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True Variable-Depth Milling of Nickel-Based Alloy IN-718

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Abstract

Rapid tool wear in machining causes increased process cost. While flank wear and crater wear have been investigated deeply by researchers, notch wear has been somewhat overlooked, despite the fact that it has an important role in the tool replacement decision. Notch wear happens due to impact forces at the depth of cut particularly during intermittent cutting. To avoid frequent tool change decisions, varying the depth of cut constantly during machining has been proposed as an alternative. In this study, milling experiments were conducted on the nickel-based alloy IN-718 where the depth of cut was varied throughout the cut. Results show favorable findings towards eliminating notch wear without compromising from machining efficiency.

Keywords: Milling, Variable depth milling, Tool wear, Nickel-based alloy, Notch wear

Nikel-Bazlı Alaşımlarda (IN-718) Gerçek Değişken-Derinlikli Frezeleme

Öz

Metal işleme sırasında takımın hızlı aşınması artan proses maliyetine neden olur. Kanat aşınması ve krater aşınması literatürde derinlemesine incelenirken, takım değiştirme kararında önemli bir rol oynayan çentik aşınması ikinci plana itilmiştir. Çentik aşınması, özellikle aralıklı kesim sırasında kesme derinliğindeki darbe kuvvetleri nedeniyle meydana gelir. Takımı sık değiştirmemek için alternatif olarak işleme sırasında kesme derinliğinin sürekli olarak değiştirilmesi önerilmiştir. Bu çalışmada, nikel-bazlı IN-718 alaşımında kesme derinliğinin kesim boyunca değiştiği frezeleme deneyleri gerçekleştirilmiştir. Sonuçlar, işleme verimliliğinden ödün vermeden çentik aşınmasını ortadan kaldırmaya yönelik olumlu bulgular göstermektedir.

Anahtar Kelimeler: Frezeleme, Değişken-derinlikli frezeleme, Takım aşınması, Nikel-bazlı alaşımlar, Çentik aşınması

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1. INTRODUCTION

In milling processes, tool contacts the workpiece to remove material [1]. When the hard and sharp tool contacts the workpiece free surface that has lower hardness value, shearing mechanism is created and the workpiece is "torn apart" [2]. During this process, the workpiece is damaged evidently more due to the shearing motion, but the tool is also worn due to the contact [3]. The amount of wear that the tool experiences depends on the tool material, workpiece material, as well as the process parameters [4,5]. However, either slowly or rapidly, the tool experiences a nondecreasing wear that makes it go from its sharp (new/unworn) stage to worn [6]. Tool wear at mild amounts are not attributed to part quality issues [2]. However, when tool wear becomes significant (over a pre-determined threshold), it starts to affect the quality of the end product; hence the tool needs to be changed (tool failure) [4-7].

Tool can wear out (fail) in two distinct ways – either at the blink of an eye due to an extreme effect or gradually [8]. If the tool is worn with an impact, it is almost impossible to stop the process immediately. Hence, the part quality is always affected in such cases. Therefore, gradual tool wear is the preferred mode of tool failure [9]. There are also multiple modes of gradual tool wear such as crater wear, notch wear, flank wear, thermal and mechanical cracking, and nose wear [3]. Although all of these types of tool wear are important and therefore should be taken care of, some of them do not appear unless extreme conditions are used, or for special tool and workpiece materials. The remaining ones play an important role in reducing end product quality and should be monitored.

The most ideal mode of tool wear is flank wear, due to its gradual nature and relatively high predictability [10]. Many researchers studied the evolution of flank wear and the best methods to alleviate it [11-16]. In processes where the friction between tool and chip is significant compared to the shearing in the primary shear zone, crater wear also becomes a factor to be reckoned with [16-17]. Usually, relatively easy fixes such as chip breakers and lubrication techniques are used to alleviate crater wear.

