IOP Conf. Series: Materials Science and Engineering **290** (2018) 012040 doi:10.1088/1757-899X/290/1/012040

Toolpath strategy for cutter life improvement in plunge milling of AISI H13 tool steel

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Abstract. Machinability of AISI H13 tool steel is a prominent issue since the material has the characteristics of high hardenability, excellent wear resistance, and hot toughness. A method of improving cutter life of AISI H13 tool steel plunge milling by alternating the toolpath and cutting conditions is proposed. Taguchi orthogonal array with L9 (3^4) resolution will be employed with one categorical factor of toolpath strategy (TS) and three numeric factors of cutting speed (*Vc*), radial depth of cut (a_e), and chip load (f_z). It is expected that there are significant differences for each application of toolpath strategy and each cutting condition factor toward the cutting force and tool wear mechanism of the machining process, and medial axis transform toolpath could provide a better tool life improvement by a reduction of cutting force during machining.

1. Introduction

Plunge milling is a milling process that differs from traditional milling methods where the cutting process performs at the end of the tool instead of the periphery, making it advantageous due to the change in the direction of the cutting forces from predominantly radial to axial. Plunge milling can be also being categorized as an alternate method when side milling is not possible due to a strong vibration. The process also called as Z-axis milling which includes three phases: plunging phase, rising phase, and offset phase [1]. Material removal occurs on the first phase of plunging, where then the cutter retracts during the rising phase and moves to the next position during the offset phase [2].

The advantage of the plunge milling process is that the process tends to be more vibration-free than conventional end-milling [3]. This is due to the feed axis coincides with the most rigid spindle axis direction. As a result, plunge milling could reduce the deformation of a workpiece and improve the machining efficiency. For that reason, plunge milling recently became popular in roughing of cavities in the die, mold, and aerospace industries.

Plunge milling is generally used for hard materials with significant gains in productivity, particularly in the case of deep workpieces. Machinability of AISI H13 tool steel is a prominent issue since the material has the characteristics of high hardenability, excellent wear resistance, and hot toughness. This is because AISI H13 tool steel is a hardened steel with an excellent mechanical property with some wide applications in the field of machining hot work molds. The material is popular in the manufacturing process of plastic injection molds, pressure casting dies, forging, extrusion tools, and many more [4]. With the tough material, the setup of cutting parameters and conditions should be set up appropriately, since in plunge milling a significant increase of radial depth and friction in rising phase have great influences on cutter life [2].

There have been many significant researches on the plunge milling utilization for hard materials machining. Zhuang et al. [5] conducted a research on the milling process for nickel-base alloy Inconel 718, a material with high strength, good ductility and anti-fatigue. The study was conducted to predict the cutting force which affects greatly on choosing milling parameters, machining time and cutting tools. A later study on the milling conditions by Sun et al. [6] on the plunge milling for damage tolerant titanium alloy, gave a result that the cutting temperature had more influence than cutting force under the same parameters, and higher cutting heat was the main reason of the tool failure.

Toolpath is another critical factor in a milling process regardless the cutting type and conditions. A poorly-defined toolpath can cause material damage, damage to the tool, and can potentially cause bodily harm. There are very real physical limits to how the toolpath should be defined. For each tool, the manner and amount of material to be removed is controlled through the speed of the tool and the path it follows. Since toolpath plays a significant role in the plunge milling process of hardened material, a method of improving cutter life of AISI H13 tool steel plunge milling by alternating the toolpath and cutting conditions is proposed.

2. Cutting toolpath

Toolpath can be simply defined as the movement of the tool during the milling operation. The best toolpath for one operation is dependent on geometry of the part, the machine characteristic, and cutting condition [7]. However, different from any other traditional milling process, a plunge milling operation has some distinctive characteristics on the process thus requiring its own strategy. In basic, for each plunging cycle, the tool should retract away from the wall during the overall retract to reduce chatter and increases tool life when machining hard materials. Retracting the tool from the wall may give a slight improvement to the tool life by 10 to 15 percent [8].

