

Comparison and Cost Optimization of Solid Tool Life in End Milling Nickel-Based Superalloy

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Abstract

Nickel-based superalloys constitute a significant portion of the materials used in important industries such as aerospace, energy production, automotive, and biomedical industries. Due to their superior properties that make them appealing for these industries such as their high strength at elevated operating temperatures, manufacturing these alloys to end product specifications has been a difficult task. Despite the several recent studies that unearth various methods to tackle different aspects of this challenge, machining of nickel-based superalloys continues to be a mostly unknown territory. Researchers have mostly worked on finding optimal machining parameters that provide milder operating conditions, lower cost of tooling, or better end-product dimensional accuracy and surface quality; however, the tool material and type are generally constant in these studies. Therefore, it is difficult to apply the information gathered from these studies when there is a change in the machine tool that has been used, as it frequently happens when tool manufacturers produce new tools that perform better.

In this study, an alternative glance at the bigger picture is presented, providing an insight toward a generalized model that directly addresses the industrial concern of process cost. Solid carbide and ceramic tools, which are known to be heavily utilized in manufacturing gas turbine components, are investigated by their performance as well as the relative cost they induce during end milling the gamma-prime strengthened nickel-based superalloy. First, the performance of solid carbide tools with no coating are compared to those with coatings of different material and cost, through a set of tool life experiments at industrially applicable machining conditions. Then, the performances of solid ceramic tools are investigated using machining conditions taken directly from gas turbine component production. Finally, a cost-based model is introduced to compare the performance of the solid carbide and ceramic tools.

Keywords: low cost manufacturing, nickel based superalloy, cost optimization, tool wear

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1 Introduction

In the industries that require high performance alloys such as the aerospace, energy production, automotive, and biomedical industries, it is important for mission-critical components to perform under aggressive operating conditions (M'Saoubi *et al.*, 2008; Ulutan & Özel, 2011). Some applications in these industries require the products to withstand high mechanical and thermal loading schemes for extended amounts of time (Ezugwu *et al.*, 1999). For such applications, conventional materials such as aluminum and steel may not perform and reliability and durability issues can arise. In these cases, using more advanced materials that can operate for longer times can be less costly in the long run, despite the higher cost of such materials. Nickel-based superalloys constitute a significant portion of these premium materials owing to their longevity after extended exposures to extreme thermomechanical loads. However, utilizing the superior properties of these materials comes at a sizable cost: as their material properties make them more durable, manufacturing these alloys also becomes more difficult (Arunachalam & Mannan, 2000).

Therefore, these industries have focused on understanding, analyzing, and optimizing the manufacturing of these superalloys. Although the most commonly used nickel-based alloy is Inconel 718, researchers have discovered even more superior properties of other nickel-based alloys such as other Inconel alloys, Incolloys, Nimonics, and Hastelloys (Mutku Kumar *et al.*, 2010; Ezilarasan *et al.*, 2013; Kadirgama *et al.*, 2011). With increasing interest in superior high temperature tensile strength, oxidation and corrosion resistance, as well as fatigue strength, gamma-prime strengthened nickel-based superalloys are of great interest to researchers (Sajjadi *et al.*, 2002; Pouranvari *et al.*, 2008). These various types of superalloys are getting progressively better for their end use, therefore the manufacturing challenges remain.

Although there are multiple machining techniques utilized today, the most common method in the manufacture of superalloys is milling (Arunachalam & Mannan, 2000). The milling process is highly complex due to the variation in the cutting force, multi-tooth interrupted chipping, and non-uniform chip loading and remains as a field yet to be explored further (Zhang & Guo, 2009). Tool wear during milling nickel-based superalloys is severe and it significantly reduces its machinability (Ezugwu, 2005). In order to allow for more widespread use and viability of nickel-based superalloys, the behavior of tool wear during the machining process needs to be thoroughly understood. Notch wear, chipping, and built-up-edge formation have been identified as major wear methods due to abrasion, adhesion and diffusion (Thakur, 2009). The most prominent wear mechanism has been found to be significant amounts of flank wear (Li *et al.*, 2006).

