Development of Advanced Carbide for Nickel-based Alloy Machining for Turbine Engines

Effective Date of Contract: October 2005
Expiration Date of Contract: August 2006

Development of an Advanced Carbide Cutting Tool for Nickel-based Alloy Machining Summary
Final Report

Kennametal, Inc.
NCDMM Project # NP05007810
August 31, 2006

Submitted by:

National Center for Defense Manufacturing & Machining

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
31 AUG 2006	**Final**	**28-10-2005 to 31-08-2006**

4. TITLE AND SUBTITLE
Development of Advanced Carbide for Nickel-based Alloy Machining for Turbine Engines

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
A.T. Santhanam

5d. PROJECT NUMBER
05-0078-10

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Center for Defense Manufacturing & Machining,1600 Technology Way,Latrobe,PA,15650

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The NCDMM placed a sub-contract with Kennametal to develop an advanced carbide tool for high productivity machining of nickel-base alloys. The contract was awarded in 2005 on a cost share basis with the total labor cost split equally between Kennametal and NCDMM.

15. SUBJECT TERMS
Kennametal; NCDMM;

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**30**	

Overview

The "Development of Advanced Carbide for Nickel-Based Alloy Machining for Turbine Engines" project was a joint effort between the NCDMM and Kennametal, Inc.. The NCDMM funded Kennametal, Inc. in this effort to develop an advanced coated carbide cutting tool for turning nickel based alloys such as Inconel 718 utilizing state-of-the-market and state-of-the-art methods. The goal of increasing machining productivity by 40% was achieved with the development of an advanced PVD coated carbide-cutting tool.

Executive Summary

In 2003, the NCDMM, a government sponsored Manufacturing Technology Center, was established to address and support the broad manufacturing and machining needs of the U.S. Department of Defense (DoD) and its industrial supply base in pursuit of state-of-the-art manufacturing and machining solutions supporting our war fighters.

To date, the NCDMM has completed more than 30 projects and generated more than $250M in stakeholder (customer) returns through program savings and cost avoidance along with the associated benefits of improved part quality, reduced rework, reduced lead times and the much needed additional capacity resulting from implementation of new, efficient manufacturing processes.

In addition to the returns generated at defense manufacturing facilities, the NCDMM has established a viable source of skilled manufacturers in support of defense primes sub-contracting requirements. This has generated in excess of $25M in new DoD business in the Western PA region and established a methodology transportable to other regions in the nation as well.

The impact of the NCDMM efforts has been demonstrated through the execution of structured projects that utilize proper manufacturing and machining technologies and practices as well as training facility staff through a managed migration of those technologies and practices, resulting in an average reduction in operation and support costs of more than 30 percent. The projects conducted by the NCDMM have lowered costs, improved quality and extended service life of the component system and the process by which that component system is supported as well as improved the skills of the workforce by the increased use of appropriate technologies and practices – moving from current, often out-dated practices, to state-of-the-market and state-of-the-art methods.

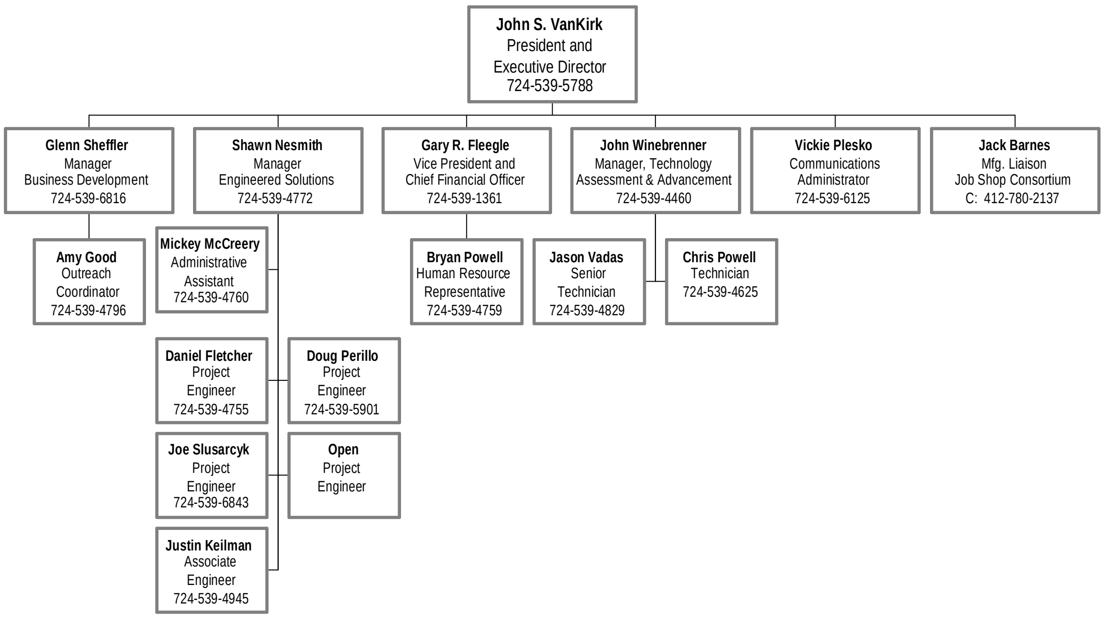
The NCDMM will continue to serve as a national resource to identify critical opportunities within the DoD Industrial Base and capitalize on those opportunities by providing and implementing solutions resulting in reduction of costs while improving product quality through cost-effective manufacturing and machining processes.

NCDMM Mission Statement

The NCDMM will deliver state-of-the-art manufacturing solutions to ensure the quality, affordability, maintainability, and rapid deployment of existing and yet-to-be-developed defense systems. Collaboration among Government, Industrial, and Academic organizations will enhance key development efforts. Disciplined training and implementation methodologies will ensure the rapid deployment of best practices to key stakeholders.

NCDMM Capabilities

The NCDMM has proven capabilities in developing and implementing state-of-the-art manufacturing and machining process technologies through the combined work of its internal technical staff and its capable Alliance Partner group. The internal NCDMM technical staff is made up of mechanical/manufacturing engineers & scientists, journeymen machinists, and manufacturing technicians, see Figure #1 below.



The NCDMM Organizational Chart

The NCDMM activities are supported with state-of-the-art manufacturing software tools and machinery. Fully functional 3D Solid Modeling Computer Aided Design and Manufacturing (CAD/CAM) software and Computer Numerical Control (CNC) program verification software is used to support the manufacturing process development and virtual "prove out" of proposed process steps.

State-of-the-art machine tools (based at the NCDMM laboratory and Alliance Partner locations) are readily available for physical process "prove out" and demonstration to the NCDMM stakeholders. A key part of the NCDMM project performance life cycle is the "Proof-of-Concept" step, which confirms process viability in real world conditions and supports stakeholder acceptance of the technology, leading to the most important step - ***process implementation*** - and the resulting cost, quality, and lead-time benefits achieved with that implementation.

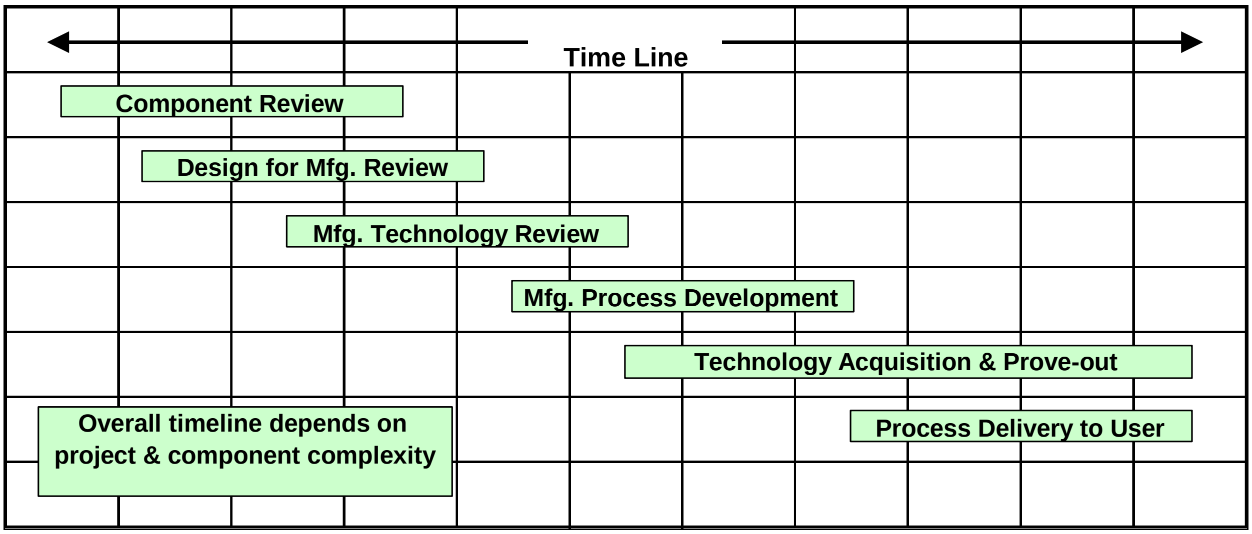
The NCDMM facilities (office space and lab facilities) are located on the world headquarters campus of Kennametal Inc., a $2 Billion supplier of metal cutting and advanced material solutions and services. Kennametal is also an Alliance Partner of the NCDMM, enabling the NCDMM to leverage additional technologies located on the Kennametal campus such as powder metal and ceramic materials processing, Chemical Vapor Deposition (CVD) and Physical Vapor Deposition (PVD) coating technology, and a variety of state-of-the-art software and hardware tools for precision measurement, microstructure analysis, surface condition monitoring, and other physical/metallurgical properties. Other Alliance Partners provide additional technologies to make up the overall NCDMM solution set.