Notch wear is another mode of tool wear that requires attention, but receives little [4,6,7,9]. Particularly in intermittent cutting processes such as milling, due to the impact forces between the tool and the workpiece at every tooth contact, a notch occurs at the contact location (see figures 1 & 2). This notch can be characterized as flank wear that grows relatively more rapidly than other flank wear locations. Per ISO regulations, allowed flank wear width before tool is deemed failed is 300µm. However, since notch wear happens more rapidly, ISO regulations allow up to 600µm notch wear width [8]. At this threshold, tool is considered worn and needs to be changed. Usually, modifying machining parameters (cutting speed, feed, depth of cut, width of cut, lubrication, etc.) is the chosen way that has been used by researchers and machine operators alike [18-23]. It is an understandable route, since particularly regular flank wear can be reduced by using a different set of parameters. Also, if the depth of cut is altered, the location of the notch wear can be modified, hence being able to utilize the tool further.

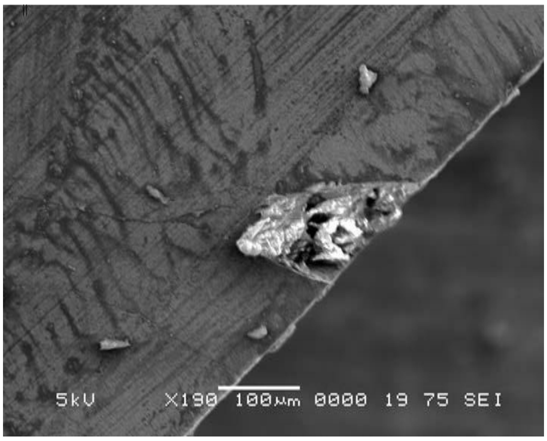

Figure 1. Notch wear initiation and propagation [6]

However, this fix is more of a patch to the problem at hand than a solution. In many cases, notch wear can be more serious than flank wear because of higher wear rate [24]. Even with the "patches" suggested by many researchers, notch wear still occurs and is detrimental to the part quality, and altering machining parameters manually at sporadic time intervals is neither automated nor practical [9]. Therefore, an automated, constant, and consistent way of altering the depth of cut without the need for an involvement of workers is needed [25]. In this study, a work towards the solution for this problem is presented.

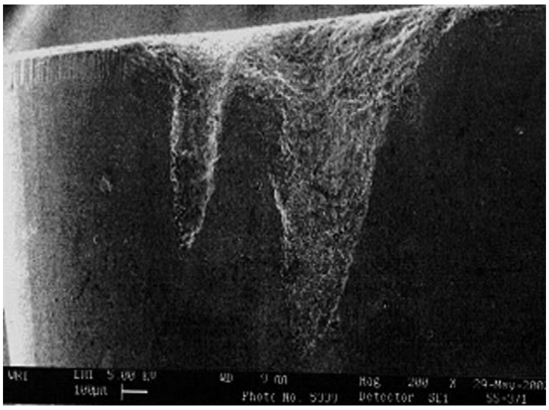

Figure 2. Notch wear [4].

In this work, first the studies relevant to the method presented here are discussed in Section 2. Then, experimental setup and the methodology are introduced in Section 3. Results are presented and discussed in Section 4, and concluding remarks and future directions are presented in Section 5.

2. LITERATURE REVIEW

Researchers have focused on flank wear and crater wear and did not pay sufficient attention to notch wear [3]. As a result, when a case occurs where the tool wears out rapidly, the knee-jerk reaction by researchers and machine operators alike is to modify cutting parameters of cutting speed and feed. It is accepted that by changing these two parameters, it is possible to reduce tool wear to acceptable levels [21,26,27]. The issue with this approach is that the reduced tool wear is on the flank or crater of the tool and the changes do not really affect notch wear [9]. The nature of notch wear states that as long as depth of cut stays constant, the impact forces keep developing the notch wear [7]. Varying the cutting speed and feed may change the speed of notch wear evolution but does not fix the problem altogether.

Varying the depth of cut, on the other hand, changes the location of the notch wear thus starts over the evolution of notch wear. It is an effective way to fight notch wear development, but not an efficient one, since either the machine operator will need to stop the process arbitrarily, adjust the parameters and restart the process, or the programmer will need to include an arbitrary change of depth of cut without any information on how the notch wear will have progressed up until that point. Therefore, intermittent variation of depth of cut is an effective but not a practical way to combat notch wear.

