Project no: **FP6-017883**

Project acronym: **MATINA**

Project title: **INNOVATIVE PVD NANO-COATINGS ON TOOLS FOR MACHINING TITANIUM AND NICKEL ALLOYS**

Instrument: **HORIZONTAL RESEARCH ACTIVITIES INVOLVING SMES.**

Thematic Priority: **CO-OPERATIVE RESEARCH**

FINAL ACTIVITY REPORT

Period covered: from: **25th July 2005 to 24th July 2007**
Date of preparation: **28th September 2007**

Start date of project: **25th July 2005** Duration: **24 months**

Project coordinator name: **Alberto García_Luis**
Project coordinator organisation name: **INASMET-Tecnalia** Revision [1]

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	X

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1. PROJECT EXECUTION

The aim of this project is the substantial improvement of **cutting tools** for the machining of **nickel** and **titanium** alloys. These alloys present several problems during machining operations, and as a result today there are important restrictions regarding tool performance that limit the economy and quality of the final parts. The most important fact when machining nickel and titanium alloys is the tendency to work harden, due to the localized overheating, and stick or adhere to the cutting tool surface. Therefore, tools with sharp edges, to avoid deforming the material before cutting it, with a very good surface finish and low chemical affinity are required, as any surface defect may cause the material to adhere to the tool.

The application of selected **PVD nano-structured coatings** with a thickness of less than 1μm can improve the life of Ni and Ti cutting tools without worsening at all tool sharpness. It will make it possible that the nickel and titanium machining benefit from a technology that has already been successfully applied (micro-coatings) to machining other materials, i.e. steel alloys, but has show little if any improvement in Ni and Ti. A good selection of PVD nano-structured coatings can decrease friction, which will result in a reduction of the overheating risk, allowing higher machining speeds or even avoiding the use of lubricant. Furthermore, a hard nano-structured coating with a nano-thickness ($<1\mu m$) can be applied to the tool maintaining its surface finishing and sharpness, thus delaying the presence of local wear defects; this will reduce material sticking and increase tool life.

This can be translated in the main industrial and economic objective of the project:

- ☑ Reduction in more than **20%** of the **costs** of the parts machined with the tools that have been coated. In this case the cost of the tool coating will be estimated considering an already industrialized coating service.

This general objective can be reached by the achievement of the following technical objectives:

- ☑ Increase of **100% in cutting speed** for machining of titanium and nickel alloys
- ☑ Increase of **40% in lifetime** of selected tools for machining of titanium and nickel alloys
- ☑ Reduction in more than **50%** of the **amount of lubricant** needed in these two machining processes

The success of the project, with the achievement of these objectives, depends on the final quality and properties of the new PVD nanostructured coatings. Therefore, it has been proposed a list of target properties for these coatings to follow-up the technical progress during the intermediate phases of the project where the development of these coatings is carried out.

The target properties of the coating to be developed and the effect on cutting tools are summarized in the following table:

Target coating properties		Effect on cutting tool
Hardness (GPa)	>40	• Increase wear resistance
Thickness (µm)	<1	• Tool sharpness stays unchanged
Adhesion to the substrate Critical load (N)	>60	• Increase tool life
Substrate roughness reproducibility (%)	95	• Decrease friction • Tool sharpness stays unchanged • Decrease metal affinity
Friction coefficient	< 0.4	• Decrease friction • Lower bearing forces at cutting edge • Lower amount of coolant needed
Max. Usage temperature (ºC)	>1100 ºC	• Increase tool life • Avoid tempering on cutting tool
Chemical reactivity with Ti and Ni alloys	Low	• Decrease metal affinity • Decrease in galling, welding, smearing

The partners involved in this project are the following:

Partic. Role[1]	Partic. Type[2]	Partic. Nº.	Participant name	Participant short name	Country
CO	RTD	1	FUNDACION INASMET	INAS	E
CR	SMEP	2	TESSCENTER S.L.	TESS	E
CR	SMEP	3	CEMECON AG	CEM	D
CR	SMEP	4	BRØDRENE JOHNSEN AS	BRJ	NO
CR	SMEP	5	DESARROLLOS MECÁNICOS DE PRECISIÓN S.L.	DMP	E
CR	SMEP	6	MORFOMICHANIKI LTD	MORFO	CY
CR	RTD	7	ARISTOTELES UNIVERSITY OF	EEDM	EL

[1] CO=Coordinator; CR= Contractor
[2] SMEP; RTD; OTH

			THESALONIKI (RC).		