Project Approach

The NCDMM project approach is based on a “Project Life Cycle” model, see Figure #2. Project progression starts with an initial encounter generated by the NCDMM, the stakeholder (customer), or the DoD. Projects can also be generated through the annual NCDMM Project Call. Projects can be Rapid Response (< 6 months, < $100K cost) or Longer Term (> 6 months, > $100K cost). Once the overall scope/project type is determined the project continues through its Life Cycle as described in Figure #2, with solution implementation and a success story development and publication being the final steps.

<u>The NCDMM Project Life Cycle</u>

In certain cases the NCDMM will propose its "Joint Ultimate Manufacturing Process Evolution and Development" (JUMPED™) process, see Figure #3. Established to be an all encompassing effort – starting with component design/inception and proceeding through complete manufacturing process delivery to the stakeholder – the JUMPED™ process strives to further reduce component cost and lead-time by allowing the NCDMM to become involved at the design stage and making recommendations that will reduce/eliminate manufacturing cost while maintaining, even enhancing, the design intent and/or function of the component. This is the ultimate way to gain the highest level of system performance (highest quality, longest life, highest readiness level) at the lowest possible costs.



JUMPED™ Process Steps and Sample Timeline

JUMPED™ Action steps include, but may not be limited to the following:

- Overall Component Review - Form, fit, function, base material selection…
- Design for Manufacturing Review – Design cost out…
- Manufacturing Technology Review - Machine, mold, grow, cast, etc…
- Manufacturing Process Development – The right technology in the right order…
- Technology Acquisition and Process Prove-out - Proof-of-Concept demonstration…
- Process Delivery to Prime or Sub Location - Technology Transfer and Implementation…

Benefits to Stakeholder:

- Ultimate Process/Technology
- Lowest Cost / Highest Quality
- Shorter Lead-times
- Improved System Readiness
- Lessons Learned Transferable to Other Products

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Submitted by

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1.0 Introduction

Modern gas turbine engines used in military fighter jets depend on nickel-base superalloys for their critical components because these materials withstand high combustion temperatures. However, the very characteristics that provide good high temperature strength in these alloys make them difficult to machine and cast a drag on machining productivity by limiting the speed capability of cutting tools.

In machining economics, the major component (~75%) of manufacturing cost lies in fixed costs (namely, machinery, labor, administration, and other overhead). Workpiece material costs typically run at 21% and tooling costs are relatively insignificant (4%) – see Fig. 1. Manufacturing cost reduction efforts are thus directed at fixed costs, primarily at reduction of component machining time through increased metal removal rates.

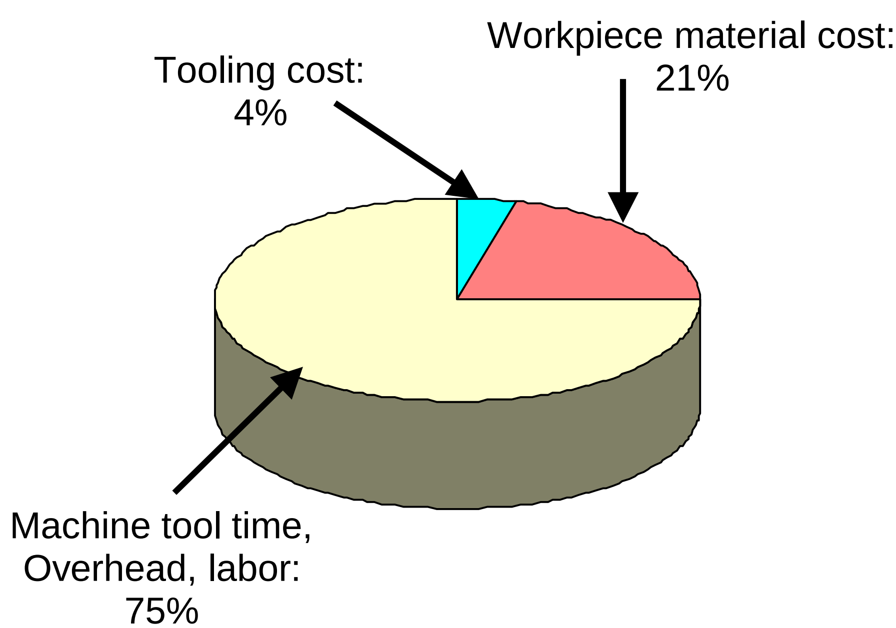


Fig 1: Components of manufacturing costs

1.1 Project description

The NCDMM placed a sub-contract with Kennametal to develop an advanced carbide tool for high productivity machining of nickel-base alloys. The contract was awarded in 2005 on a cost share basis with the total labor cost split equally between Kennametal and NCDMM.

1.2 Project objective

Develop an advanced coated carbide tool for machining nickel-base alloys with 40% higher productivity than the currently existing technology. The focus of the project is turning of Inconel 718 alloy.

1.3 Funding

The total NCDMM funding for the project was $150,000 ($120,000 for labor and $30,000 for workpiece material). Kennametal started working on the project on November 7, 2005.

2.0 Project team

A project team was assembled with the following members:

A.T. Santhanam (Project leader)
Aharon Inspektor
Ron Penich
Krishnan Narasimhan
Ken Niebauer
Nick Waggle
Kent Mizgalski (Project manager)

3.0 Project tasks

Task 1: Review current Inconel machining practice

Task 2: Establish the current state of the art in Inconel 718 turning

- Establish baseline data through benchmark machining tests
- Identify tool failure modes
- Identify technical approach to develop advanced cutting tool

Task 3: Develop an advanced cutting tool for Inconel 718 turning

Task 4: Write final report

4.0 Current Inconel machining practice

4.1 Literature review

Based on the literature review on the metallurgy and machinability of nickel-base superalloys, the specific challenges in Inconel machining are as follows:

- The high strength of nickel-base superalloys at cutting temperatures causes high cutting forces, generates more heat at the tool tip compared to alloy steel machining, and limits their speed capability.
- The low thermal conductivity of these alloys transfers the heat produced during machining to the tool and increases tool tip temperatures that can cause excessive tool wear, thus limiting the highest achievable cutting speeds as well as the useful life of the tool.
- The presence of hard, abrasive intermetallic compounds and carbides in the microstructure of these alloys causes severe abrasive wear on the tool tip.
- The high capacity for work hardening in nickel-base alloys causes depth-of-cut notching (on the tool) that can lead to burr formation on the workpiece.
- The chip produced during machining is tough and continuous, which require acceptable chip control geometry.

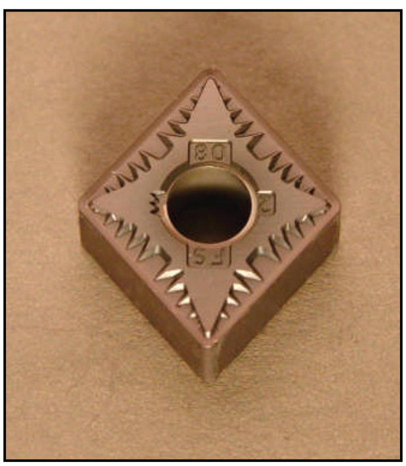
4.2 Field Survey

Based on a field survey, medium machining of aircraft engine parts (nickel-base alloys) is generally done with carbide tools at 180 sfm, 0.008 ipr, and 0.030” doc. For 40% improvement in metal removal rate (MRR), a decision was made to increase the machining speed to 250 sfm while keeping the feed and doc constant (0.008 ipr and 0.030” doc).