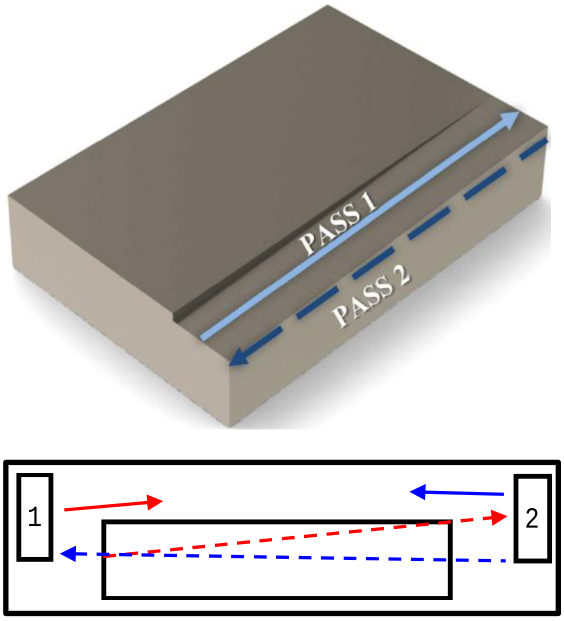

Figure 3. Tool path in regular variable-depth milling: (top) a 3D-illustration [5], (bottom) a 2D-illustration of tool path [9]

Another approach can be to constantly alter the depth of cut based on the amount of tool progress (see figure 3). This way, notch wear will not happen at a finite number of locations on the flank, but rather be distributed along the flank uniformly [5,9]. Hence, varying the depth of cut constantly throughout the cut can have the following benefits:

1. Notch wear will be distributed along the flank and not concentrated on one (or a finite number of) location(s). Therefore, crack initiation at the notch wear location will not be an issue.
2. If the depth of cut is constantly varying, then the impact forces will change location constantly as well. Therefore, reasons for crack propagation will also be minimized.

Varying the depth of cut (variable-depth milling, or VDM) arbitrarily may create issues with planning and programming of the process, as well as uniform distribution of notch wear. Researchers have worked on dividing a straight rectangular-prism cut into two triangles and machining a triangle per pass as shown in Figure 3 [5]. However, there are two major problems with this method. First, constantly decreasing the depth of cut from maximum to zero and repeating this cycle will reduce overall impact forces but the initial contact between the tool and the workpiece at the maximum depth of cut will still create impact forces and vibrations that may carry along throughout the cut. Therefore, it is critical to start at zero depth of cut and constantly and smoothly increase to maximum depth of cut throughout the pass. This way, initial high impact forces will be eliminated and instead the tool will feel the impact and vibration effects toward the end of the cut (after which there will be no tool-workpiece contact so no part quality effects).

Second problem with VDM is that since the tool axis is not orthogonal to the tool path, load of the cut is not distributed uniformly on the tool cutting face (see figure 4) [9]. This causes the tool to experience premature catastrophic failure, leaving the application of variable-depth milling (VDM) with no practical value. Therefore, it becomes important to orient the tool so that the tool axis is orthogonal to the tool path [9]. For this purpose, a true-VDM procedure has been proposed in a previous study, where the workpiece is constantly tilted at a certain angle and back to create the triangular paths without affecting the orthogonality between the tool axis and the tool path [9] (see figure 5). To accomplish the tilting of the workpiece, a 4- or 5-axis CNC can be utilized. Although theoretically manual tilting of the workpiece in a knee-mill with the use of angled vices is possible as well, it would not be practical to do so because of the amount of time that would be required to constantly tilt the workpiece and back. A retrofit equipment can be used in a 3-axis CNC to accomplish the tilting, however programming the retrofit may create timing issues. Therefore, a 5-axis CNC was utilized in the previous study [9] as well as this one.

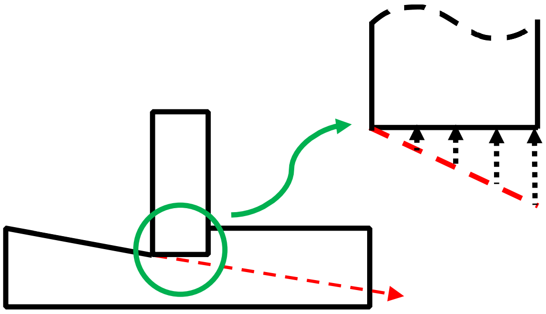

Figure 4. Illustration of cutting forces in VDM [9]