Other machining outputs, particularly surface roughness, are dependent upon the condition of the cutting tool (Kasim *et al.*, 2013). Therefore, with high amounts of tool wear, leading to high tooling expenditures and possible reductions in machined component quality, the performance of tooling is of great importance. One of the methods utilized to combat tool wear in superalloys is tool coating. Coatings provide a barrier to heat build-up in the tool, lower friction at the tool-workpiece interface, and high hardness values (Ucun *et al.*, 2013). Researchers have found that tool life can be considerably increased through the use of coatings, potentially reducing the overall cost of manufacturing (Takacs *et al.*, 2003). Although coatings have been observed to extend tool life, they cost more than a comparable solid carbide tool. The cost contribution for coating machine tools and the potential benefits provided by such coatings is not well understood, particularly in machining gamma-prime strengthened nickel-based superalloys.

Therefore, the authors propose in this study a method to determine the possible cost implications of using tool coating and changing machining parameters when using solid end mills, and optimize the process based on the total cost to aid with the decision making process in the industrial applications. First, the theory of cost optimization used in this work is illustrated in Section 2. Then, the experimental design that allows a comparison of different material tools, machining parameters, and the use of different type and cost tool coatings using this theory is presented in Section 3. The results

of the experiments are illustrated and discussed in Section 4, where the performance of different types of tools are compared first within then between each other. The results of the cost optimization method applied on the comparison are also illustrated in this section, which is followed by the conclusions in Section 5.

2 Cost Optimization Theory

In order to compare the performance of different tools, a model to optimize the total process cost is suggested in this study, and then applied to an industrially relevant problem for demonstration. Since this study focuses on tool selection and the material is constant between tests, the cost of material was not included in the theory, but the cost of tools and coatings were. In addition, all aspects of idle time, relevant labor, inventory, and procurement costs were collected in the tool change cost to simplify the problem. This compact cost term plays a significant role when the speed and efficiency are considered.

The total cost of the process C_{total} is modeled as Eq. (1), where C_{tool} is the total tooling cost, C_{change} is the total cost of tool changes, and $C_{machining}$ is the cost of machining time required to complete the process. C_{tool} can be written as Eq. (2), where T is the total number of tools used for the process, and c_{tool} is the cost of a single tool. C_{change} can be written as Eq. (3), where t_{change} is the time to change a single tool (that includes a collection of non-machining time), c_{change} is the cost of a single tool change. $C_{machining}$ can be written as Eq. (4), where t_{tot} is the total time spent for machining (tool-workpiece contact time), and $c_{machining}$ is the cost of machining per unit time, excluding material cost, but including machining labor cost, advantage of finishing the process early. T can be calculated using Eq. (5), where V_{tot} is the total amount of material to be removed, and $MRPT$ is the amount of material removed per tool. $MRPT$ can be calculated using Eq. (6), where NMR is the normalized volumetric material removal, and VB_t is the threshold value of tool flank wear that determines tool failure and thus the need for tool change. NMR is defined in this study as the ratio of the volumetric material removal (MR) to the average tool flank wear (VB) given by Eq. (7). NMR can be expressed as the amount of material that can be removed per unit tool, where the unit can be the amount of average tool flank wear (VB), or the number of tools for a certain amount of material removal. In order to calculate NMR , a few measurements (MR_j) should be taken from different phases of tool wear (VB_j), and the mean value of the ratios should be used. These VB_j values should be selected as significant values (indicating there is noticeable tool wear) but also should be distributed along the life of the tool before failure. MR for an end-milled slot can be calculated using Eq. (8), where a_p is the depth of cut, w is the width of cut, and l_c is the length of the slot. Then, the number (and/or portions) of slots machined by the time of tool wear measurement (M_j) would give the volume of material removed at that time (MR_j).