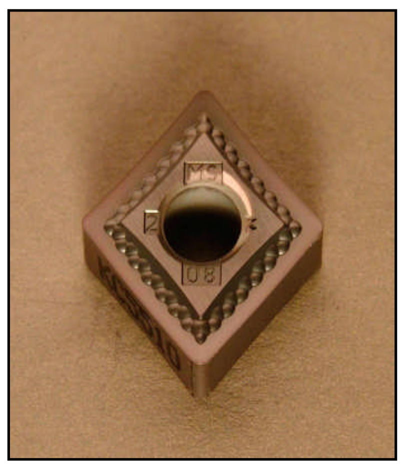
5.0 Benchmark testing

5.1 Benchmark test at 180 sfm

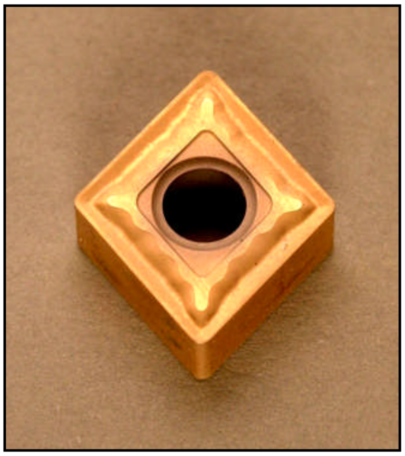
Initial benchmark test was conducted on Inconel 718 at 180 sfm, 0.008 ipr, and 0.030” doc under flood coolant. Six tools were evaluated (Fig. 2):



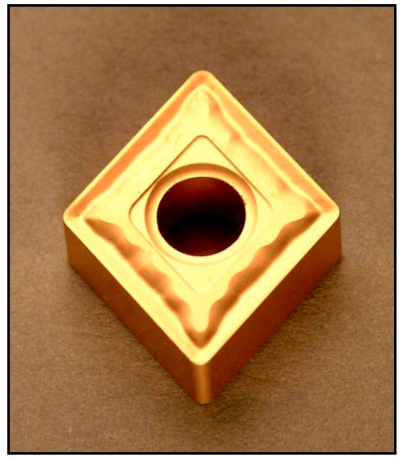
Kennametal KC5510
CNMG432-FS



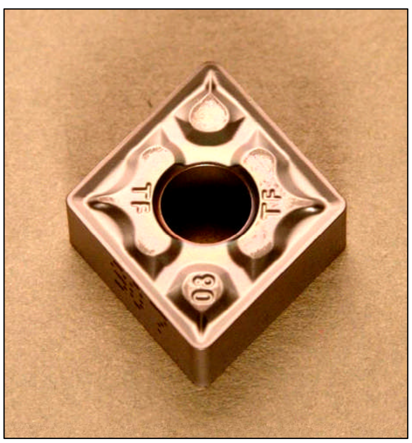
Kennametal KC5510
CNMG432-MS



Sandvik GC1005
CNMG432-QM



Sandvik S05F
CNMG432-QM



Iscar IC907
CNMG432-TF

Greenleaf GA5026
CNGG432-TF

Fig. 2: KMT and competitor tools used for benchmark test at 180 sfm

The results of the metalcutting test at 180 sfm are presented in Table 1. At this condition, S05F (CNMG432-QM) showed the longest tool life (18.1 min) closely followed by Iscar IC907 (CNMG432-TF), Greenleaf GA5026 (CNMG432-TF), and Kennametal KC5510 (CNGG432-FS). The insert failure modes at this speed were depth-of-cut notching (DOCN) or trailing edge wear (TW) or nose wear (NW). Built-Up-Edge (BUE) was observed very early in the test.

Table 1: Results of Benchmark tests at 180 sfm, 0.008 ipr, 0.030" doc

No.	Tool Material	Geometry	Tool Life(min) / Failure Mode			Mean T.L. (minutes)
			Rep 1	Rep 2	Rep 3	
1	KC5510	CNMG432MS	6.3 NW	5.9 NW	4.7 NW	**5.6**
2	GC1005	CNMG432QM	9.2 TW	5.9 TW	Not run	**7.6**
3	S05F	CNMG432QM	19.9 TW	20.0 NW TW	14.4 DOCN	**18.1**
4	IC907	CNMG432TF	9.4 TW	23.9 DOCN	Not run	**16.7**
5	GA5026	CNGG432TF	17.9 TW	12.9 DOCN	17.9 DOCN	**16.3**
6	KC5510	CNGG432FS	17.7 DOCN	13.9 DOCN	14.7 DOCN	**15.4**

5.2. Chip control study

A chip control study was made at 180 and 250 sfm over a range of feed rates (0.006 – 0.012 ipr) and depth-of-cuts (0.030 – 0.060") for all the tool geometries. At 180 sfm, only Kennametal CNGG432-FS geometry exhibited good chip control over the entire range of feed rates and depth of cuts. The minimum feed rate and doc for effective chip control in other geometries is shown in Table 2. Cutting forces were also measured for all geometries. An attempt was made to relate tool life to the resultant cutting force (see Fig. 3). No correlation was observed.

Table 2: The minimum feed rates and doc for effective chip control in KMT and competitor tools

	180 sfm	250 sfm
CNMG432-FS Kennametal	Everywhere	Everywhere
CNMG432-MS Kennametal	0.010 ipr / 0.045"	0.010 ipr / 0.060"
CNGG432-TF Greenleaf	0.008 ipr / 0.045"	0.008 ipr / 0.045"
CNMG432-TF Iscar	0.010 ipr / 0.060"	0.010 ipr / 0.060"
CNMG432-QM Sandvik	0.010 ipr / 0.045"	0.010 ipr / 0.060"

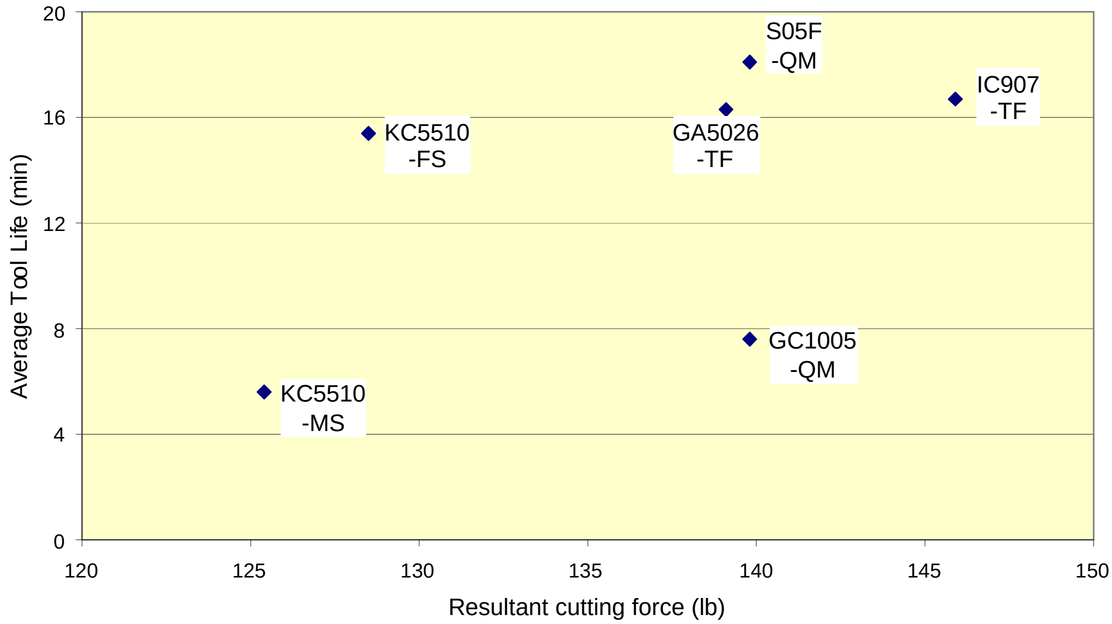


Fig. 3: Cutting force versus Tool life @ 180 sfm, 0.008 ipr, 0.030" doc

5.3 Benchmark test at 250 sfm

A second benchmark test was conducted at 250 sfm, 0.008 ipr, and 0.030" doc under flood coolant.