Several studies that relate toolpath strategy to the milling process of hardened materials can be found in the recent years. Liang et al. [9] performed a study in plunge milling by addressing a novel approach to optimize tool orientation and tool location determination of an open blisks. The result shows that the application of modified particle swarm optimization method (PSO) optimized the tool orientation and corresponding non-interferences locations, proving the approach to be efficient and reliable to plan toolpaths for four-axis plunge milling.

Sun et al. [10] in their study proposed for a new plunge milling tool path generation method using medial axis transform to control the radial depth to improve the cutting efficiency and cutter life. The method was based on the inscribed circle of the offset contour generated by medial axis transform, and the result showed that radial depth can be easily controlled in this method. Experiments showed that both the cutting efficiency and the cutter life were improved.

Another study by Pralea & Nagit [11] put the effort to construct a type of milling based on the plunge milling and raster milling toolpath strategy, only this time it was not being used for roughing but only for finishing vertical and angled surfaces of components of injection molds, with the help of a three-axis vertical machining center. This toolpath strategy designed, with a commercial CAM program, for finishing the vertical and angled walls, offers a better surface roughness, and a better dimensional control (accuracy), both for the milling tool and for the work piece.

Almost all the studies mentioned indicate that the most critical factor in the outcome of the milled model is the strategy for removing the material. This strategy will vary depending on the geometry of the workpiece and the material being used. There are several types of cutting toolpath strategy that have been used in milling process, and some are directly adapted to the plunge milling operation.

3. Toolpath strategies in plunge milling

The idea on the selection of the toolpath strategy return to the basic criterion that a pattern should results in less machining time or the short path length [7]. There are many popular software in the market equipped with CAM supporting plunge milling toolpath, and most of them are adapted from the conventional milling strategy. But even if the software does not support the function, a little bit of g-code programming and some decent adjustments with any CAD software may do the work.

Several types of commercial strategy for moving the tool that may commonly be found are the rough parallel (direction parallel), which is also known as zigzag toolpath, and constant scallop (contour parallel) which is also called as spiral toolpath [7, 12]. These conventional strategies are appealing and widely used for machining in many CAD/CAM software, e.g. Mastercam, Cimatron, etc. This is because these toolpath strategies are both computationally tractable and geometrically appealing [13]. For the sake of the introduction to the experimental stage of the research, a recent method of medial axis transform toolpath is also introduced in the description at section 3.3.

3.1 Rough parallel

Rough parallel or zigzag toolpath is typically the first toolpath used in a model to removes bulk of material from all surfaces. It is the path segments which correspond to back and forth motion in a fixed direction within the boundary of a 2D cross-section [7]. Kim and Choi [14] divided the toolpath into three types of directions: 1) unidirectional path, 2) pure zig-zag path, and 3) smooth zig-zag path with contour parallel path. Their study for the proposal of machining time model that takes the effects of tool acceleration and deceleration showed that the smooth zigzag path was the most efficient regardless of the feed rate and the path interval.

The rough parallel toolpath moves the tool in equally spaced parallel passes in the XY plane across the surface. Like all rough toolpaths, it cuts the surface in several Z steps. Rough toolpaths are done with large diameter tools and coarse settings to remove material efficiently before cutting a finish pass with finer settings.

According to Held et al. [15], it will be more advantageous to use the rough parallel strategy for rather simple shapes or when utilizing small tools. This is because the more complicated the shape of the pocket area and the larger the tool will lead to the better offset curve milling seems to be.

3.2 Constant scallop

Constant scallop or spiral toolpath comprises of a series of contours that are parallel to the boundary of a 2D cross-section [7]. The constant scallop height toolpath moves the tool over the surface in a spiral motion, from the inside-out or the outside-in. The step-over is a fixed amount, but it is calculated parallel to the surface at the location being milled (rather than in the XY plane as with the parallel toolpath). It will make small pockets in some places, if necessary. This toolpath is an excellent toolpath for rolling terrain. It gives a very uniform, consistent result on all surfaces when used with a ball endmill. Usage with one large blanket terrain surface with smaller road surfaces will provide a better resulting surface.

