Insert comparison in high-speed cutting of titanium alloy Ti-6Al-4V and nickel-based alloy IN-738

Durul Ulutan*, Hemanth Potluri, Abram Pleta, and Laine Mears
** International Center for Automotive Research, Clemson University, Greenville, SC 29607*
dulutan@clemson.edu

Abstract: Due to increasing performance requirements, titanium alloys, particularly Ti-6Al-4V, have been more frequently used in the aerospace, automotive, and biomedical industries recently. Therefore, improving the manufacturing approach for these difficult to machine alloys have been of interest to researchers. However, in many instances, little attention is paid to proper tool selection, where it usually plays an important role in machining different materials. This study presents an experimental analysis on how different types of inserts perform while machining Ti-6Al-4V under various machining conditions in terms of different performance measures such as resultant machining force, spindle power consumption, and tool flank wear. The same types of inserts are also used in machining a nickel-based superalloy IN-738, and it was found that the inserts that are particularly suggested for machining Ti-6Al-4V are not as suitable for machining IN-738. While comparing these insert types, effects of machining conditions, namely the cutting speed, feed, and depth of cut are also investigated and presented.
Keywords: Machining, superalloy, titanium, insert, Ti-6Al-4V

1. INTRODUCTION

Titanium alloys are known for their superior corrosion resistance, high specific strength at elevated temperatures, high fracture resistance, and excellent weight-to-strength ratio [Ulutan and Özel, 2011; Choragudi *et al.,* 2010]. Because of their superior properties, titanium alloys are widely used in the aerospace, automotive and biomedical industries. However, titanium chemically reacts with many tool materials [Rahman *et al.*, 2006], and it has high strength that makes it difficult-to-machine in terms of higher machining forces and spindle power consumption than other comparable materials such as aluminum or steel. Nickel-based alloys such as IN-738 are also used in applications with elevated temperatures where high strength and corrosion and creep resistance properties are essential [Li *et al.*, 2006; Henderson *et al.*, 2010]. Therefore, with similar characteristics and applications, the natural intuition for the industrial processes would be to machine these alloys under similar conditions. However, because of the differences in their chemical compositions and structures, this assumption would be counter-productive for an untrained machinist. In fact, it is essential to employ significant care in determining the set of machining parameters, as well as the selection of the machine and the tool.

Also, in a typical machining process, heat generated as a result of friction and shearing mechanisms during machining processes is distributed between the tool, workpiece, and chips. Most of the heat generated is carried away from the process by the chip, a phenomenon beneficial to tool life. However, since titanium has very low thermal conductivity, most of the heat generated during machining is transferred to the tool, which weakens the tool and decreases its usable life, and increases the difficulty and cost of machining titanium and its alloys [Choragudi *et al.*, 2010]. Titanium alloys also have a tendency to weld to the cutting tool during machining, which results in chipping of the tool leading to premature tool failure. Therefore, whenever titanium and its alloys are manufactured using conventional machining processes like turning, milling, drilling, reaming, sawing and grinding, it is at the expense of frequent tool change. Consequently, titanium alloys have low machinability in terms of cutting forces, spindle power consumption, and tool wear compared to the other materials frequently used in the same industries.

High-speed machining (HSM) is a relatively recent method of machining where five to ten times the conventional machining speeds are employed. HSM has advantages of producing burr-free edges, high quality surfaces, virtually stress-free components, and success in machining thin-wall workpieces. With the help of HSM, higher productivity in aerospace and automotive manufacturing has been possible, particularly with aluminum and steels. However. HSM of titanium and its alloys has met faced lower success due to its low machinability: HSM relies heavily on the fact that majority of the generated heat during the process is removed with the chip, which helps in reducing thermal warping that increase tool life, but this fact does not apply to titanium. HSM also introduces the possibility of chatter during machining, which also increases tool wear [Ezugwu and Wang, 1997]. Because of the increased tool wear and chatter, the importance of tool selection increases.