Table 3: Results of Benchmark tests at 250 sfm, 0.008 ipr, 0.030" doc

No.	Tool Material	Geometry	Tool Life (min) / Failure Mode				Mean T.L. (minutes)
			Rep 1		Rep 2		
1	KC5510	CNMG432MS	3.8	TW	1.9	NW	**2.9**
2	GC1005	CNMG432QM	7.8	CR	3.9	TW	**5.9**
3	S05F	CNMG432QM	8.5	NW	8.9	NW	**8.7**
4	IC907	CNMG432TF	12.1	NW	11.1	NW	**11.6**
5	GA5026	CNGG432TF	8.1	NW	8.8	DOCN	**8.4**
6	KC5510	CNGG432FS	8.4	NW	6.3	NW	**7.3**

The results of the metalcutting test at 250 sfm are presented in Table 3. As expected, tool lives decreased at this higher speed. Iscar IC907 (CNMG432-TF) had the longest tool life (11.6 min), followed by Sandvik S05F (CNMG432-QM), Greenleaf GA5026 (CNGG432-TF), Kennametal KC5510 (CNGG432-FS and CNMG432-MS). The predominant tool failure mode at 250 sfm was nose wear.

A detailed study was undertaken on tool failure mechanisms at 250 sfm. As observed at the lower speed, coating flaking very early in the test caused BUE to occur. As the flowing chip removed the BUE, tool wear occurred more rapidly causing additional build-up and finally nose wear.

5.4 Performance goal

The project goal was set at achieving 40% higher machining productivity with the same tool life as seen with the best available carbide cutting tool under current metalcutting conditions (Fig. 4). In other words, the tool life goal of the advanced cutting tool at 250 sfm is 18 min (based on end-of-life criterion of 0.012" NW) – see Table 1. At 250 sfm, the current market best tool gives a tool life of 11.7 min.

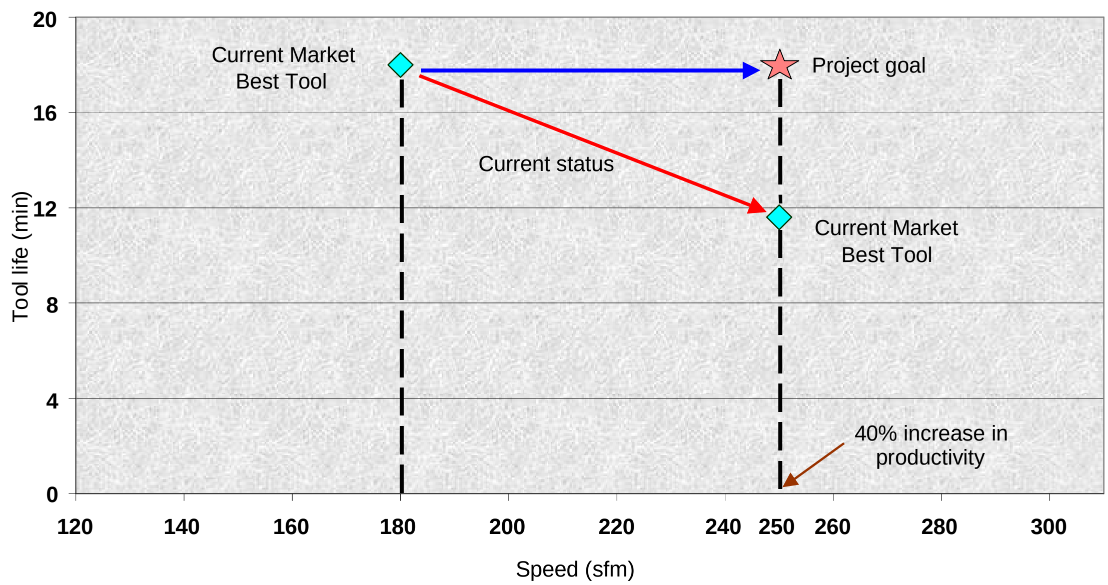


Fig. 4: Schematic representation of project goal

6.0 Product Development

It became clear from benchmark testing that rapid insert nose wear resulting from premature coating flaking limits tool life at 250 sfm. Product development efforts were therefore focused on improving the nose wear resistance and thus the tool life of the cutting tool. Specifically, the effects of micro - and macro - geometries of the tool inserts, substrate changes, and coatings (on tool life) were studied. In addition to standard coatings available from coating vendors, new PVD (Physical Vapor Deposition) and CVD (Chemical Vapor Deposition) nanolayered coatings were evaluated. Several DOE's (Design of Experiment) were designed and executed in a logical sequence:

- Geometry DOE
- Substrate DOE
- Coating DOE

6.1 Geometry DOE

It was believed that the role of insert geometry (both macro- and micro-geometry) in tool performance must first be understood. Accordingly, a geometry DOE test was designed with different chip grooves and hone sizes. A WC-6%Co substrate ("Substrate A") with PVD AlTiN coating was selected for this DOE. Seven tools were evaluated at 250 sfm, 0.008 ipr, and 0.030" doc.

The results of this test are presented in Table 4. As observed in the benchmarking test at 250 sfm, the primary tool failure mode was nose wear. Both macro- and micro-geometry were found to have a profound effect on tool life. The –FS insert showed ~35% improvement in tool life with increase in hone size from 0.0004" to 0.0015". Tool life, however, decreased on the CNGP432 insert from 10.9 min to 7.7 min when the hone size was slightly increased from

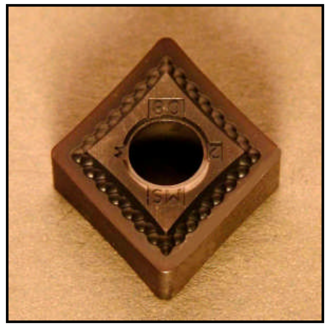
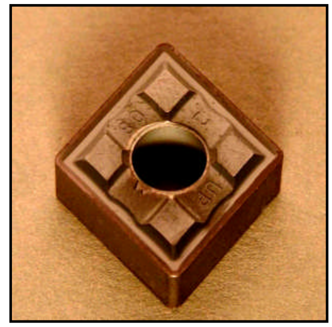
0.0009” to 0.0012”. The CNMG432-MS geometry with 0.0015” hone showed a tool life 10.2 min compared to a tool life of 2.9 min for the same geometry with 0.0006” hone (250 sfm benchmark test). The best tool life (13.1 min) was seen with CNMG432-UP geometry. The longer tool life could be correlated with improved resistance to coating flaking due to insert geometry changes.

Table 4: Results of Geometry DOE test at 250 sfm, 0.008 ipr, 0.030” doc (Substrate A / PVD AlTiN coating)

No.	Tool Micro-geometry	Macro-geometry	Tool Life / Failure Mode						Mean T.L. (minutes)
			Rep 1		Rep 2		Rep 3		
1	0.0004" hone	CNGG432-FS	4.8	NW	7.4	DOCN	6.3	NW	**6.2**
2	0.0015" hone	CNGG432-FS	8.7	NW	8.9	NW	7.6	NW	**8.4**
3	0.0015" hone	CNMG432-MS	11.8	DOCN	10.0	NW	8.9	NW	**10.2**
4	0.0015" hone	CNMG432-LF	9.9	NW	10.9	NW	9.6	NW	**10.1**
5	0.0015" hone	CNMG432-UP	11.1	NW	16.6	NW	11.5	NW	**13.1**
6	0.0004" hone	CNGP432	9.6	NW	11.4	NW	11.9	NW	**10.9**
7	0.0015" hone	CNGP432	7.3	NW	8.1	NW	7.8	NW	**7.7**

6.2 Substrate DOE

Having established the need for larger micro-geometry (hone size), attention was focused on substrate effect. A substrate DOE involving two substrates and two geometries (2x2 matrix) was designed as shown in Figure 5. Substrate A is a WC-6%Co grade with ~1µm carbide grain size. Substrate B is a WC-5.7%Co-2.0%TaC grade with a carbide grain size similar to that of Substrate A. All the test inserts had a nominal hone size of 0.0015”.

Substrate/Coating \ Insert Geometry	CNMG432-MS	CNMG432-UP
A (WC-6%Co) / PVD AlTiN	★	★
B (WC-5.7%Co-2.0%TaC)/ PVD AlTiN	★	★

Fig. 5: Substrate DOE design

Testing was done at 250 sfm, 0.008 ipr, and 0.030” doc. The results are presented in Table 5.