There has been a growing interest for the utilization of spiral toolpath for pocket machining [16]. However, Held [15] mentioned that the shape of the contour affects the suitability of spiral toolpath for high speed machining. If a pocket is very long and narrow, one spiral toolpath may not be efficient to cover the entire contour. Patel [17] also stated that the longest toolpath length and longer cutting time were obtained for spiral-look toolpath strategy rather than the zigzag type.

3.3 Medial axis transform

Medial axis, also referred as the topological skeleton, is the set of all points having more than one closest point on the object’s boundary. The medial axis transform is a complete shape descriptor which comprises of medial axis together with the associated radius function of the maximally inscribed discs. It is a technique that first proposed in 1967 as a mean to describe figure [18]. Due to its shape, a medial axis of a figure is also called the skeleton or the symmetric axis of the figure.

Medial axis transform has been used in plunge milling process by Sun et al. [10] to obtain a new milling tool path to control the radial depth. The toolpath generation process by this method comprised of six steps: The calculation of offset contour (1), the calculation of medial axis (2), the calculation of inscribed circles along medial axis (3), the tool path generation (4), cutter locations generation (5), and link of cutter locations (6).

The medial axis transform toolpath generation was claimed to be able to control the radial depth during machining process, thus avoiding an excessive amount of cutting force applied at some locations on the toolpath [10].

The medial axis transform toolpath differentiates in a way the cutter moves its location from one point to another. Rather than moving the cutter subsequently along the path like in the conventional end-milling toolpath, the cutter moves along the path of the inscribed circles generated from the medial axis (skeleton) of the cutting profile. Figure 1 provides a simplified example on the comparison between the conventional milling toolpath and medial axis transform toolpath for an isosceles trapezoid milling profile [10].

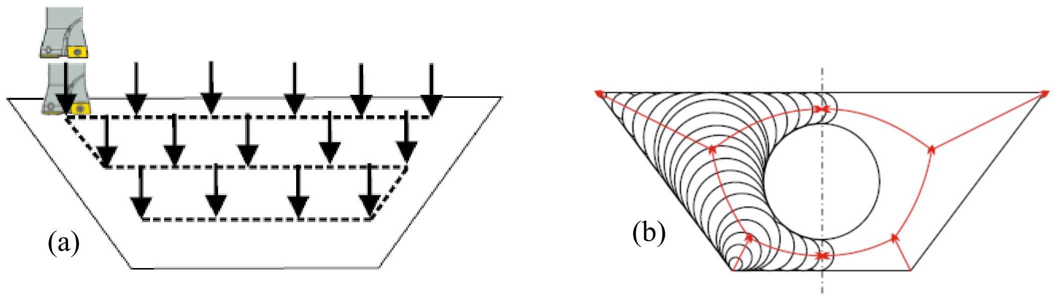

Figure 1. Conventional milling toolpath (a) and medial axis transform skeleton (b) [10]

4. Experiments

The investigation covers the observation of tool life within different cutting conditions and toolpath strategies within the frame of Taguchi Orthogonal Array.

4.1 Materials and Equipment

AISI H13 tool steel has been widely used in hot forging, extrusion, and pressure die casting due to its good wear resistance and large high-temperature strength. A block-shaped with the size of 130 mm x 100 mm x 60 mm will be used in all milling tests. Table 1 shows the chemical properties of the steel under consideration.

Table 1. Chemical Composition of AISI H13 Tool Steel

C	Si	P	S	Cr	Mo	V	MN
0.32 -0.40	0.80 – 1.20	0.011	0.002	4.55 – 5.50	1.00 – 1.50	0.80 – 1.20	Bal.