Researchers have spent significant time on developing efficient tools for high speed machining of titanium alloys, particularly Ti-6Al-4V (Ti-6-4). Uncoated and coated carbide tools have been tested [Ezugwu *et al.*, 2005], as well as cubic boron nitride (CBN), ceramic, and poly-crystalline diamond (PCD) tools. Despite this significant research on different tools, tool performance during machining of Ti-6-4 has not been fully understood. There is not a consensus on the results of machining Ti-6-4 in the literature, particularly because a lack of complete and comprehensive study of the effects of tool selection for HSM. This study aims to contribute to filling in that void by investigating high speed machining of Ti-6-4 with two inserts that are different grades of carbide and are coated with different methods, to compare their performance in different cutting speeds, feeds, and depths of cut. One of these inserts (R390-11T308M-PM-1030) is suggested by the manufacturer (Sandvik) for general machining practices, including steel, nickel-based alloys as well as titanium and its alloys. On the other hand, the other insert (R390-11T308M-PM-S40T) is suggested particularly for machining titanium and its alloys, particularly at higher machining speeds. Therefore, to illustrate the advantage of using a particular type of insert, high speed machining tests of a nickel-based alloy IN-738 were conducted in addition to Ti-6-4 tests, under the same machining conditions.

2. EXPERIMENTAL SETUP AND DESIGN

Materials used for this experimental study are Ti-6-4 and IN-738, where all blocks that were tested were cut out from the same block of each material to ensure accuracy of the results. An OKUMA GENOS M460-VE 3-axis CNC machine was used to end mill (in down-milling direction) rectangular blocks of Ti-6-4 and IN-738 of size 60 x 80 mm, using a water soluble coolant. A 2-flute indexable tool holder with diameter of 15.875 mm was used, and the width of cut was chosen to be 9.5 mm that corresponds to 60% engagement, as this was the maximum recommended engagement for the particular tool holder. Full length of the blocks (60 mm) was utilized for machining. At the chosen width of cut, 8 tests were conducted on each block: 4 tests with 2 replications.

Two different types of inserts were used in different tests – both provided by Sandvik: R390-11T308M-PM-S40T and R390-11T308M-PM-1030, which will be referred to as "S40T" and "1030". The two types of inserts are the same in terms of their geometry and chip breakers; however, they are different grades of cemented carbide, and while 1030 inserts are coated with multi-layer TiAlN using physical vapor deposition (PVD), S40T inserts are coated using medium-temperature chemical vapor deposition (CVD) in thin layers of similar (undisclosed) coating. Although 1030 inserts are suggested for machining most hard-to-machine heat-resistant superalloys, S40T inserts are advised for machining titanium and its alloys, so a comparison of these two types of inserts is essential in machining Ti-6-4. A fresh set of inserts was used at each test to ensure comparability of different test results.

During machining, forces were measured in three orthogonal directions using a 6-axis Kistler dynamometer with a sampling frequency of 6 kHz. Spindle power consumption was also measured at 50 Hz, and since spindle power is significantly stable compared to cutting forces at intermittent machining processes, the sampling frequency was satisfactory. The average tool flank wear (VB) was measured along the cutting edge of the tool.

Tests for Ti-6-4 were designed in a fashion that the effect of each parameter can be observed – therefore selecting at least a high and a low level of cutting speed, feed, and depth of cut. The behavior of the inserts at higher speeds were the main interest, therefore one more (higher) level of cutting was added to result in a 3x2x2 full design of experiments (DoE) study. Three levels of cutting speed at 50, 150, and 250 m/min, feed at 0.1 and 0.5 mm/rev, and depth of cut of 0.5 and 1.5 mm were used to investigate the effects of different sets of parameters among the two inserts (Table 1). These parameters were selected at both their relatively mild values to show the behavior of the inserts under normal machining conditions, and at their relatively aggressive values to show the behavior of the inserts under high material removal rate conditions.

Tests for IN-738 were designed in a fashion that there would be a satisfactory amount of tests – both in mild and aggressive conditions – to compare the effect of using the two inserts in machining IN-738 vs. Ti-6-4. Since the effect of the insert was only expected in machining Ti-6-4, the anticipated result was that the S40T inserts would exhibit advantage over 1030 tools in machining Ti-6-4 whereas they would not create significant difference in machining IN-738. Therefore, the study is focused on the effectiveness of using these inserts on Ti-6-4 (and not IN-738), which is why the full design of Ti-6-4 experiments were not repeated for IN-738 experiments. Hence, only the low depth of cut was investigated to depict the differences between machining the two materials, while the other parameters were kept the same. These machining conditions, as well as the results for IN-738 experiments can be found in Table 2.

3. RESULTS AND DISCUSSIONS

The most important search in this study is the answer to whether or not a particular type of insert is more beneficial in machining a specific material. After this investigation, the effects of the three parameters on machining Ti-6-4 is investigated using Figures 1-3, which show for Ti-6-4 machining the effects of cutting speed, feed, and depth of cut on the resultant force, spindle power consumption, and tool flank wear respectively.