Table 5: Results of the Substrate DOE test at 250 sfm, 0.008 ipr, 0.030” doc

No.	**Tool Material**	**Geometry**	**Tool Life / Failure Mode**			**Mean T.L.** (minutes)
			Rep 1	**Rep 2**	**Rep 3**	
1	Substrate A / PVD AlTiN	CNMG432-MS	12.8 NW	9.6 NW	9.2 MW	**10.5**
2	Substrate B / PVD AlTiN	CNMG432-MS	17.1 NW	19.1 NW	12.3 NW	**16.2**
3	Substrate A / PVD AlTiN	CNMG432-UP	12.7 NW	16.2 NW	13.9 NW	**14.3**
4	Substrate B / PVD AlTiN	CNMG432-UP	15.0 NW	14.1 NW	16.0 NW	**15.1**

It can be seen from Table 5 that for both geometries (-MS and –UP), substrate B provides longer tool life than substrate A. The tool life improvement is greater for the –MS geometry than for the –UP geometry. Figure 6 shows nose wear as a function of time for all the four tools in Rep. 3. It is interesting to note that the initial part of the wear curves for all the four tools is similar. At least for the –MS geometry, once the coating wears through, there is a significant difference in the rate of progress of the nose wear between the two substrates, with substrate B showing greater resistance to wear progression.

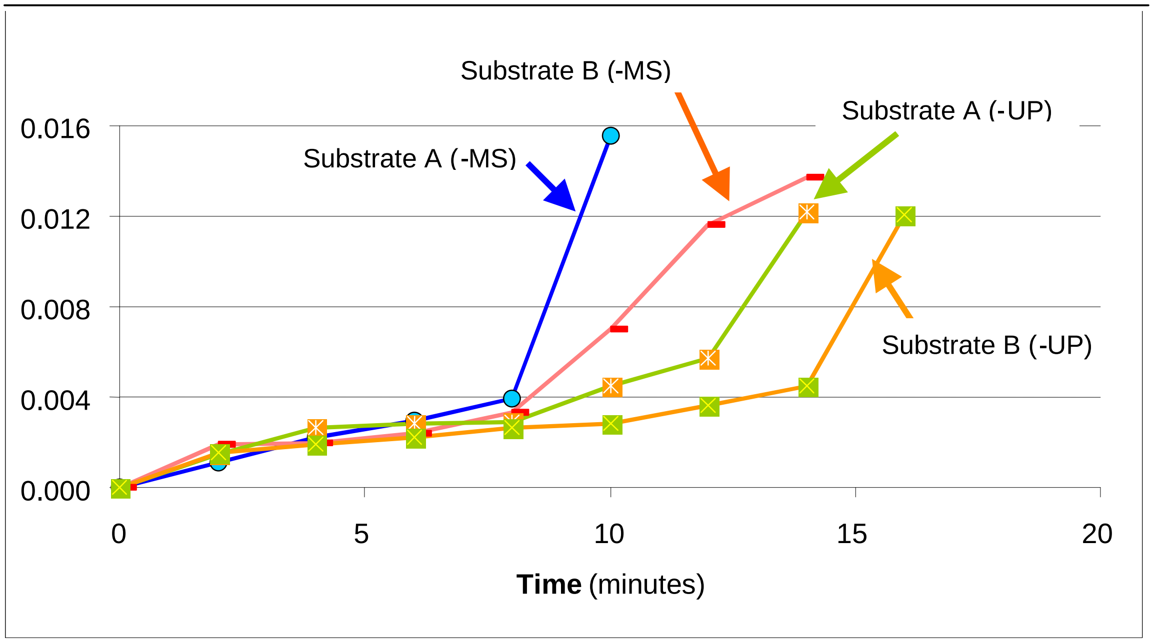


Fig. 6: Nose Wear Vs. Time for Rep 3 in Substrate DOE Test

6.3 Coating DOE

The experiments conducted so far used the current best in-house PVD coating (i.e. AlTiN). It was of interest to evaluate other PVD coatings from outside coating vendors as well as newer PVD and CVD technologies developed in Kennametal.

6.3.1 Nanolayered PVD coating

The nano PVD coating for this application was made by co-deposition of Ti, Al-based compounds. This mixing of several compounds, on a very fine scale, has a synergistic effect on the coating, providing improved oxidation resistance and higher Microhardness (2600-2800 Kg/mm^2) vs. 2200 Kg/mm^2 for standard PVD TiN and 2400 Kg/mm^2 for PVD TiAlN coating.

6.3.2 Nanolayered CVD coating

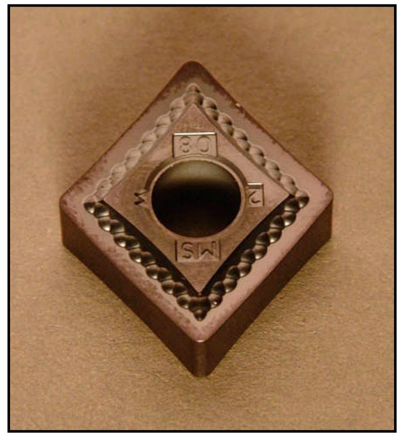
Nanolayered CVD coatings with TiCN and TiN compositions had been developed in Kennametal to achieve enhanced abrasive wear resistance, edge toughness, build-up-edge resistance, and excellent adhesion to the cemented carbide substrate. Multiple nanolayers were deposited based on TiN and TiCN compositions using a conventional CVD reactor. Very fine grain structures of the coatings could be achieved by a judicious control of coating process parameters. The average thickness target for the TiN-TiCN coated inserts used in this study was 3 µm.

6.3.3 Coating DOE1

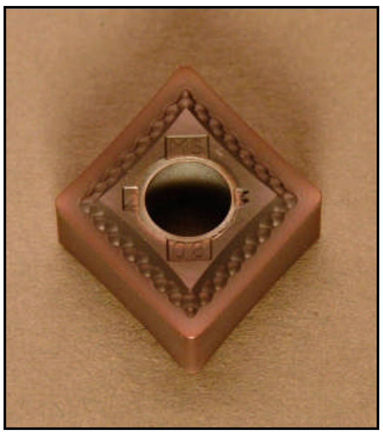
The first coating DOE consisted of eight candidates (Fig. 7):

1. PVD AlTiN (~3 µm)
2. PVD AlTiN post-coat treated (~3 µm)
3. Nano PVD (Al,Ti)N (~3 µm)
4. PVD Alox SN2 (~6 µm)
5. PVD TiNAlox SN2 (~3 µm)
6. PVD Alcrona (~3 µm)
7. Nano CVD TiN/TiCN/… (~3 µm)
8. PVD TiB_2 (~2 µm)

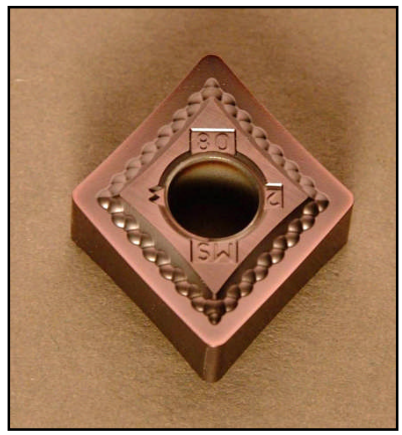
PVD AlTiN



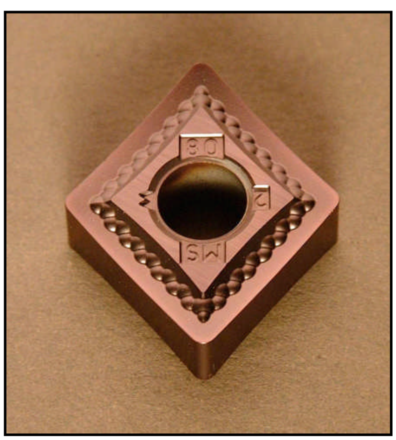
PVD AlTiN post-coat treated



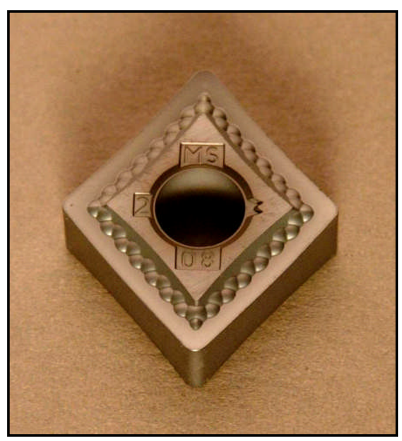
Nano PVD (Al,Ti)N



Alox SN2



TiNAlox SN2



Alcrona

Nano CVD TiN/TiCN/….

PVD TiB_2

Fig. 7: Candidates used in Coating DOE

The above coatings were deposited on Substrate B (CNMG432-MS inserts). In addition to the above candidates, four controls were used: S05F (-QM), IC907 (-TF), GA5026 (-TF), and KC5510 (-MS). The inserts were evaluated at 250 sfm, 0.008 ipr, and 0.030” doc. The metalcutting results are presented in Table 6.