All machining tests will be conducted on Mazak Nexus 410A-II (Mazatrol Matrix Nexus CNC) three-axis vertical machining center, equipped with maximum spindle rotation speed of 12,000 rpm and motor output (30 minute rating) 16.0 hp/11 kw. All processes will be conducted under dry condition.

Sandvik CoroMill 210 roughing cutter with diameter 25 mm will be used in the milling tests. The insert (ISO Standard R210-09 04 12M-MM 2030) is a double coated consisting of TiN and TiAlN at the outer and inner layer, with 0º rake angle and 7º clearance angle. The details of the insert geometry are shown in Figure 1. Only one of the teeth will be used to avoid the effects induced by small difference between the teeth, and to keep the cutting condition constant during tool wear analysis.

4.2 Experimental Procedures

Taguchi orthogonal array with L9 (3^4) resolution will be employed for toolpath strategy and cutting conditions effects toward cutting forces and tool life. The L9 orthogonal array is meant for understanding the effect of 4 independent factors with each having 3 factor level values (UMass Amherst, 2011). It is assumed that the array shows no interaction between any two factors.

One categorical factor of toolpath strategy (TS) and three numeric factors of cutting speed (Vc), radial depth of cut (a_e), and chip load (f_z), are employed into the design. Other parameters will be held invariable. Cutting side step will be set to 1.0 mm, axial depth cut at 3 mm, and tool overhang at 4 x D of tool diameter (100 mm). The set of 9 runs orthogonal array will be replicated three times, resulting a total of 27 runs experiment. The layout of the L9 orthogonal array experiment is provided in table 2. The profile of the machined area will have the shape of round-corners rectangle with the dimension of 110 mm x 80 mm as illustrated at figure 2.

Table 2. Taguchi L9 Orthogonal Array layout

Std	Run	Toolpath	Cutting Speed (m/min)	Radial Depth of Cut (mm)	Chip Load (mm/tooth)
1	1	Rough Parallel	100	0.75	0.05
9	2	Medial Axis Transform	200	1.25	0.05
8	3	Medial Axis Transform	150	0.75	0.15
2	4	Rough Parallel	150	1.25	0.10
6	5	Constant Scallop	200	0.75	0.10
4	6	Constant Scallop	100	1.25	0.15
7	7	Medial Axis Transform	100	1.75	0.10
5	8	Constant Scallop	150	1.75	0.05
3	9	Rough Parallel	200	1.75	0.15

Three type of toolpath strategies will be utilized for the first phase of machining study. Rough Parallel (*RP*), Constant Scallop (*CS*), and Medial Axis Transform (*MA*) toolpath. The simplified illustration of the three toolpath layouts are presented in figure 3.

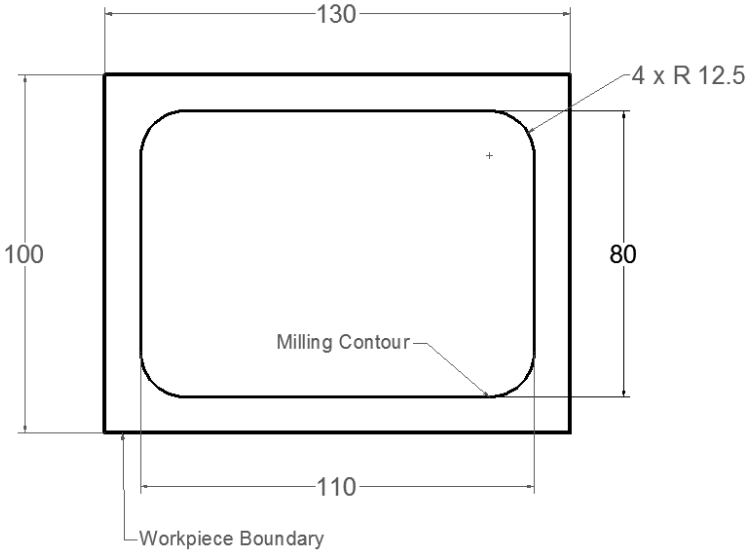

Figure 2. Workpiece profile for machined area and dimensions

Numerical computing software Matlab R2014b will be used for the skeletonization of the profile area skeleton for medial axis transform toolpath generation.