$$C_{total} = C_{tool} + C_{change} + C_{machining} \quad (1)$$

$$C_{tool} = T * c_{tool} \quad (2)$$

$$C_{change} = T * t_{change} * c_{change} \quad (3)$$

$$C_{machining} = t_{tot} * c_{machining} \quad (4)$$

$$T = \frac{V_{tot}}{MRPT} \quad (5)$$

$$MRPT = NMR * VB_t \quad (6)$$

$$NMR = \text{mean}_j \left(\frac{MR_j}{VB_j} \right) \quad (7)$$

$$MR_j = M_j a_p l_c w \quad (8)$$

The total machining time t_{tot} can be calculated using Eq. (9), where MRR is the material removal rate. MRR in end milling can be represented as Eq. (10), where N is the spindle speed, and f is the feed. In addition, a new definition of efficiency is suggested where the conflicting manufacturing objectives of maximizing MRR and minimizing VB are addressed at the same time, normalized material removal rate ($NMRR$), and is defined by Eq. (11). In order to use this variable, tool flank wear measurements are taken at a predetermined amount of material removal MR_x , and then these measurements (VB_x) are used as a normalizing factor of the relevant test for material removal rate (Eq. 11). If MR_x is kept high to assure that the tool flank wear (VB_x) is close to the threshold flank wear VB_p , MRR can be calculated from the $NMRR$ value. Then, combining all terms (Eq. 2-6 & 9-11) and plugging into Eq. (1), the total cost of machining a certain volume of material becomes as shown in Eq. (12).

$$t_{tot} = \frac{V_{tot}}{MRR} \quad (9)$$

$$MRR = N f a_p w \quad (10)$$

$$NMRR = \frac{MRR}{VB_x} \quad (11)$$

$$C_{total} = \frac{V_{tot}}{VB_t * NMR} * (c_{tool} + t_{change} * c_{change}) + c_{machining} * \frac{V_{tot}}{NMRR * VB_t} \quad (12)$$

This total cost can then be used in comparing tests with different tools as well as machining conditions. In order to demonstrate how this method is applied, end milling experiments were conducted with solid carbide and solid ceramic tools, where the cost effect of different coatings were investigated for the carbide tools, and the cost implications of using different machining conditions were investigated for the ceramic tools.

3 Experimental Design

In order to conduct the tool life experiments, a gamma-prime strengthened nickel-based superalloy was prepared to 80 x 60 x 25 mm blocks, where all blocks were cut down from the same bulk material to avoid material composition differences affect the results. The workpiece material was fixed on a vice that is mounted on a Kistler 6-component dynamometer that measured machining forces in three directions. An OKUMA GENOS M460-VE 3-axis CNC machine equipped with a Tool Monitor Adaptive Control (TMAC) system capable of measuring spindle power consumption was utilized for the experiments (Figure 1). All tests were conducted in the down-milling direction, and end milling passes that utilize the full length of the block (60 mm) were taken during each test. As recommended by the solid tool manufacturers, a water-soluble coolant was used during solid carbide machining tests, whereas dry machining experiments were conducted for the solid ceramic tool tests. For the force and power measurements, the average values were calculated between 40-50 mm cutting distance, which is conventionally the peak region for the two variables. In addition to these measurements, tool flank wear was also measured using an Olympus optical microscope, similar to the

methodology described in Henderson's work (Henderson *et al.*, 2012). Based on several measurements on any flank face, average flank wear (VB) as well as maximum flank wear (VB_{max}) were calculated. The experiments were concluded only when (a) VB reached a value higher than 300 μm , (b) VB_{max} reached a value higher than 500 μm , or (c) severe crater wear (higher than 200 μm) was observed to conclude tool failure. Finally, using the efficiency metric material removal rate (MRR) and the productivity metric volumetric material removal (MR), comparisons between tools and machining conditions were completed.