Table 6: Results of Coating DOE1 test at 250 sfm, 0.008 ipr, 0.030” doc

No.	Tool Material	Geometry	Tool Life / Failure Mode			Mean T.L. (minutes)
			Rep 1	Rep 2	Rep 3	
1	Substrate B / AlTiN	CNMG432-MS	13.9 NW	16.8 NW	16.8 NW	15.8
2	"B"/ AlTiN Post-coat treated	CNMG432-MS	17.0 NW	18.9 CR	12.2 NW	16.1
3	"B"/ Nano PVD (Al,Ti) N	CNMG432-MS	13.5 NW	19.5 TW	16.7 NW	16.6
4	"B"/ Alox SN2	CNMG432-MS	-	15.3 NW	14.5 NW	14.9
5	"B"/ TiNAlox SN2	CNMG432-MS	-	14.0 NW	15.8 NW	14.9
6	"B"/ Alcrona	CNMG432-MS	4.4 NW	4.4 NW	4.5 NW	4.4
7	"B"/ Nano CVD TiN/TiCN/..	CNMG432-MS	9.6 NW	7.1 NW	7.7 NW	8.2
8	"B"/ TiB_2	CNMG432-MS	1.2 NW	1.1 NW	-	1.1
9	KC5510 (0.001" hone)	CNMG432-MS	6.9 NW	5.0 NW	7.8 NW	6.6
10	Sandvik S05F	CNMG432-QM	9.1 NW	7.6 NW	7.4 NW	8.0
11	Iscar IC907	CNMG432-TF	12.9 NW	13.2 NW	13.9 NW	13.3
12	Greenleaf GA5026	CNGG432-TF	9.9 NW	12.6 NW	10.3 NW	10.9

It can be seen from Table 6 that none of the new coating candidates showed significant tool life improvement over the standard PVD AlTiN coating for CNMG432-MS inserts (substrate "B") at 250 sfm. The nano PVD coating shows some promise with the best mean tool life of 16.6 min. In the second rep it showed a tool life of 19.5 min indicating the potential of this coating. The TiB_2 coating is ineffective in this application. The nose wear curves for Rep 2 are given in Fig. 8. Note the significant difference in nose wear rates among the coatings. This is probably related either to the reactivity of the coating to the workpiece and/or to differences in their flaking tendency.

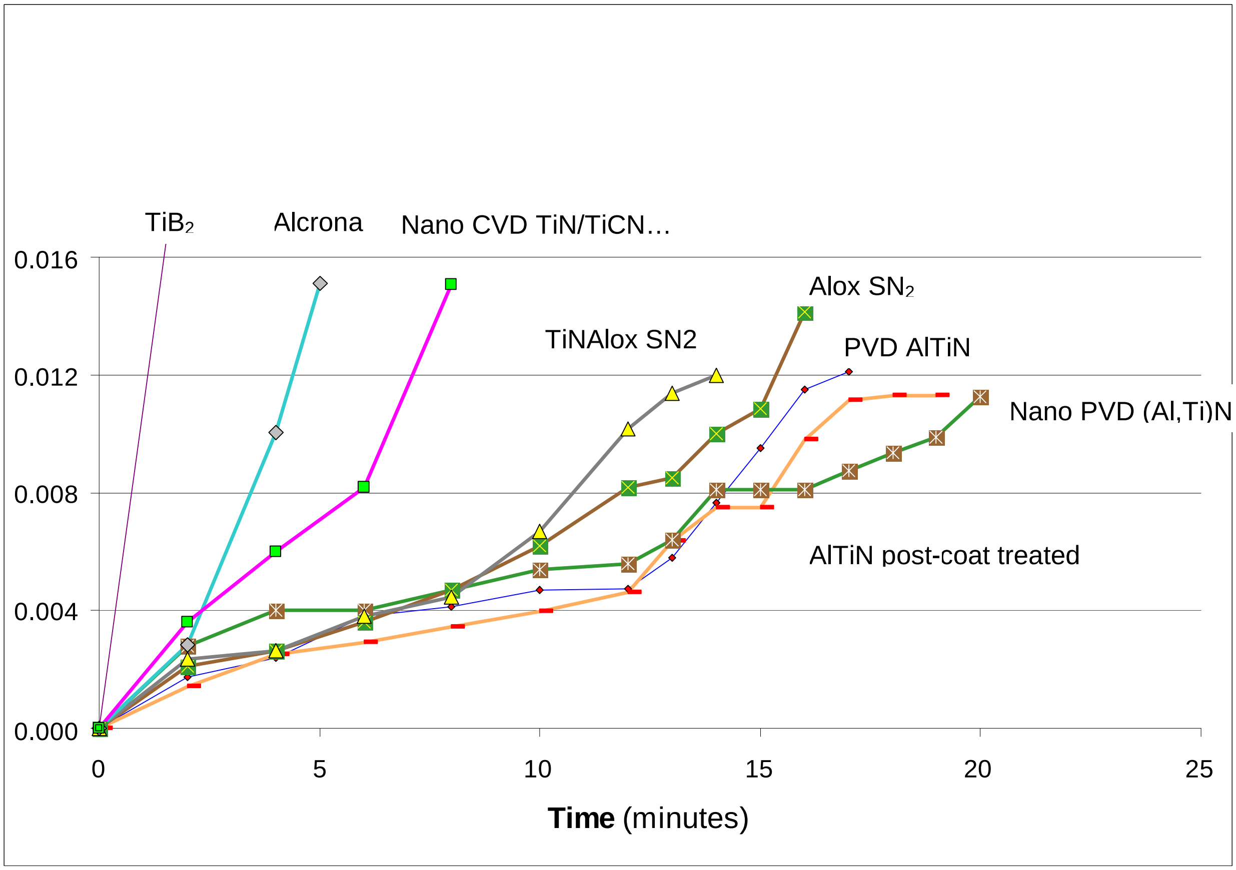


Fig. 8: Nose Wear Vs. Time for Rep 2 in Coating DOE1 Test

6.3.4 Coating DOE2

The second coating DOE was applied to substrate A (CNMG432-MS inserts). The TiB_2 was dropped due to its poor showing in coating DOE1. Also, only IC907 (-TF) was kept as a control because of its superior performance among the competitor grades. The metalcutting data are presented in Table 7.

Table 7: Results of Coating DOE2 test at 250 sfm, 0.008 ipr, 0.030" doc

No.	Tool Material	Geometry	Tool Life / Failure Mode						Mean T.L. (minutes)
			Rep 1		Rep 2		Rep 3		
1	Substrate "A"/ AlTiN	CNMG432-MS	10.0	NW	10.4	NW	5.9	MW	**8.7**
2	"A" / AlTiN Post-coat treated	CNMG432-MS	11.8	NW	9.4	NW	8.9	MW NW	**10.0**
3	"A" / Nano PVD (Al,Ti) N	CNMG432-MS	17.5	NW	18.0	NW	17.3	NW	**17.6**
4	"A" / Alox SN2	CNMG432-MS	9.8	NW	11.7	NW	10.9	NW	**10.8**
5	"A" / TiNAlox SN2	CNMG432-MS	13.4	NW	12.8	NW	11.6	NW	**12.6**
6	"A" / Alcrona	CNMG432-MS	4.3	NW	3.1	NW	3.3	NW	**3.5**
7	"A" / Nano CVD TiN/TiCN/..	CNMG432-MS	8.2	NW	7.1	NW	7.2	NW	**7.5**
8	Iscar IC907	CNMG432-TF	11.9	NW	9.9	CR	13.1	NW	**11.6**

The mean tool lives in this test are lower than those observed in Coating DOE1, reflecting the role of substrate differences. The only exception is the nano PVD coating that is showing longer mean tool life (17.6 min vs. 16.6 min in DOE1). The Alcrona coating continues to show poor performance and will dropped from further consideration. The nano CVD coated tool will also be dropped in future tests. The associated nose wear curves for Rep 1 of this test are given in Fig. 9.