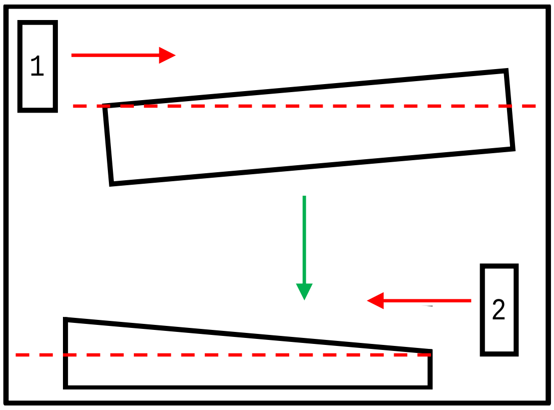

Figure 5. Tool path in true-VDM [9]

In the previous study [9], this method was coined and detailed. However, the method was only tested with an aluminum alloy (Al-6061). This alloy, however widely it may be used, has a low hardness value (HRB 60). Therefore, its machinability is very high and the effectiveness of the true-VDM method cannot be observed well with this material. Usually, materials that induce high tool wear are difficult-to-machine, high-hardness materials such as nickel-based alloys. These alloys have hardness value so high compared to aluminum alloys, their hardness values are not even measured using the same hardness scale (Rockwell B). Because of this superior hardness property as well as roughly three-fold strength compared to aluminum alloy Al-6061, their tool wear-inducing characteristics are more observable. Therefore, the nickel-based alloy IN-718 is used in this study to reveal the effectiveness of true-VDM.

3. MATERIALS AND METHODS

3.1. Experimental Setup

Milling experiments were conducted in order to investigate the effectiveness of the method. Specimens of rectangular prism shape and roughly 75 mm in width, 150 mm in length and 75 mm in depth were used as the workpiece. A “pass” was characterized as a straight cut from one side of the specimen to the other (75 mm cutting length). In terms of the workpiece material, IN-718 was used (see table 1 for its chemical composition). A three-flute cutter from Sandvik (RA 390-019M19-11M) with suitable inserts (Sandvik R390-11 T3 08M-1130) were used to machine the workpiece. On each face, 8 rectangular slots were completed, then the part was faced again to reveal a new machinable surface. For each slot, fresh unworn set of inserts were used to be able to keep track of zero-to-worn inserts. To be able to accomplish the tilting motion required to achieve “true-VDM,” a 5-axis Haas CNC milling center was used.

3.2. Measurements

While machining, forces in three directions (cutting speed, feed, depth of cut) were measured using a Kistler 3-component dynamometer (9257BA). After machining was complete, inserts were inspected by the help of an Olympus optical microscope. The digital photos of the flank region were carefully measured for any signs of notch wear. For regular milling, maximum wear located at the depth of cut was taken as the notch wear. For true-VDM, the maximum width of the flank wear at any location was taken as the notch wear since no specific maximum wear width location existed. For regular end milling tests, average resultant force between 85% to 95% of the pass length was taken as the indication of severity. For true-VDM, the maximum resultant force throughout the pass (which happens at the maximum depth of cut) was taken. Since the material removal rate (*MRR*) was similar at those times between end milling and true-VDM, the forces were expected to be similar.

Table 1. Chemical composition of IN-718

Element	Percentage (%)
	IN-718
Nickel	50-55
Chromium	17-21
Iron	17
Molybdenum	3
Niobium	5
Manganese	0.35
Silicon	0.35
Carbon	0.08
Phosphorus	0.01
Sulfur	0.01
Aluminum	0.6
Titanium	1
Cobalt	1
Boron	0.005
Copper	0.3
Tantalum	0.05

3.3. Experimental Design

In order to understand true-VDM and its effects, tests with the same parameter sets were repeated for both end milling and true-VDM. When comparing in terms of maximum force, this makes sense since the *MRR* at the measurement location (end of cut) is the same. However, using the same parameter would always favor true-VDM in terms of notch wear due to the lower overall *MRR* associated with the process. This will not be a fair comparison since the true-VDM method uses twice as much time to complete the same cut. Therefore, in terms of notch wear, the two methods are compared at the same material removal rate (*MRR*), which means either the feed, the cutting speed, or the depth of cut is doubled (1). In this equation, *MRR* is the Material Removal Rate, w is the width of cut, a_p is the depth of cut, V_c is the cutting speed, D is the diameter of cutter, and f is the feed per revolution of the cutter (Equation 1).