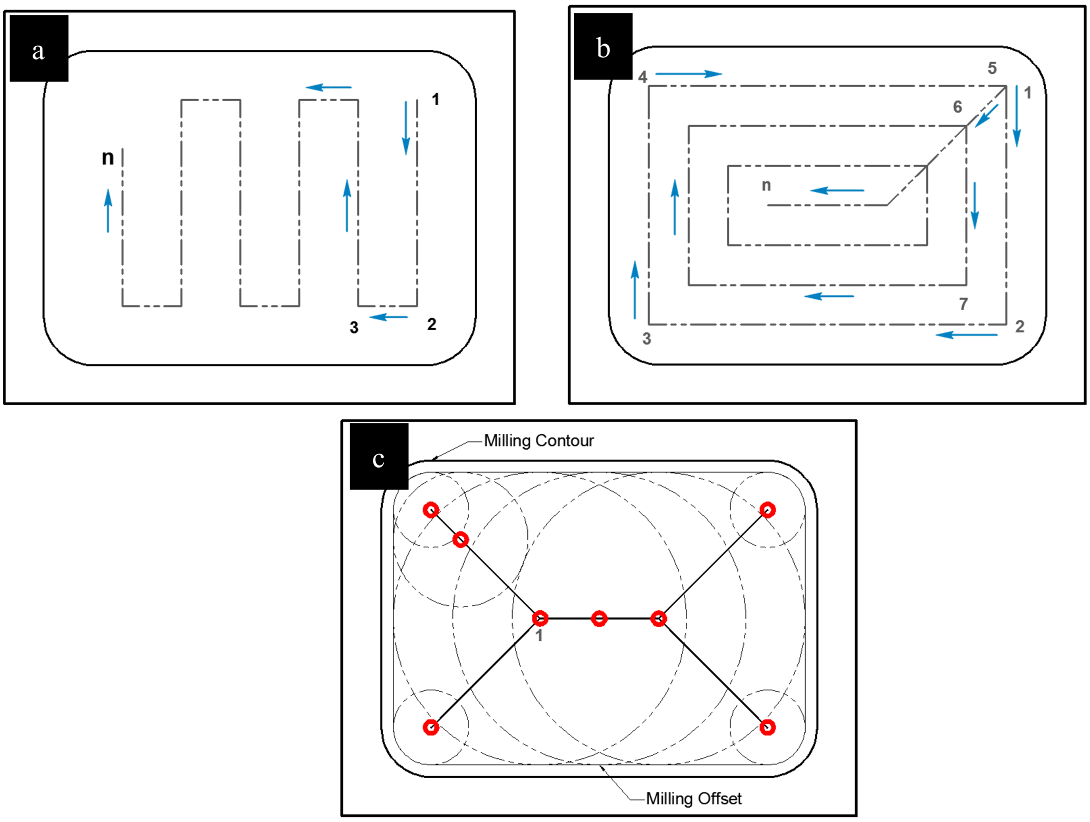

Figure 3. Three types of toolpath strategies: rough parallel (a), constant scallop (b), and medial axis transform (c)

The measured responses will be focused on the cutting force induced and the tool wear. Cutting forces will be measured by a Kistler 9257B three-piezoelectric dynamometer, paired with Kistler 5019A charge amplifier and the corresponding data acquisition and processing system.

The tool wear will be observed periodically with Union Optical Hisomet-II Measuring Microscope (510D Stages). When the tool flank wear reach or increase by the value of 0.3 mm, the tool life will be recorded. The tool life will be represented by the volume V of the removed metal. The worn tools are also expected to be examined by means of scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy.