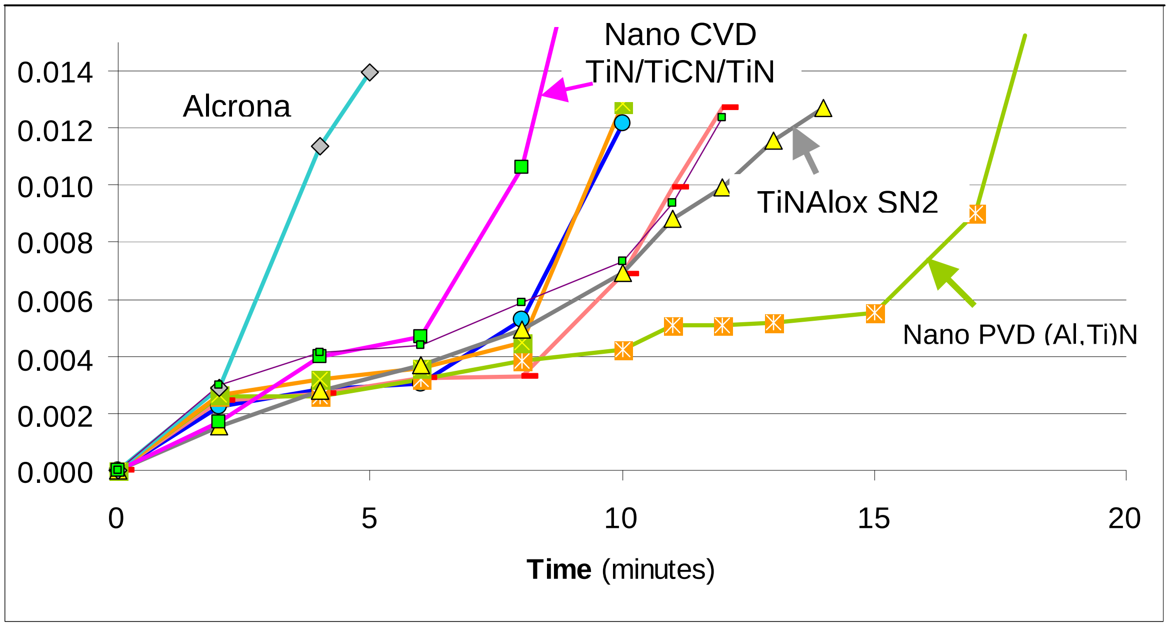


Fig. 9: Nose Wear Vs. Time for Rep 1 in Coating DOE2 Test

6.3.5 Coating DOE3

The third coating DOE was applied to substrate B (CNMG432-UP inserts). As discussed before, only five internal candidates and Iscar IC907 were evaluated in this test. The metalcutting data are presented in Table 8.

Table 8: Results of Coating DOE3 test at 250 sfm, 0.008 ipr, 0.030" doc

No.	Tool Material	Geometry	Tool Life / Failure Mode						Mean T.L. (minutes)
			Rep 1		Rep 2		Rep 3		
1	Substrate "B" / AlTiN	CNMG432-UP	18.2	NW	13.6	NW	16.9	NW	**16.2**
2	"B" / AlTiN Post-coat treated	CNMG432-UP	15.0	NW	15.6	NW	14.5	NW	**15.0**
3	"B" / Nano PVD (Al,Ti) N	CNMG432-UP	11.6	TW	9.8	NW	11.9	NW	**11.1**
4	"B" / Alox SN2	CNMG432-UP	13.5	NW	13.6	NW	13.9	NW	**13.7**
5	"B" / TiNAlox SN2	CNMG432-UP	10.7	NW	10.4	NW	12.6	NW	**11.2**
6	Iscar IC907	CNMG432-TF	11.4	NW	12.9	NW	9.9	NW	**11.4**

In this test, substrate "B" with the AlTiN coating had the best tool life. Post-coat treatment of AlTiN coating had no positive effect on tool performance. The poor performance of the Nano PVD (Al,Ti)N coating in this test is probably a result of poor hone shapes on these –UP inserts. Other PVD coatings also fared worse than PVD AlTiN. The tool wear curves are shown in Fig. 10.

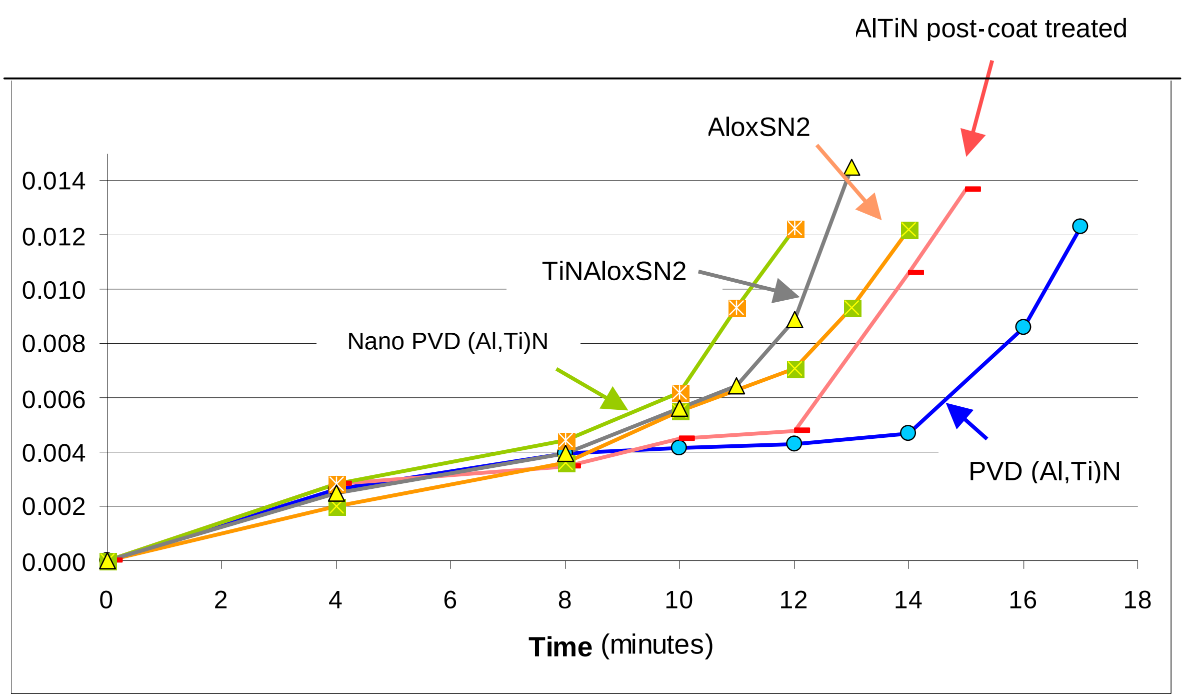


Fig. 10: Nose Wear Vs. Time for Rep 3 in Coating DOE3 Test

6.3.6 Coating DOE4

CNMG432-UP inserts in substrate A were used for the fourth coating DOE. As in Coating DOE3, five internal candidates and Iscar IC907 were evaluated in this test. The metalcutting data are presented in Table 9. In this test, the post-coat treatment improved the mean tool life by 20% over the untreated insert and it showed the best tool life. Again, Nano PVD (Al,Ti)N coated inserts had poor hone shapes. The associated wear plots are given in Fig. 11.

Table 9: Results of Coating DOE4 test at 250 sfm, 0.008 ipr, 0.030" doc

No.	Tool Material	Geometry	Tool Life / Failure Mode		Mean T.L. (minutes)
			Rep 1	Rep 2	
1	Substrate "A" / AlTiN	CNMG432-UP	12.9 NW	13.0 NW	12.9
2	"A" / AlTiN Post-coat treated	CNMG432-UP	17.1 NW	13.9 NW	15.5
3	"A" / Nano PVD (Al,Ti) N	CNMG432-UP	13.8 NW	14.0 NW	13.9
4	"A" / Alox SN2	CNMG432-UP	11.1 NW	11.6 NW	11.4
5	"A" / TiNAlox SN2	CNMG432-UP	8.9 NW	5.9 NW	7.4
6	Iscar IC907	CNMG432-TF	13.0 NW	11.8 NW	12.4