Figure 1 shows that even with changing parameters, the resultant forces incurred by machining Ti-6-4 do not change much between the two types of inserts. In fact, the average difference of the resultant force in all tests between the two inserts is less than 1%. The differences in individual tests are less than 45%, and there is no statistically significant difference between the two inserts (p=0.98). Figure 2 shows that with most of the parameter sets, the two inserts performed very similarly, and in fact, the average difference in the spindle power consumption between the two inserts is 7%, with S40T requiring less power on average. All of the differences are below 27% for individual tests, and with the exception of two tests, S40T tests mostly required less power. Although there is an observable trend of less power consumption with S40T inserts, there is no statistically significant difference (p=0.9) between the two inserts.

Figure 3, on the other hand, shows that during machining Ti-6-4, S40T inserts wear considerably less than the 1030 inserts on average. Table 1 also reflects this fact for individual tests and reveals that for all of the tests conducted, S40T inserts wore less than 1030 inserts. In fact, an average of 30% less tool wear was observed when using S40T inserts, and statistically relatively significant difference was found (p=0.087). Although the p-value is still more than 0.05, this shows that with the addition of only a few more tests, it can be concluded that there is a definite difference between the performances of the two inserts.

As a result, it was observed that S40T inserts incur similar resultant forces and require similar amount of power for machining, but they wear out significantly less than the 1030 inserts while machining Ti-6-4. This makes Ti-6-4 more machinable using S40T inserts, and can reduce the tooling cost as much as 30% only by changing the inserts being used. Since the costs of the inserts are the same, using S40T for machining Ti-6-4 can be advised.

Table 1: Comparison of inserts by machining performance for Ti-6-4 (absolute values for both inserts and the difference (Diff) in percentage given with respect to 1030 results).

Cutting Speed	Feed	Depth of Cut	Resultant Force			Power Consumption			Tool Wear		
			1030	S40T	Diff	1030	S40T	Diff	1030	S40T	Diff
[m/min]	[mm/rev]	[mm]	[N]	[N]	%	[W]	[W]	%	[μm]	[μm]	%
50	0.1	0.5	59	56	-4	36	29	-19	61	41	-33
50	0.1	1.5	148	123	-17	89	87	-2	56	43	-23
50	0.5	0.5	118	118	0	89	82	-8	55	38	-30
50	0.5	1.5	314	295	-6	262	248	-5	71	60	-15
150	0.1	0.5	51	51	0	74	69	-6	75	44	-41
150	0.1	1.5	216	129	-40	295	226	-23	74	41	-44
150	0.5	0.5	114	112	-2	227	213	-6	74	56	-24
150	0.5	1.5	449	493	10	1215	890	-27	123	105	-14
250	0.1	0.5	55	56	3	128	123	-4	68	47	-30
250	0.1	1.5	183	263	44	410	468	14	58	46	-20
250	0.5	0.5	123	127	4	369	336	-9	79	67	-15
250	0.5	1.5	852	888	4	1464	1597	9	288	71	-75

Table 2: Comparison of inserts by machining performance for IN-738 (absolute values for both inserts and the difference (Diff) in percentage given with respect to 1030 results).

Cutting Speed	Feed	Depth of Cut	Resultant Force			Power Consumption			Tool Wear		
			1030	S40T	Diff	1030	S40T	Diff	1030	S40T	Diff
[m/min]	[mm/rev]	[mm]	[N]	[N]	%	[W]	[W]	%	[μm]	[μm]	%
50	0.1	0.5	97	113	16	52	61	17	79	75	-5
50	0.5	0.5	402	393	-2	193	226	17	255	175	-31
150	0.1	0.5	299	297	-1	245	316	29	184	270	47
150	0.5	0.5	599	713	19	572	710	24	419	406	-3
250	0.1	0.5	490	576	18	463	624	35	263	412	57
250	0.5	0.5	815	868	7	824	971	18	350	482	38