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The main results obtained in the project could be summarised as follows:

- The milling of Ti-6Al-4V alloy and Inconel 718 alloy was selected as the machining process to be studied in the framework of this project.

- The cutting tools to be studied and tested are mills manufactured by Tesscenter. Tesscenter has provided uncoated mills and mills coated with standard coatings.
- At a lab scale inserts (with two different wedge radius) are being used in the machining tests with the new developed coatings.

- BRJ has defined a complex part in Inconel 718 to be machined and used as demonstrator.

- DMP has defined a complex part in Ti-6Al-4V to be machined and used as demonstrator (see Fig. 1).

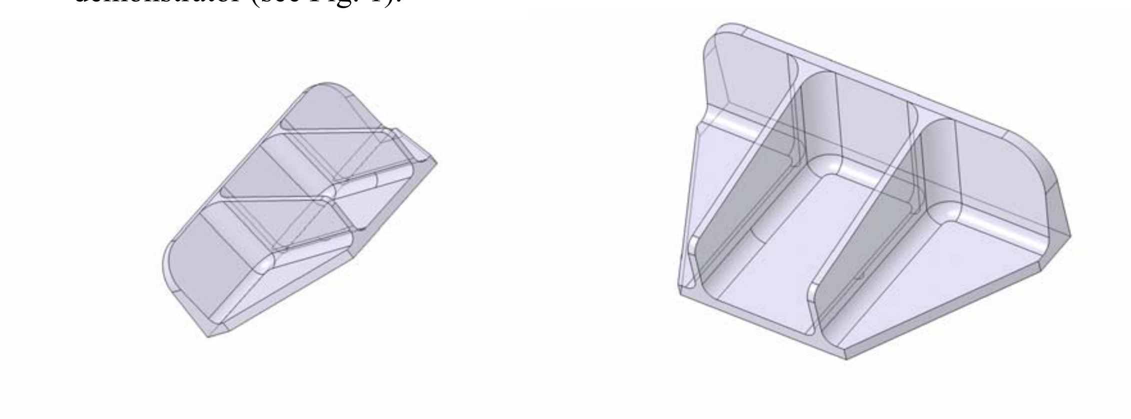

Fig 1: Ti6Al4V demonstrator defined by DMP

- Inasmet has designed new coatings based on CrAlXN where X is a doping element . Inasmet has worked in the development of nano-structured coatings of CrAlZrN, CrAlYN and CrAlBN

- Different deposition parameters has been analysed as the influence of the target doping power, process temperature, nitrogen partial pressure. Inasmet has optimised the coating synthesis and has selected the following coatings to be applied on the tools to perform the machining tests:

Table I: Properties of the coatings selected to be applied on the cutting tools

	Cr-Al-N	Cr-Al-Zr-N	Cr-Al-Y-N
HU (GPa)	30.3	32.9	32.3
Hpl (GPa)	29.2	33.5	45.7
Elastic work (%)	73	74.2	92.1
Residual stress (GPa)	-0.07	-0.24	-0.46
Critical load (N)	44	44.7	53 N
Oxidation resistance (°C)	900	900	700
Friction coef. vs. steel[3]	0,54	0,55	0,49
Friction coef. vs. Ti[4]	0,58	0,58	0,57
Cristal size (nm)	6.6	6.9	6.4
Al content (% at.)	12	5.8	8.4
Dopant content (%)	0	2.6	0.73