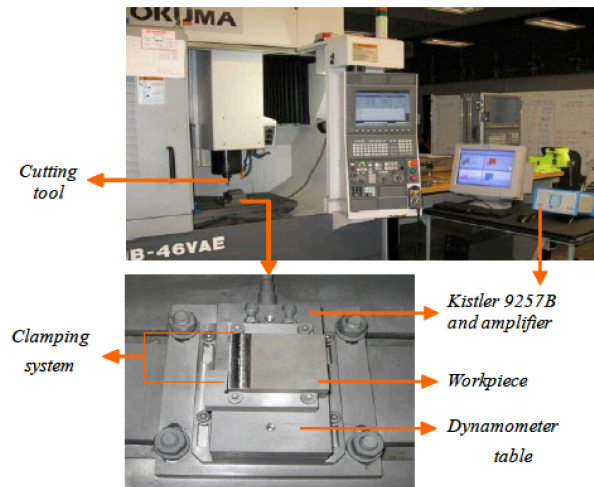


Figure 1: Experimental setup

For the experiments, 6-flute solid carbide tools with 25.4 mm diameter and 6-flute solid ceramic tools with 12.7 mm diameter were utilized. For the solid carbide tools, a tool with no coating was used as the baseline, and two different coatings were placed on the cutting edge of some tools to create the other two types of tools used: Baseline with low cost coating (LCC), and baseline with high cost coating (HCC). As their name implies, the cost for these coating materials and methods differed slightly, allowing a comparison between the coating types as well as against the baseline tool. It was provided that the cost of LCC was 50% of the carbide tool cost, whereas the cost of HCC was 70% of the baseline tool cost. Therefore, one can assume the baseline tool cost as C for comparison, which would make the LCC cost $1.5C$, and the HCC cost $1.7C$. For the solid ceramic tools, the same fresh unworn tools were used for each test, but the tools were not changed between passes to allow tool life investigations. It was observed that these tools did not wear quickly to exceed the threshold determined for roughing operations they are used for. Hence, the tests were stopped at a predetermined number of passes (26) and the tool wear was used to normalize the efficiency (MRR) and the productivity (MR) measures for comparison. This number of passes also allows comparison with solid carbide tests, where 13 passes equal to the same amount of material removal due to the difference in width of cut. It was reported that the solid ceramic tools cost three times the solid carbide tools; therefore their cost is represented as $3C$.

For both carbide and ceramic tools, 10% maximum tool engagement was advised by the manufacturer, therefore the width of cut (WoC) was chosen to be 2.54 mm for the solid carbide tools and 1.27 mm for the ceramic tools. For the carbide tools, since the aim was to compare the tools with and without coating, same machining conditions were used for all tests: $V_c=20$ m/min cutting speed, 0.15 mm/rev feed, and 6.5 mm depth of cut (DoC) (Table 1). For the ceramic tools, since the aim was to compensate for the higher cost, more aggressive parameters were chosen. Cutting speed and feed were varied in order to compare the tool performance in different regions, but a constant depth of cut at the same value (6.5 mm) was utilized (Table 1). Since the cost of experiments was high and the

introduction of the methodology does not require replications, one test at each condition was deemed sufficient.

Table 1: Design of experiments for solid carbide and ceramic tool life testing

Test	Spindle Speed	Cutting Speed	Feed	DoC	WoC
	N RPM	V_c m/min	f mm/rev	a_p mm	w mm
Carbide (all)	250	20	0.15	6.5	2.54
Ceramic 1	10,000	400	0.09	6.5	1.27
Ceramic 2	12,000	480			
Ceramic 3	15,000	600			
Ceramic 4	10,000	400	0.18	6.5	1.27
Ceramic 5	12,000	480			
Ceramic 6	15,000	600			

4 Results and Discussions

4.1 Solid Carbide Tool

The results of the tool life tests for solid carbide tools revealed that the resultant force and spindle power consumption had very similar trends; therefore only force results are presented (Figure 2). It can be observed from this figure that all tools exhibited very similar resultant force values in the first few passes, whereas after about 5 passes, the baseline tool starts inducing significantly higher (10-30%) forces compared to both types of coated tools. Therefore, addition of tool coating decreased the resultant force values as well as the spindle power consumption. This can be attributed to two aspects of tool coating: (1) the coatings have lower friction coefficients than the baseline carbide material that helps reduce the machining forces, and (2) as the tool wears out, the force increase is more severe compared to the coating wearing out and revealing the baseline material for machining. It was also observed that addition of coating resulted in a more stable transient cutting regime compared to the baseline uncoated tool, reinforcing the friction reduction hypothesis.