On the contrary, the results of IN-738 machining tests do not point to any significant difference between the two inserts. For most of the tests (4 out of 6) conducted with IN-738 as the workpiece material, resultant machining forces were higher when S40T type inserts were used. In the other 2 cases (out of 6 experiments), the difference between resultant forces when machined with 1030 and S40T inserts was less than 2% (in favor of S40T). Overall, S40T inserts induced 9% higher machining forces compared to 1030 inserts, and the difference between the two inserts were far from being significant in terms of forces (p=0.78). Considering the spindle power consumption, all tests with S40T inserts indicated higher amounts, between 17 to 35%, and 23% on average. On average, 23% more power consumption was observed using S40T (p=0.62). For the tool wear, half of the experiments (without any patterns in machining parameter effects) showed higher tool wear for 1030 inserts, while the other half showed higher tool wear for S40T inserts (p=0.59). Therefore, although statistically insignificant, S40T inserts induced higher forces and spindle power consumption, while not reducing tool flank wear. As a result, use of S40T inserts in machining IN-738 against the 1030 inserts cannot be advised.

Since the S40T inserts did not conclude in favorable results for machining IN-738 but they induce significantly less tool wear while machining Ti-6-4 compared to the 1030 inserts, the manufacturer suggestion was experimentally proven through this work. It was shown again that the choice of insert can be crucial in machining processes, saving from unnecessary temporal and financial expenditures. In addition, Figure 1 and Figure 2 show that with all increasing parameters, both the resultant force and the spindle power consumption increase fairly linearly during machining Ti-6-4. However, as seen from Figure 3a, the increase in tool wear may not be linear with increasing cutting speed, while it still follows a linear increase with increasing feed and depth of cut.

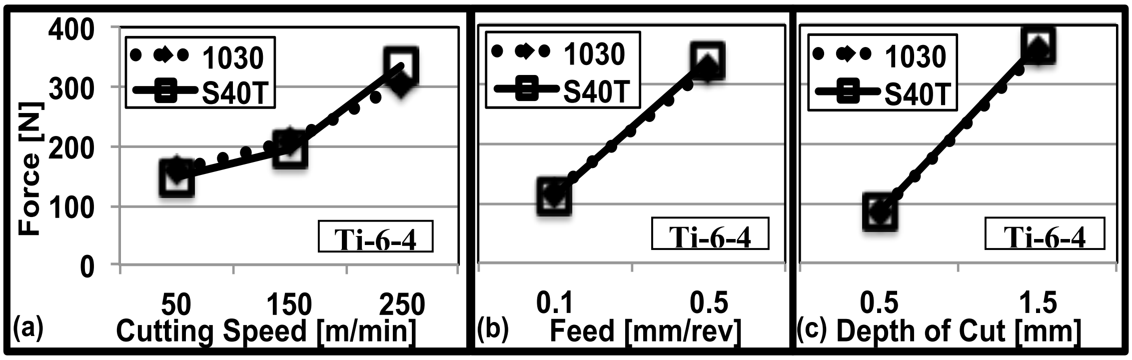

Figure 1: Comparison of the effects of (a) cutting speed, (b) feed, and (c) depth of cut on the resultant force during machining Ti-6-4 with the two inserts – 1030 and S40T.

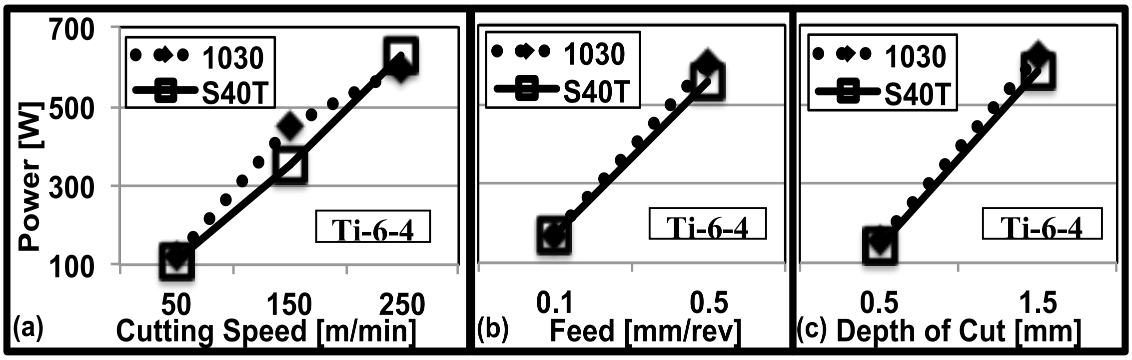

Figure 2: Comparison of the effects of (a) cutting speed, (b) feed, and (c) depth of cut on the spindle power consumption during machining Ti-6-4 with the two inserts – 1030 and S40T