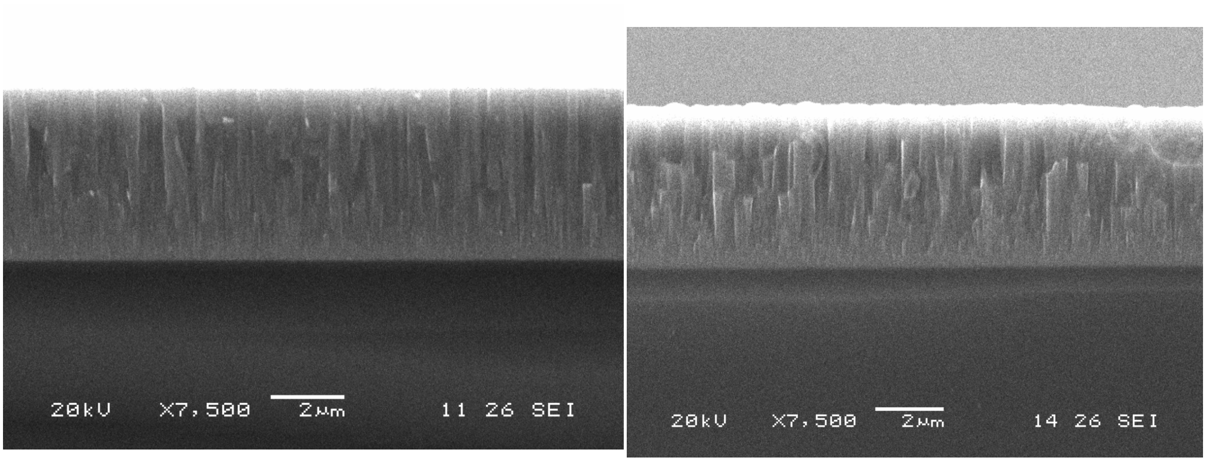

Fig. 2 : SEM photograph (x7500) of the cross-section of CrAlZrN coating(left) and CrAlYN coating (right)

- CEM has coated some inserts with their standard coatings as Tinalox and Supernitride in other to have another reference.

- EEDM has performed a large amount of machining tests at a lab scale with the coated inserts with two different wedge radius (5 and 30 microns). The main tests performed were:
  - Determination of stress-strain curves of the applied coatings
  - Impact tests of the applied coatings at elevated temperatures
  - Cutting performance evaluation of coated tools in milling Inconel 718
  - Cutting performance evaluation of coated tools in milling Ti6Al4V

The coatings applied on the inserts that EEDM studied were:

[3] Ball material: AISI 52100 steel, ball diameter=10mm, load=100 g, lineal speed=0.1m/s, RH=50%, 1hour,
[4] Ball material: Ti-6Al-4V, ball diameter=6mm, angular speed=75rpm, load= 1680 g, 20 min

- TiN/TiAlN (applied by Tesscenter)
- Tinalox (applied by CemeCon)
- SN (applied by CemeCon)
- CrAlN (applied by Inasmet)
- CrAlZrN (applied by Inasmet)
- CrAlYN (applied by Inasmet)

<u>Some highlights from the impact tests at elevated temperatures:</u>
From the impact tests it was determined the coating resistance vs. the temperature. There were observed different coating behavior depending on the temperature range. For temperatures lower than 60ºC the best coating impact performance was observed for the TiN/TiAlN followed by the CrAlN>SN>Tinalox. In the range temperature of 300 ºC to 600 ºC the coating impact resistance ranking was CrAlN>TiN/TiAlN>SN>Tinalox.
For the temperature range from 60 to 300 ºC , it is not possible to establish a general coating resistance ranking.

<u>Cutting performance evaluation of coated tools in milling Inconel 718</u>:
The flank wear evolution of TiN/TiAlN coated tools (K05-K20) at various undeformed chip lengths was studied (v=26 m/min, αz= 2mm, hcu=0.06 mm, α/κ/γ=11/75/0º). A flank wear of 0,2 mm was observed for 1750 cuts when the chip length (Icu) was 3.2 mm, 1250 cuts for Icu=4.6 mm, 600 cuts for Icu=7.3 mm and 230 cuts for Icu=15.8 mm.
The flank wear evolution at different feed rates (hcu=0.06 mm and hcu=0.12 mm) was studied for the Tinalox, SN and TiN/TiAlN (v=26 m/min, αz= 2mm, αxy=0.2 mm, α/κ/γ=11/75/0º). In both cases the wear resistance ranking was TiAlN/TiN>SN>Tinalox.
For these coatings the flank wear evolution at different speeds was evaluated (hcu=0.06mm, αz= 2mm, αxy=0.04 mm, α/κ/γ=11/75/0º):

- For vc=15m/min → TiN/TiAlN>Tinalox >SN
- For vc=26 m/min→SN>Tinalox>TiN/TiAlN
- For vc=35m/min → TiN/TiAlN>Tinalox >SN