$$\mathrm{MRR} = w a_p \left(\frac{V_c}{\pi D} f \right) \tag{1}$$

Experimental design for all tests is provided in Table 2, where the width of cut was 18.75 mm. All tests were replicated 3 times to alleviate the effect of any outliers. Test numbers in Table 2 are used to refer to the test (and is not an indication of the order of the tests being executed). Groupings in Table 2 refer to how tests are compared to each other based on having the same *MRR*. This is used when comparing end milling to true-VDM in terms of tool notch wear amount. Two of the tests (the mildest–test 1 – for true-VDM and the most severe –test 18–for end milling) cannot be compared to another test because their *MRR* values are unmatched. It must be noted that since *MRR* values here show the maximum *MRR* during true-VDM, the actual *MRR* during any true-VDM process is half of what is stated there. Due to this reason, any group with a letter assigned to it in end milling (*e.g.* Group B) is later compared to group of true-VDM tests with a letter that comes after the first one (*e.g.* Group C) so that the actual *MRR*s match.

4. RESULTS AND DISCUSSIONS

Experiments defined in the previous section were completed with both end-milling and true-VDM methods. Measured resultant forces aligned in a similar fashion for all the experiments (see figure 6 for an illustration that shows the general trend). For end milling tests, since the depth of cut was constant throughout the cut, once full immersion of the cutter into the workpiece was achieved, a somewhat-constant resultant force was observed until the tool started leaving the workpiece. On the other hand, true-VDM tests showed that the forces increased from zero to maximum in a smooth manner, proportional to the depth of cut. The important comparison here is between the maximum value of the resultant force during true-VDM and the average value of the resultant force in end milling. In order to make a fair comparison, averages of the resultant force between 85% to 95% of the cutting length were taken as the force value for any specific test. These measurements are provided in Table 3, where $F_{R,end}$ is the average resultant force between 85% to 95% of the cutting length during end milling, whereas $F_{R,tVDM}$ is the same for true-VDM.

Table 2. Experimental design for end milling and true-VDM tests

Test	Group	Cutting Speed	Feed	Depth of Cut	MRR
		V_c	f	a_p	
		m/min	*mm/rev*	*mm*	mm^3/s
1	A	25	0.05	0.25	1.6
2	B	50			3.3
3	C	100			6.5
4	B	25	0.1		3.3
5	C	50			6.5
6	D	100			13.1
7	C	25	0.2		6.5
8	D	50			13.1
9	E	100			26.1
10	B	25	0.05	0.5	3.3
11	C	50			6.5
12	D	100			13.1
13	C	25	0.1		6.5
14	D	50			13.1
15	E	100			26.1
16	D	25	0.2		13.1
17	E	50			26.1
18	F	100			52.2

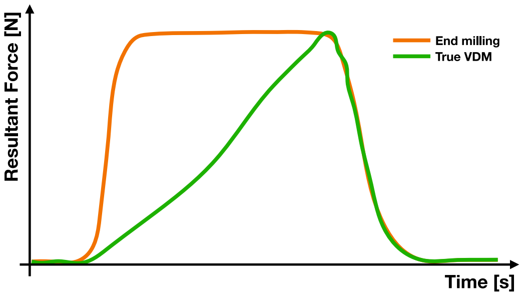

Figure 6. Illustration of resultant force development during end milling and true-VDM

At this point, it is important to remember that the resultant force measurements and comparison is only to affirm that the two processes, at their maximum depth of cut, are similar and that true-VDM can actually be confirmed as a division of the regular end milling processes into two triangular pieces. Indeed, there was a 16% difference or less between the maximum resultant forces during end milling and true-VDM under the same conditions, except for test 18. That is because test 18 is the experiment with the most severe cutting conditions.