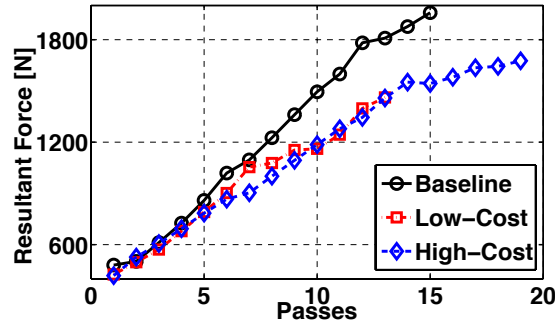


Figure 2: Resultant machining force evolution for all types of carbide tooling

It was also observed that all three types of tools exhibited similar wear behaviors until failure (Figure 3). Low cost and high cost coated tools induced approximately the same amount of average tool flank wear (VB) until failure (Figure 3a), which was slightly (~20%) more than the baseline tool throughout the tool life. This could be due to the more rapid wearing of the coating material than the

baseline carbide material, which did not necessarily lead to tool failure under the predefined thresholds. Also, despite this trend, the maximum tool flank wear measurements revealed (Figure 3b) a rapid deterioration and eventual failure due to VB_{max} of tool in the cases of the baseline and LCC tools, whereas the HCC tool failure happened only due to crater wear criterion. Under these failure modes, the baseline tool lasted 15 passes, whereas the LCC only lasted 13 passes (13% less tool life) and the HCC did not fail before pass 19 (27% more tool life). Therefore, despite the lower machining forces induced by the LCC tool, its lower tool life did not favor a choice over baseline considering its higher cost. However, given the additional tool life provided with the HCC tool as well as the reduced machining forces, it is competitive with the baseline tool. Further comparison between the HCC and the baseline tools as well as the ceramic tools is provided in Section 4.3.

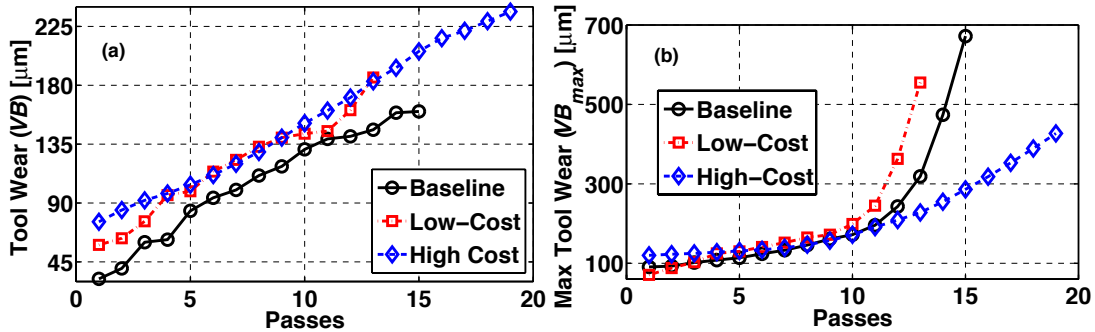


Figure 3: Evolution of (a) average and (b) maximum tool flank wear

4.2 Solid Ceramic Tool

The results of the solid ceramic tool life tests also showed (Figure 4) that the resultant machining force and spindle power consumption are well correlated ($R^2=84\%$) for constant machining conditions; therefore it was concluded that presenting both would be redundant. It should still be noted that when the machining conditions changed (different cutting speed or feed), the ratio used to convert force and power changed. A comprehensive visualization of machining forces is provided in Figure 5, where the boxplot and colorplot of the six tests can be found. Whereas the boxplots provide distribution of resultant force values in each test for all 25 passes, the colorplots show early stages of the tool life tests (fresh tool) in blue and the later stages (worn tool) in red, in a gradual color scheme. Although both the boxplot and the colorplot for each test show the same values, it is possible to compare different tests between each other using the boxplot and have an insight to how the force evolved with tool wear for each test using the colorplot. The tests with the same feed are also represented with the same shapes in the colorplot for convenience. The limits of the boxes in the boxplot show the 1st and the 3rd quartile of the data, whereas the whiskers show the 2nd and 98th percentile. In the case of Figure 5, there was no outlier (outside of 2nd-98th percentile limits) in any of the plots.

