0.8 bar, a breaking of the part edge (shown in Fig. 19) occurred at the end of the DE segment (see Fig. 13).

Fig. 16. Flattened burrs on the climb milling trajectory.

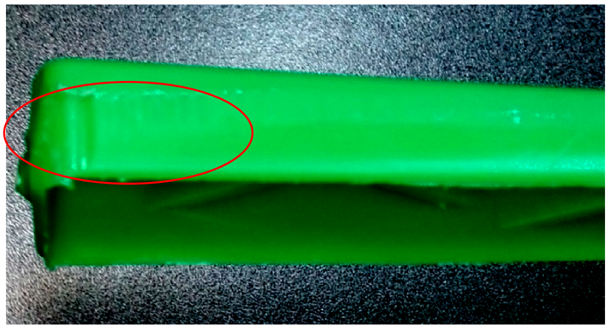

Fig. 17. Chipped part edge on the climb milling trajectory.

Fig. 18. Chipped part edge at entry point on the conventional milling trajectory.

Fig. 19. Breaking of the part edge at the end of the DE segment on the conventional milling trajectory.

7. CONCLUSIONS

By analyzing the results obtained during the experimental procedures, the following conclusions were drawn:

1. Up to 0.5 bar compliance level (about 5 N radial contact force, according to the diagram in Figure 8) for the climb milling trajectory, the machining force at the interface between the tool and the workpiece is not high enough to ensure the removal of the burrs. The tool is easily pushed away from the outer edge of the part even by the thinnest burrs.
2. The above effects occur in the case of the conventional milling trajectory up to 0.6 bar compliance level (about 6 N radial contact force, according to the diagram in Fig. 8). Because the chip is thinner at the beginning for the conventional milling approach, it is more difficult for the tool to achieve cutting conditions, as the material is much thinner when each tooth engages the part and thus the tool is pushed away rather than milling, due to very low pressure in the compliance circuit.
3. For the climb milling approach, above 0.5 bar pressure in the compliance circuit (about 5 N radial contact force, according to the diagram in Fig. 8), the radial contact force is high enough to deform and flatten the burrs rather than the tool being deflected. There is still no milling occurring, as the machining force is still too low but, due to the spindle speed, high friction occurs between the tool and the part. Also, the high spindle speed leads to local melting of some burrs due to high temperatures generated at the interface between the tool and the workpiece. The same effect can be observed in the case of the conventional milling trajectory above 0.6 bar compliance level (about 6 N radial contact force according to the diagram in Fig. 8).
4. Given the described experimental conditions, the optimal pressure interval for the climb milling approach (the pressure interval for the compliance circuit inside which best deburring results are achieved) is between 0.7 and 1.1 bar (about 7–11 N radial contact force, according to the diagram in Fig. 8). Inside this compliance pressure interval almost all the burrs are removed without significantly affecting the part outer edge. By comparison, for the conventional milling trajectory, the optimal compliance pressure interval is between 0.8 and 1 bar (about 8–10 N radial contact force, according to the diagram in Figure 8). The smaller optimal pressure interval for the conventional milling approach is justified by the cutting edge of the tool being subjected to higher friction and cutting forces.
5. When increasing the compliance pressure above 1 bar for the conventional milling trajectory (about 10 N radial contact force, according to the diagram in Fig. 8), the tool starts milling the outer edge of the part, which indicates failure of the passive force control – the compliance principle. Taking into account that the compliance pressure is still at a relatively low level and that the teeth of the tool, in conventional milling, are gradually entering the material - the chip being narrower at the beginning of the cut - the tool is drawn towards the material of the part as it advances along the path - basically indicating a lack of rigidity of the tooling system with respect to the cutting conditions.
6. Also, for the lead in segment of the conventional milling trajectory (AB trajectory segment as shown in Fig. 13), above 0.7 bar compliance pressure, a chip of the part edge appears as the tool engages the workpiece. This is due to the high feed rate necessary to compensate the high spindle speed of the deburring tool. As the tool enters the material, until the cut stabilizes and the tool is pushed outwards due to the compliance system, the first teeth that engage the part are cutting into the plastic and chipping the edge. This effect does not occur in the case of the climb milling trajectory, as the lead in movement is tangent to the machining path. Thus, the lead in movement must be done tangent to the edge of the part, either by the tool entering along the edge or by programming the approach motion in the form of an arc.

Taking into account the above aspects, it can be concluded that, given the available experimental conditions and the part used, the climb milling approach is more efficient, as in this case the heaviest cut is made as the tool enters the workpiece and the chip becomes narrower towards the end of the cut. Thus, the climb milling approach determines reduced tool wear and generates a better surface finish quality

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