Table 3. Comparison of resultant forces

Test	$F_{R,end}$	$F_{R,tVDM}$	Difference (absolute)
	N	**N**	**%**
1	43	46	6
2	62	58	6
3	80	82	2
4	65	69	6
5	100	103	3
6	152	139	8
7	137	138	0
8	219	210	4
9	273	255	6
10	81	77	4
11	105	119	13
12	158	150	5
13	146	124	15
14	202	180	10
15	280	276	1
16	264	221	16
17	380	335	11
18	640	451	29

Due to the severity of machining parameters, the inserts exceeded the maximum allowed notch wear (600 µm) in all three replications–meaning they failed due to the severe cutting conditions. Even during that test, the difference between the resultant forces of the two methods happened to be 29%, and the average difference between forces in all of 18 tests was measured at 8%. To confirm, the measurements were subjected to a statistical significance test that is the t-test. The null hypothesis here is that the two set of samples come from the same distribution as depicted in (2), where H_0 and H_1 are the null and the alternate hypotheses, and μ_1 and μ_2 are the means of the two samples. Since the samples come from changing parameters, a two-tailed paired t-test was chosen. The result of p=0.08 shows that there is not a statistically significant difference between the two result sets. Therefore, the two test methods can be said to result roughly in the same resultant force values in general since they represent the same process (Equation 2).

$$H_0: \mu_1=\mu_2, \qquad H_1: \mu_1\neq\mu_2 \qquad (2)$$

After showing that the resultant forces are not different between the two methods, it is essential to get to the main hypothesis of this article – that the true-VDM method results in significantly lower notch wear compared to end milling at the same *MRR*. To test the difference, results of notch wear (averages of measurements of three replications and for all experiments in the same group with the same *MRR*) are tabulated as shown in Table 4. In this scenario, the null hypothesis is that the notch wear during true-VDM is not lower than the notch wear during end milling, which means that the alternate hypothesis is that it is lower (3). In this equation, H_0 and H_1 are the null and alternate hypotheses, and μ_1 and μ_2 are the mean notch wear of true-VDM samples and end milling samples, respectively. Since it is claimed that the notch wear should be lower, a one-tailed t-test was chosen. Just like the previous test though, since the measurements come from changing parameters, a paired test should be applied. In sum, the one-tailed paired t-test between the results shown in Table 4 results in p=0.041 (Equation 3).

$$H_0: \mu_1\nless\mu_2, \qquad H_1: \mu_1<\mu_2 \qquad (3)$$

Since there are only 5 pairs of values to compare, the fact that p<0.05 was found is even a stronger indication that the null hypothesis cannot be accepted. Therefore, it can be concluded that true-VDM method results in significantly lower notch wear compared to end milling even under the condition of same actual *MRR* (different parameters but same total time to remove the same volume of material). It was observed that true-VDM led to 25-48% less notch wear, an average of 37%. Taking that average as a reference, it can be claimed that after the volume of material machined with end milling when the inserts fail, roughly half that amount of material could have been additionally machined if true-VDM was used.

Table 4. Comparison of notch wear
Note: *shows failed insert during test

Group	$VB_{N,end}$	**Group**	$VB_{N,tVDM}$	*Difference*
	µm		**µm**	**%**
A	84	B	63	25
B	134	C	81	39
C	197	D	135	31
D	422	E	216	48
E	749*	F	421	43

5. CONCLUSIONS

In this work, a relatively new process called “true variable depth milling” (“true-VDM”) was investigated and compared to conventional end milling using the nickel-based alloy IN-718. Since the premise of true-VDM is lowering the amount of notch wear by uniformly distributing it along the flank face while not affecting the machining dynamics otherwise, resultant forces and notch wear incurred by the two methods were measured and compared.

The first comparison was made between resultant forces incurred by the two methods. This comparison showed that there is no significant difference between the resultant forces (p=0.08), measured at their maximum values (to prevent bias toward true-VDM). Therefore, it was concluded that the machine dynamics are not different for the true-VDM method compared to end milling. The second comparison was made between the notch wear incurred by the two methods. This comparison showed that the notch wear caused by true-VDM is significantly less than that of end milling (p=0.041). Therefore, it was concluded that the tool can be used roughly 50% more with true-VDM, which can lead to a significant decrease in machining costs.

The main hurdle with the application of the true-VDM technique is that it requires a mechanism of sorts to constantly tilt the workpiece and back. Therefore, this method can be more suitable to industries and companies with relatively large already-established machining volumes – since those would be the prime suspects for having or acquiring 4- or 5-axis CNC machines. In smaller size industries, depending on how frequently the design of the cut is altered, retrofit techniques can be developed so that purchasing of expensive machinery that is the 5-axis CNC may not be necessary.

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