As it can be observed from Figure 5, there was no significant difference between machining forces of different tests. This is due to the fact that the machining conditions are aggressive in all the tests, and the changes in those conditions did not affect machining difficulty significantly. On the other hand, it is worth noting that the spindle power consumption changes significantly due to the fact that spindle rotation at higher speeds consumes more machine power regardless of machining. It was also noted that the average (VB) and maximum (VB_{max}) tool wear values had similar trends and the tools were very close to failure for all tests. However, in order to compare the tests fairly, recently coined metrics of productivity in terms of normalized volumetric material removal (NMR), and efficiency in terms of normalized material removal rate ($NMRR$) were used.

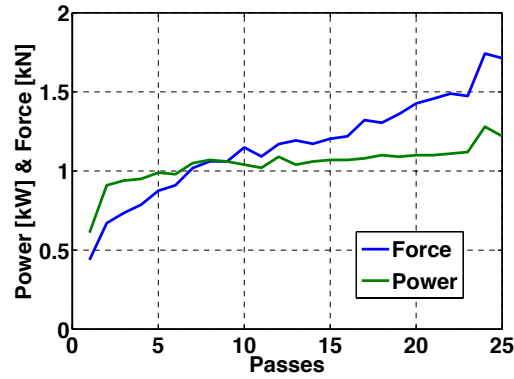


Figure 4: Sample graph (for Test 1) to represent force and power evolution with passes

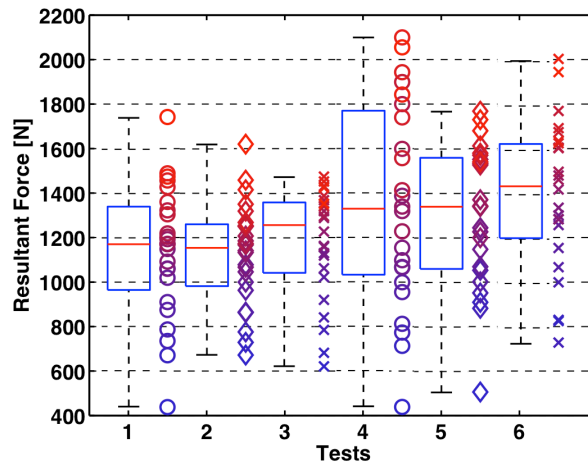


Figure 5: Boxplot and colorplot of machining forces for the six solid ceramic tests (refer to Table 1 for machining conditions of each test)

Table 2: Results for the solid ceramic tool life tests in terms of NMR (MR/VB) and $NMRR$ (MRR/VB)

Test	Cutting Speed V_c m/min	Feed f mm/rev	DoC a_p mm	Average MR/VB NMR $mm^3/\mu m$	MRR/VB $NMRR$ $mm^3/min/\mu m$
1	400	0.09	6.5	14.7	12.6
2	480	0.09	6.5	16.2	15.7
3	600	0.09	6.5	15.9	19.6
4	400	0.18	6.5	13.9	26.9
5	480	0.18	6.5	12.6	30.5
6	600	0.18	6.5	15.9	43.0

The findings of the solid ceramic tests are shown in Table 2. It was observed from the boxplot of NMR comparison (Figure 6) that although similar values were encountered, machining conditions for Tests 2,3, and 6 resulted in significantly higher productivity compared to the other tests. On average, tests at lower feeds (Tests 1-3) resulted in slightly better NMR values, but the combination of high speed and feed (Test 6) was also competitive. At this point, comparing $NMRR$ values between the tests with better and comparable NMR results is a good way of finding the optimal machining

conditions. Since tool wear values were not too different between tests, higher cutting speed and feed tests resulted in better $NMRR$ as expected. Therefore, selecting test 6 conditions provided very similar productivity (same amount of material removal per tool) compared to test 2&3 conditions, while achieving this in less than half of the time per tool.

