Project no.FP6-515840

Project acronym: **Foremost**

Project title: *Fullerene-based Opportunities for Robust Engineering: Making Optimised Surfaces for Tribology*.

Instrument: Integrated Project.

Thematic Priority: NMP3

Publishable Final Activity Report

Period covered: from 1 Sept. 2005 to 28 February 2010

Date of preparation: 9 April 2010

Start date of project: 1 Sept. 2005

Duration: 54 Months.

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Revision: 01

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1. Summary

Certain inorganic compounds that normally occur as large flat platelets can be synthesized into much smaller nano-spheres or nano-tubes. Due to their size, shape, chemistry, and structure, materials based on these nano-objects (see ISO TS 27687:2008 Terminology for nano-objects – nanoparticle, nanofibre and nanoplate) have special properties compared to materials based on conventionally sized constituents of the same composition. The natural next step to take advantage of the unique mechanical resistance and lubrication power of these **fullerene-like materials** is to integrate them into coatings and surfaces by creating a new generation of nanocomposite materials.

The objective of this project was to provide industry with radically new coatings and lubricants to significantly reduce and control friction and wear in rolling and sliding contacts to:

- substantially extend operational life
- significantly reduce maintenance requirements
- markedly reduce environmental impact

of a wide range of machines incorporating transmission trains, sliding bearings, spherical joints, ball screw systems, etc.

These innovative coatings and lubricants are based on **the incorporation of nanoparticles of inorganic fullerene-like materials (IFLMs),** either by

- introducing preformed *IFLMs* into the deposition process/lubricant/paint or by
- forming the *IFLM* components *in-situ* during the deposition process.

For coatings, the incorporation of *IFLM* nanoparticles into a*freely and independently selected* matrix allows independent control of friction and wear, together with consistent tribological performance. Given the remarkable stability of the *IFLMs* (e.g. the metal chalcogenide systems are stable at contact stresses >20 GPa, compared with C_{60} which decomposes at ~2GPa) such **independent control of friction and wear** is especially pertinent for systems requiring very high load bearing capacity with very low friction, requirements often in direct conflict with today's coatings such as the DLCs.

The new materials developed in the project can be grouped into three categories:

- Nanocomposite hard coatings, containing friction reducing IFLMs.
- Nanocomposite polymeric coatings and paints containing IFLMs.
- Liquid and solid lubricants containing IFLMs.

A large variety of IFLM containing coatings and lubricants were developed**,** and a number of potential solutions for each end user application were identified on the basis of the coatings-specific requirements of each application.

Pure sliding laboratory tests indicate that for some industrial applications IFLM containing coatings can give significant reductions in friction coefficient. For example, excellent results were obtained in pure sliding tests on Ni+P+IF WS_2 coatings for which at low humidity level the coefficient of friction decreased to between 0.02-0.04 and remains constant during thousands of cycles. Similar behaviour was also identified in the coatings containing fullerene-like structures grown "in situ".

Tribological testing was undertaken not only to perform the preliminary ranging trials to select the most promising coatings for each application, but also to determine the coordinates within the contact conditions where the IFLM containing coatings and lubricants offer maximum benefit.

Excellent results have been obtained for sliding/rolling applications, like gears or cam/tappet system, where the FOREMOST coatings and lubricants were significantly better that all the state-of-the-art presently available competitors. Very good results have been also obtained for different fretting fatigue applications for the aerospace industry.

To make these materials available to the industry, NanoMaterials completed installation of all process equipment plus infrastructure of a Pilot Unit for cost-effective production of fullerene-like WS_2 nano-spheres with a production capacity of 75 kg/day.

Under a scientific point of view, important contributions have been made in the synthesis of new kinds of inorganic layered compounds as nanospheres and nanotubes.

Another project objective successfully achieved was to provide full chemical, structural and mechanical characterization of IFLM coatings. Within these studies IFLM lubrication mechanisms were elucidated, being by pressure induced exfoliation of IFLM structures and further formation of a self-lubricant tribofilm.

The FOREMOST project has also provided relevant contributions on health and safety aspects concerning inorganic fullerene-like nanoparticles.

2. Project Consortium

The *FOREMOST* consortium combines the technical expertise of leading coating organisations and research institutes with the high technical expertise and commercial demands of some of Europe's premier engineering companies. It is further supported by leading academic and research organisations with complementary expertise in the fields of tribology, chemical and structural analysis, and mechanical testing and evaluation. Up to 33 organizations from 13 countries have participated in *FOREMOST*.