A correlation was found for the results of the cutting performance of the coating tools and the impact force tests.
In the machining tests with inserts in milling Inconel 718 with inserts coated with CrAlN, CrAlYN, CrAlZrN at different cutting speeds and comparing the results with the impact test. The tests parameters were ρ=30 μm (hcu=0.096mm, αz= 2mm, αxy=0.2 mm, Icu=4.65 mm α/κ/γ=11/75/0º) and the number of cuts when flank wear reached the 0,2 mm was recorded for the different cutting speeds. The coatings are classified as a function of the number of cuts:

- vc=15 m/min: CrAlYN> CrAlN>CrAlZrN
- vc =25 m/min: CrAlYN> CrAlN>CrAlZrN
- vc =35 m/min: CrAlN>CrAlZrN>CrAlYN

They also evaluated these coatings when milling Inconel at different cutting speeds (vc=50,100, 200 m/min). But in this case the coatings always show the same tendency.
<u>TiN/TiAlN>CrAlYN>SN>Tinalox>CrAlN>CrAlZrN</u>
These data were validated in end-mills.

Cutting performance evaluation of coated tools in milling Ti6Al4V:

The cutting performance at different speeds was evaluated (hcu=0.12mm, αz= 2mm, αxy=0.02 mm, α/κ/γ=11/75/0º):

- For vc=50 m/min → TiN/TiAlN>CrAlN>SN
- For vc=100 m/min→ TiN/TiAlN>CrAlN>SN
- For vc=200 m/min → TiN/TiAlN>CrAlN>SN

For the CrAlN family (CrAlN, CrAlZrN and CrAlYN) coatings the flank wear evolution was evaluated for inserts with different radius ρ=5 µm and ρ=30 µm (**vc=100 m/min** hcu=0.12mm, αz= 2mm, αxy=0.2 mm, Icu=5.27 mm α/κ/γ=11/75/0º): For the tools with a radius of ρ=5 µm the ranking of number of cuts performed up to a flank wear of 0,2 mm is CrAlZrN >CrAlN>CrAlYN. On the other hand the ranking for the tools with ρ=30 µm was the following: CrAlYN>CrAlN>CrAlZrN.

When we compared all the coatings with the same cutting parameters when milling Ti6Al4V the cutting performance was:

- vc=100 m/min hcu=0.12mm, αz= 2mm, αxy=0.2 mm, **Icu=5.27 mm** α/κ/γ=11/**75**/0º):
TiN/TiAlN>CrAlYN>CrAlN>SN>CrAlZrN
- vc=100 m/min hcu=0.12mm, αz= 2mm, αxy=0.2 mm, **Icu=4.11 mm** α/κ/γ=11/**90**/0º):
TiN/TiAlN>CrAlYN> SN >Tinalox>CrAlN> >CrAlZrN

- BRJ has performed machining tests on Inconel 718 and DMP on Ti6Al4V with mills coated with the developed coatings and the reference one to machine the demonstrators already defined in the project

- MORFO has performed machining tests in Ti6Al4V with the mills coated with the developed coatings and the reference one.

- In the industrial machining tests it was found a decrease of 4 % in the machining costs when using the CrAlN coating for machining Ti6Al4V and a decrease of 30% when machining Inconel.

- CEM worked in the scaling-up process of the CrAlN coating successfully. The properties achieved in the up-scaled coating were the same as the original one.

Table II: Comparison of the coating properties produced at a lab and at an industrial scale

	CrAlN (Inasmet)	CrAlN (CemeCon)
Thickness (µm)	5,7	5,7
Substrate	AISI M2 steel	AISI M2 steel
HU (GPa)[5]	30,3	31,22
Hpl (GPa)	29,2	31,5
Elastic work (%)	73	72
E* (GPa)	304	223
Critical load (N)	44	39
µ vs. steel[6]	0,54	0,57
µ vs. Ti[7]	0,58	0,55

[5] Fischescope H100, max. load 10mN, 40 steps, loading-unloading
[6] Ball material: AISI 52100 steel, ball diameter=10mm, load=100 g, lineal speed=0.1m/s, RH=50%, 1hour,

[7] Ball material: Ti-6Al-4V, ball diameter=6mm, angular speed=75rpm, load= 1680 g, 20 min

2. DISSEMINATION AND USE

INASMET and EEDM will play an important role in the **dissemination** of the new coatings and machining processes. They will take advantage of their multiple industrial connections, and during the Exploitation phase they will promote and apply the new treatments for selected companies, that do not conflict with the Consortium, and will allow an increase in the market share and the finding of new application niches. From a marketing point of view, the dissemination of the results will be addressed towards the following sectors:

- Aeronautics (mainly aircraft frame and structures manufacturing)
- Machine shops
- Tool manufacturers
- Machine tools manufacturers
- Other sectors that manufacture titanium parts: biomedicine, automotive, etc.