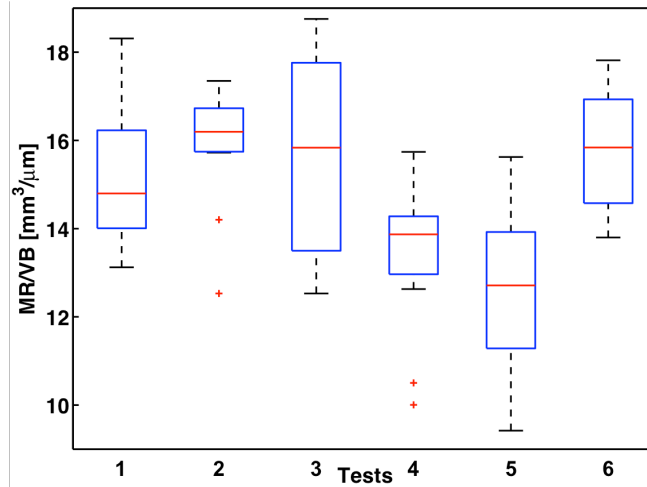


Figure 6: Boxplot of NMR (MR/VB) values for the six solid ceramic tests

4.3 Comparison of Solid Tools

Although it is important to compare carbide and ceramic tools within themselves, industrial challenges often include tool selection without a thorough understanding of tool capabilities and the cost implications of each tool. In this section, the theory developed in Section 2 to optimize total process cost is employed to compare the performance of the solid carbide and ceramic tools under different conditions. Numerical assumptions made for this problem are summarized in Table 3. It was assumed that 0.1 m^3 of total material removal was needed: a big number that might represent weekly, monthly, or any long-term requirement. For the carbide tools, the cost for a single tool is C , $1.5C$, and $1.7C$ for the baseline, LCC and HCC tools, respectively, whereas the ceramic tool costs three times the carbide tool ($3C$). NMR values for the solid carbide tools were calculated by taking the average of the ratio of MR after each pass and VB values shown on Figure 3a using Eq. (7), whereas average NMR values shown in Table 2 were used for the solid ceramic tools. The value of the threshold tool flank wear VB_f can be assumed any value for the sake of comparison, and it differs in practice. For this study, $VB_f=300 \text{ }\mu\text{m}$ of flank wear was assumed to be the threshold that triggers the tool change requirement.

Calculating the cost of a single tool change c_{change} is more difficult, as there is a need to assign a cost to the amount of time spent, and it is not plausible to disclose industrially proprietary information about such relationships. Also, not all of the elements involved in the tool change cost can be easily quantified in terms of monetary representations. Therefore, it was assumed for the sake of this study that the elements summarized as the cost of tool change are equivalent to having an hourly rate of $60C$, or $1 \text{ }C/\text{min}$. However, considering the uncertainties involved in determining this rate, also a range of values were considered, and the rate was evaluated within the range of $0.1\text{-}2 \text{ }C/\text{min}$. The cost of machining was assumed to be at a $120C$ hourly rate, or $2 \text{ }C/\text{min}$, but a range of $1\text{-}2.5 \text{ }C/\text{min}$ was included in the investigation. The tool change time t_{change} was assumed to be 1 minute, but a range of $0.5\text{-}2 \text{ min}$ was considered.

The results when all the nominal values were plugged into Eq. (12) are shown in Table 4. Based on the nominal costs shown in this table, the performances of solid carbide and ceramic tools are

comparable, as the two minimum total costs are for the baseline carbide tool and the ceramic tool run at the high speed and feed combination (approximately 10,000C). The coated carbide tools did not perform well, as they came last in the comparison within the 9 tests considered. Figure 7 shows the effect of investigating a whole range instead of just the nominal values, and it can be observed that the baseline tool is the best choice under these conditions, whereas the ceramic tool can be a competing alternative when it is used at the higher cutting speed and feed (Test 6).