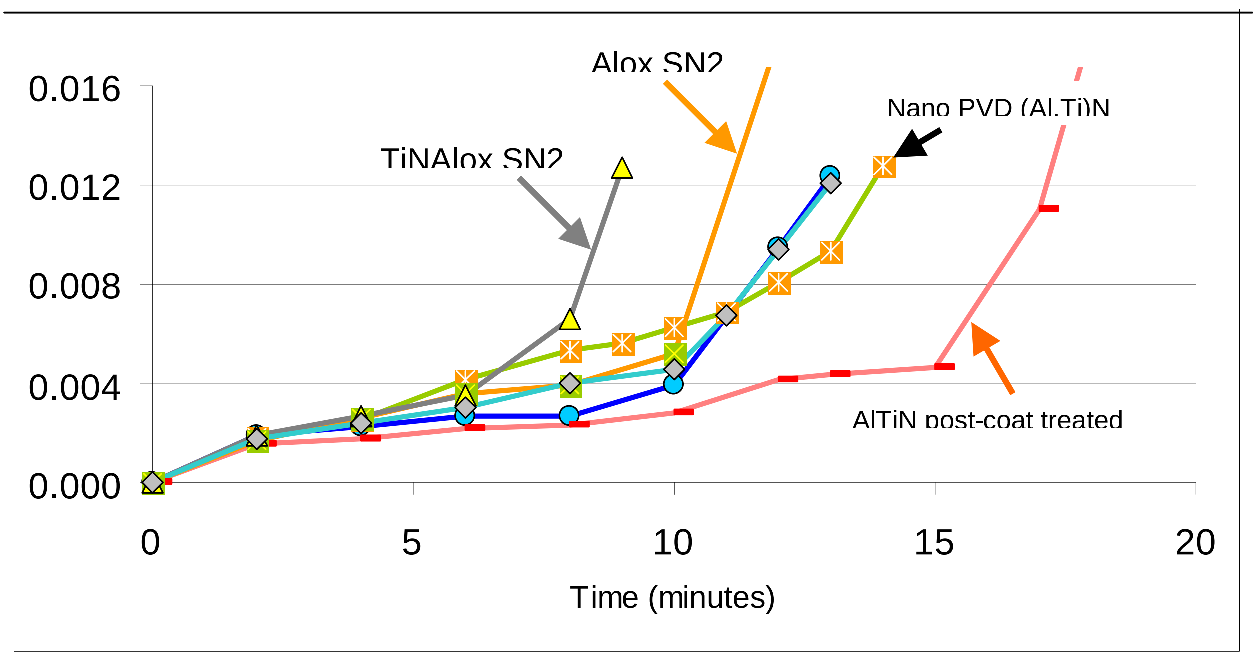


Fig. 11: Nose Wear Vs. Time for Rep 1 in Coating DOE4 Test

6.4 Progress towards tool life goal

The progress towards the project tool life goal is shown as a bar chart in Figure 12. The best mean tool life of 17.6 min (98% of tool life goal) was seen with CNMG432-MS insert on substrate A, a large hone size (0.0017”), and Nano PVD (Al,Ti)N coating. This is six times longer than the current KC5510 insert (-MS) with a nominal hone size of 0.0006”. Closely following this candidate are the –MS and –UP inserts in substrate B and AlTiN or Nano PVD (Al,Ti)N coating. They show tool lives within 10% of the top performer.

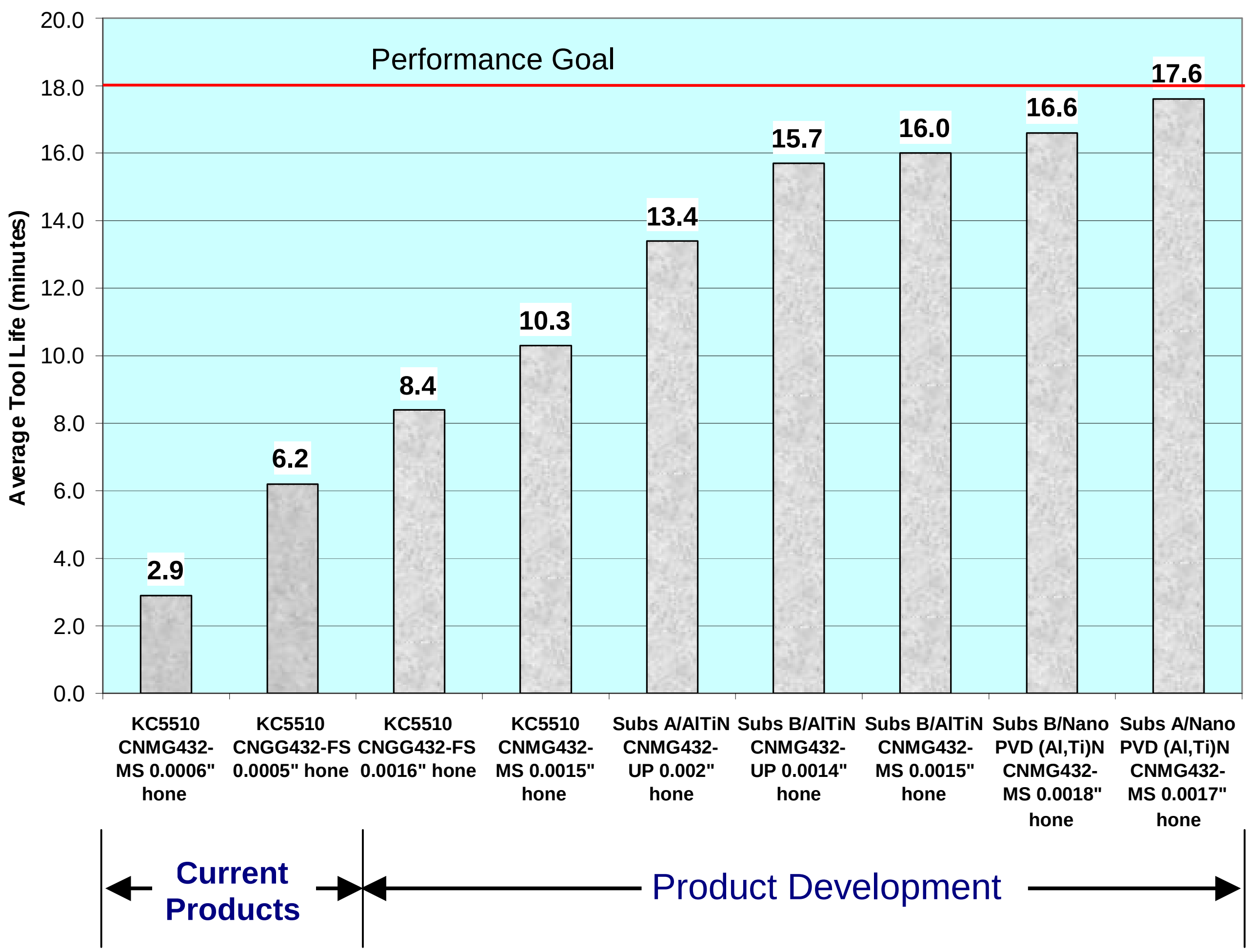


Fig. 12: Progress towards tool life goal at 250 sfm, 0.008 ipr, 0.030” doc

6.5 Additional metalcutting tests

Additional metalcutting tests were performed on CNMG432-MS and CNMG432-UP inserts in substrate B with PVD AlTiN coating over a range of metalcutting conditions (150-300 sfm, 0.008-0.010 ipr, and 0.030-0.060" doc). The inserts had a nominal hone size of 0.0015". The results presented in Table 10 show the superiority of the CNMG432-UP over the CNMG432-MS insert in Inconel 718 turning under the conditions investigated.

Table 10: A comparison of the performance of CNMG432-MS and CNMG432-UP insert (Substrate B) in Inconel 718 turning

Metalcutting conditions			Average Tool Life (minutes)	
sfm	ipr	doc (in)	Substrate B / PVD AlTiN	
			CNMG432-MS	CNMG432-UP
150	0.008	0.030	23.5	32.1
250	0.008	0.030	15.8	16.2
300	0.008	0.030	6.6	7.2
200	0.010	0.030	12.2	17.1
150	0.008	0.060	5.5	14.5
250	0.008	0.060	3.5	4.4

7.0 Summary

- The project goal of 40% higher productivity with acceptable tool life in Inconel 718 turning has been achieved through carefully planned and executed DOE's (Design of Experiments) involving changes in substrates, insert macro- and micro-geometries, and nano CVD and PVD coatings.
- We have identified optimum design features of the insert (substrate, macro- and micro-geometry, and coating) to maximize performance in general purpose turning of Inconel 718.
- Substrate and geometry (both macro- and micro-) had the greatest impact on tool life. Additional performance enhancement could be obtained through choice of coating.
- The best mean tool life at 250 sfm, 0.008 ipr, 0.030" doc was achieved with a CNMG432-MS style insert made from a straight WC-6%Co grade (substrate A) and a Nano-PVD (Al,Ti)N coating. However, the AlTiN coated –UP and –MS inserts in substrate B also showed tool lives within 10% of the Nano PVD (Al,Ti)N coated inserts.
- With PVD AlTiN coating, substrate B (WC-5.7%Co-2%TaC) was superior to substrate A (WC-6%Co) [see Table 5] and the –UP geometry was superior to –MS geometry [see Table 10].
- A direct correlation was obtained between hone size and tool life with 0.0015" as the preferred nominal hone size.
- Future effort may be targeted at optimizing nano PVD and CVD coatings for nickel-base alloy machining.

8.0 Acknowledgement

The author gratefully acknowledges the contribution of the project team members and that of the members of the Materials Analysis and Global Machining Technology departments. Doug Moore of the Kennametal Knowledge Center assisted with the photography of the test inserts.