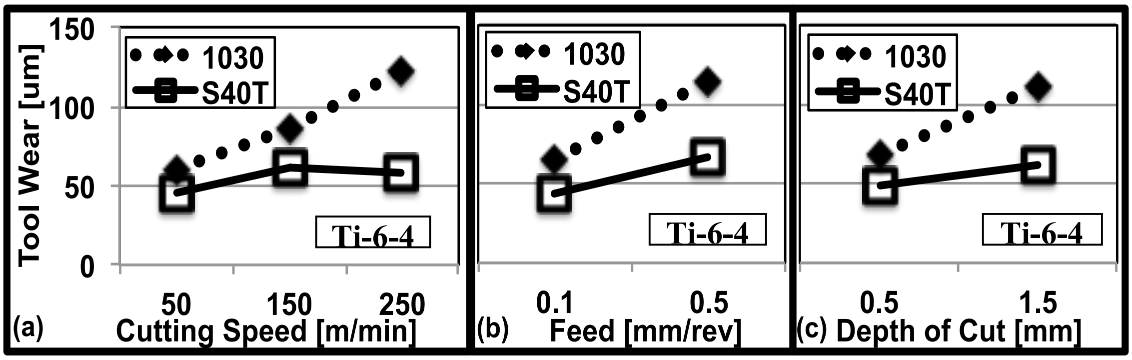

Figure 3: Comparison of the effects of (a) cutting speed, (b) feed, and (c) depth of cut on the average tool flank wear during machining Ti-6-4 with the two inserts – 1030 and S40T.

4. CONCLUSIONS

This preliminary study aimed to shed more light on characterization of machining Ti-64, particularly the effects of machining parameters and the importance of selecting the right tool. It was found that the performance measures (resultant force, spindle power consumption and average tool flank wear) increase fairly linearly with increasing machining parameters, which makes the outputs of the machining process predictable. Also, it was shown that although the S40T inserts did not provide significant benefit in terms of forces and power consumption, they reduced the tool wear by 30% compared to the 1030 inserts, particularly because of the differences in grades as well as coating application. However, the same inserts did not provide any benefit while machining IN-738. In fact, the machining forces, spindle power consumption, and tool wear were higher while machining with S40T compared to 1030 type inserts. Therefore, machining with S40T inserts are advised only when the material is Ti-6-4. It is still required to expand the comparison of inserts at different machining conditions to have more significant results and more confidence in advising the S40T type inserts.

ACKNOWLEDGMENTS

The authors wish to thank GE Power & Water for support of this work.

REFERENCES

[Choragudi *et al.*, 2010] Choragudi, A.; Kuttolamadom, M.A.; Jones, J.J.; Mears, M.L.; Kurfess, T.; "Investigation of the machining of titanium components for lightweight vehicles"; *SAE 2010 World Congress*; 2010.

[Ezugwu and Wang, 1997] Ezugwu, E.O..; Wang, Z.M.; "Titanium alloys and their machinability – a review"; *Journal of Materials Processing Technology 68.3*, pp. 262-274; 1997.

[Ezugwu *et al.*, 2005] Ezugwu, E.O.; Da Silva, R.B.; Bonney, J.; Machado, A.R.; "The effect of argon-enriched environment in high-speed machining of titanium alloy"; *Tribology Transactions 48,* pp. 18-23; 2005.

[Henderson *et al.*, 2010] Henderson, A.J.; Bunget, C.; Kurfess, T.R.; "Cutting force modeling when milling nickel-base superalloys"; *Proceedings of the ASME International Manufacturing Science and Engineering Conferece (MSEC 2010),* pp. 193-202; 2010.

[Li *et al.*, 2006] Li, H.Z.; Zeng, H.; Chen, X.Q.; "An experimental study of tool wear and cutting force variation in the end milling of Inconel 718 with coated carbide inserts"; *Journal of Materials Processing Technology 148,* pp. 296-304; 2006.

[Rahman *et al.*, 2010] Rahman, M.; Wang, Z.-G.; Wong, Y.-S.; "A review on high-speed machining of titanium alloys"; *JSME International Journal Series C 49.1*, pp. 11-20; 2006.

[Ulutan and Özel, 2011] Ulutan, D.; Özel, T.; "Machining induced surface integrity in titanium and nickel alloys: a review"; *International Journal of Machine Tools and Manufacture 51.3*, pp. 250-280; 2011.