Additional data of cutting temperature will also be taken by TP8 ThermoPro infrared thermal imaging camera. The data will be helpful to understand the effect of machining temperature for the resulted cutting forces and tool wear. All data will be processed for analysis of variance by Stat-Ease Design Expert v7.

5. Expected & Preliminary results

5.1 Expected results

There are several expected results based on the established theories of the topics contribute to the research. But in general, it is expected that:

1. There are significant differences for each application of toolpath strategy and each cutting condition factor toward the cutting force and tool wear mechanism of the machining process.
2. Medial axis transform toolpath as an alternate toolpath is expected to provide a better tool life improvement by a reduction of cutting force during machining.
3. Optimization of significant factors is expected to improve the machinability in terms of shorten machining time by providing a lesser number of cutter locations.

5.2 Preliminary test

A preliminary test was conducted to test the initial weariness of the tool inserts prior deciding the depth of the plunge milling operation. Three different variables were employed within Taguchi L9 framework. Cutting speed (A) was set to 120 – 240 m/min, feed rate (B) at 0.05 – 0.1 mm/tooth, and depth of cut (C) at 0.1 – 0.2 mm. The layout and the result of the tool wear is presented at table 3.

Table 3. Taguchi L9 Orthogonal Array Layout & Result

Run	Block	A Cutting speed (m/min)	B Feed rate (mm/tooth)	C Depth of cut (mm)	Tool wear (mm)
1	Block 1	120	0.05	0.2	0.301
2	Block 1	120	0.1	0.1	0.203
3	Block 1	240	0.05	0.2	0.114
4	Block 1	240	0.1	0.1	0.337

Based on the result, the model of F-values imply that the model is insignificant relative to the noise. The highest rate for tool wear happened during the cutting speed of 240 m/min and feed rate of 0.1 mm/tooth (Run 4) at 0.337 mm, while the lowest one occurred at 0.203 mm when the cutting speed set to 120 m/min and feed rate at 0.1 mm/tooth. The representative graph is presented on figure 4.

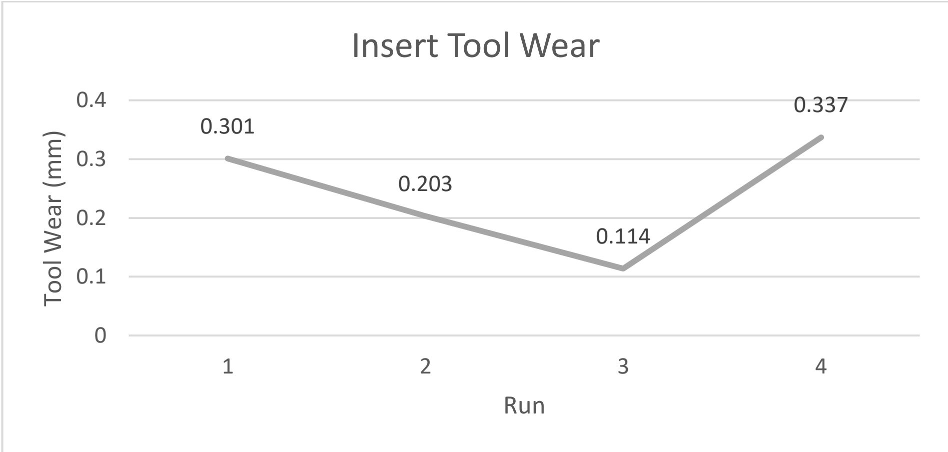

Figure 4. Insert tool wear on the preliminary test of AISI H13 milling

Further calculation and application of inserts was then set based on the preliminary results of the tool weariness displayed during the milling of AISI H13.

6. Conclusion

The main contributions of this work include the machinability in practical plunge milling process for the hard material AISI H13 which has been widely employed in many industrial processes. Aside of that, the application of the non-conventional milling toolpath for plunge milling in the attempt of evading the large radial depth effects is also a significant issue, since a large radial depth may lead to unacceptable large cutting force and make the cutter wear quickly.

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