Table 3: Numerical assumptions for the model

Item	Unit	Value	Range
c_{tool} (Solid Carbide Baseline Tool)	C	1	
c_{tool} (Solid Ceramic Tool)	C	3	
c_{tool} (LCC)	C	0.5	
c_{tool} (HCC)	C	0.7	
c_{change}	C/min	1	0.1-2
$c_{machining}$	C/min	2	1-2.5
t_{change}	min	1	0.5-2
V_{tot}	m ³	0.1	
VB_t	μm	300	

Table 4: Results of cost optimization

Tool	Test	NMR	NMRR	C_{tool}	C_{change}	$C_{machining}$	C_{total}
		mm ³ /μm	mm ³ /min/μm	C	C	C	C
Carbide	Baseline	57.3	7.45	582	582	8,949	10,112
Carbide	LCC	59.1	5.11	846	564	13,046	14,456
Carbide	HCC	57.3	4.91	989	582	13,578	15,148
Ceramic	1	14.7	12.6	6,803	2,268	5,291	14,361
Ceramic	2	16.2	15.7	6,173	2,058	4,246	12,477
Ceramic	3	15.9	19.6	6,289	2,096	3,401	11,787
Ceramic	4	13.9	26.9	7,194	2,398	2,478	12,071
Ceramic	5	12.6	30.5	7,937	2,646	2,186	12,768
Ceramic	6	15.9	43.0	6,289	2,096	1,550	9,936

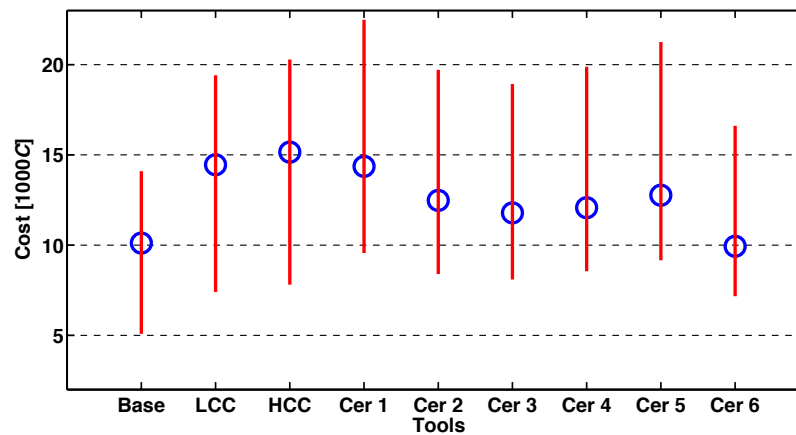


Figure 7: Costs of each tool at the nominal values and ranges of variables

5 Conclusions

In this study, a model of the total process cost in machining nickel-based superalloys was developed. Using this model, an attempt to propose a solution to the unknowns in the tool selection decisions was presented. It is believed that the ranges of the model parameters can be determined with more certainty and the costs can be represented as actual monetary values in real-life applications, and with the help of this model, possible cost savings can amass to significant amounts. Major conclusions drawn from this work are as follows:

- When machining with the solid carbide tools, addition of coating led to significant (~20%) decreases in machining forces. However, use of coating brought extra amount of tool flank wear, and in the case of a low-cost coating, premature tool failure (13% early) compared to the baseline tool. The high-cost coating, on the other hand, prolonged the tool life significantly (27%) compared to the baseline tool without coating.
- When machining with the solid ceramic tools, it was found that higher feed values (Tests 2, 3, 6) resulted in higher productivity (*NMR*). Owing to the high cutting speed and feed values, Test 6 resulted in the best efficiency (*NMRR*).
- The developed model was used in order to assess the performance of all tests and tools. Based on assumed values of unknown parameters, the carbide and ceramic tools performed similarly. Among the carbide tools, baseline tool was found to be the best option, since the extra tool life brought by the high cost coating did not justify the cost of the coating. In terms of the ceramic tools, since there was not a difference in tool material, the test with the best *NMRR* and *NMR* combination (Test 6) was the least costly option. Between the baseline carbide tool and the ceramic tool with the highest machining conditions, there was not too much difference to favor either direction.

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