Dissemination is planned to be done by means of:

- ***Workshops*** that will be held at the countries in the project with participation of RTD and Industrial partners. Companies in the area belonging to any of the above-mentioned sectors that can be interested in the project results would be invited to participate. These workshops will be held the year after the completion of the project. In the mid-term selected workshops will also be organized about specified subjects that will be studied with during the Exploitation Term.

- ***Papers and contributions*** in specialized Conferences or Journals. These contributions will be oriented in three directions:
  - Surface Technologies
  - Machining Processes
  - Aeronautic Industry

  The contributions will deal with either one of these subjects or with two or the three of them, depending on the nature of the Journal or Conference. The higher effort will be made the year after the completion of the project, where at least three contributions (one of each subject) will be published. To avoid conflicts with Intellectual Property Rights, the permission of all the partners will be needed before the publication of any project result, as stated in the Consortium Agreement.

The following table shows the dissemination plan of the project:

Table III: Dissemination Plan

Planned Dates	Type		Type of audience	Countries addressed	Size of audience	Partner responsible /involved
March 2007	1. Workshops to present the results of the project to industrial companies and RTD centres	General based on coating results	*Research/ Industry*	**Spain**	*100*	**INASMET**
Jan.2008		***General***, based on project results	*Industrial*	**Spain** **Greece**	*25* *25*	**INASMET,** DMP, Tesscenter **EEDM**
Sept. 2006	2. Contributions in specialized Conferences or Journals	Coatings	*Research*	**Germay**	*250*	*INASMET*
Sept. 2007		Machining processes	*Research*	**Greece**	*250*	*EEDM*
April 2008		Coatings	*Research*	**Spain**	*250*	*INASMET*
Sept. 2007		Aeronautics	*Research*	**Norway** **Spain**	*150* *150*	*BRJ* *DMP*
Jun.2008	3. Participation in Fairs and Exhibitions	International	*Industrial*	**Germany** **Spain**	*400* *400*	*CemeCon* *Tesscenter*

In the table IV is presented a detailed list with the technical contributions already done or to be done in a near future.

Table IV: Technical contributions in Journals or Conferences

Date	Conference/ Journal	Type of contribution	Title	Partner responsible
June 2006	ICV-2006	Oral	Tribo-mechanical properties of CrAlN coatings doped with Yttrium and Zirconium	INASMET
Sept. 2006	PSE2006	Poster	Effect of alloying elements on the tribo-mechanical behaviour of nanocristalline Cr(Al)N coatings	INASMET
2007	CIRP ANNALS-MANUFACTURING TECHNOLOGY 56 (1): 77-80 2007	Paper	An innovative methodology for the performance evaluation of coated cemented carbide inserts in milling of Inconel 718	EEDM
Oct. 2007	"THE" coatings	Oral	Performance of CrAlN PVD coatings on cemented carbide inserts in milling aerospace alloys	EEDM/ INASMET

The consortium has decided to publish some papers with the coating properties and with some machining results but without explaining the coating parameters involved in the industrial process. Anyway a short description of the exploitable results is shown below:

Exploitable result 1: PVD coating applied on cutting tools

A PVD coating applied by magnetron sputtering on cutting tools has shown an increase in productivity up to 30% when machining Ti alloys. This coating is based on CrAlN.

The **sectors of application** are: Aeronautical, Biomedical, Energy, Manufacturing
Time to market: 2008
Owner: CemeCon

Exploitable result 2: Fabrication of aircraft components using the newly developed machining processes

The machining procedures used in the project with the selected coatings and tools will be used by the machining workshops to machine similar components in the near future.

The **sectors of application** are: Aeronautical, Biomedical, Energy
Time to market: 2008
Owner: Morfomichaniki, BRJ, DMP