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3. General Context and Main Objectives of the Project

Fullerene-like materials can be defined as materials made up of two-dimensional lamellar basic units of nanoscale dimensions with closed and curved shapes. They can grow in the solid phase into three-dimensional networks or architectures displaying a wide range of morphologies. The basic origin of these new phases lies in the role of dangling bonds at the periphery of sheets of such small sizes, which destabilise planar structures and induce closing. As already emphasised, the atomic-scale structure of these materials involving strong covalent inter-atomic bonding and non-compact space filling, make them strong candidates for breakthrough developments, of potentially high interest in many industrial fields.

Fullerene structures made with carbon atoms were well known for several decades. Then the NanoMaterials Synthesis Group headed by Professor Reshef Tenne at the renowned Weizmann Institute of Science in Israel discovered a new class of three-dimensional inorganic nanostructures. They found that certain inorganic compounds that normally occur as large flat platelets can be synthesized into much smaller nano-spheres or nano-tubes; hence the name **inorganic fullerene-like materials**, or IFLM nanoparticles.

IFLM compounds are abundant, in particular among the transition-metal chalcogenides (sulphides, selenides, and tellurides), halides (chlorides, bromides, and iodides), oxides (hydroxides), and numerous ternary and quaternary compounds. However in contrast to graphite, each molecular sheet of the fullerene structure consists of multiple layers of different atoms chemically bonded to each other. This initial discovery by the Weizmann group elicited a substantial effort of many other groups. The carbon nitride, and in particular the fullerene-like CNx ($0 < x \leq 0.3$) compound discovered at Linköping University in 1995 [1], is also an interesting material from the research and application point of view [2, 3].

The natural next step to take advantage of the unique mechanical resistance and lubrication power of these fullerene-like materials is to integrate them into coatings and surfaces by creating a new generation of nanocomposite materials, as was intended in the present project.

The overall objective of the project is to provide industry with a **new generation of composite coatings systems and surface engineering solutions, based on the incorporation of inorganic fullerene-like nanoparticles into coatings and lubricants**, to significantly reduce and control friction and wear in rolling and sliding contacts in order to **extend operational life, reduce maintenance requirements and reduce the environmental impact** of a wide range of mechanical systems.

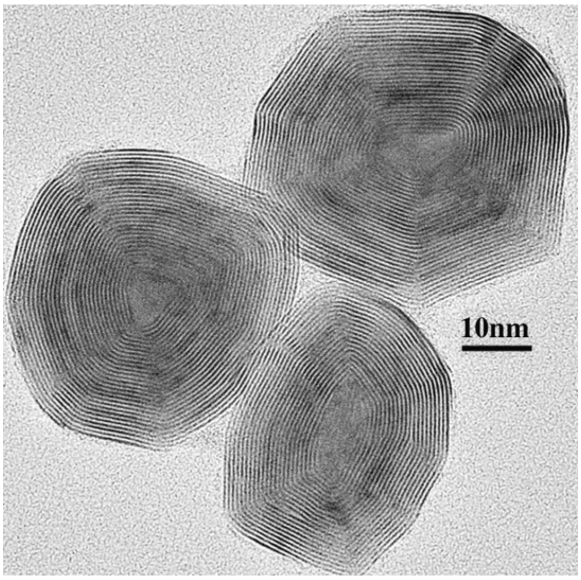

Figure 1: Transmission Electron Microscopy image of WS_2 Fullerene-like particles (IFLMs) synthesised by NanoMaterials Ltd.

The new materials to be developed in the project can be grouped into three categories:

- **Nanocomposite hard coatings**, consisting of a **hard matrix** deposited by PVD, CVD, PACVD or electro and electroless plating and **containing lubricating IFLM nanoparticles**. It was expected that this approach would allow coatings to be synthesised with a hardness level over 30 GPa whilst keeping the friction coefficient lower than 0.1.
- **IFLM particles incorporated into polymers and paints for surface applications.** These new products will focus on the replacement of fluorinated hydro-carbon materials by IFLM incorporated plastic, paints and resins.

  It is also an objective of the project to **replace soft metallic coatings** (i.e. direct cadmium and lead coatings) presently used by the aerospace industry**.**
- **Lubricants and greases** containing IFLM nanoparticles as friction reduction agents **offering the advantages of such nanomaterials** to complex systems where only some parts have been coated with the new coatings. Besides, synergies with adopting the lubricant to the new coating are vital to reach the lowest possible frictional losses.

The end-users participant in the project established a list of specific applications to be tested in the project, in order to better focus the development of new coatings and lubricants to meet the specific requirements of these applications. Table 2 summarizes these applications used to validate the new coating materials and lubricants developed in FOREMOST.

Table 2: Specific applications being tested in the project

Industrial Sector	Type of application element		Partner involved
Aerospace	Anti-fretting applications	Helicopter fuselage control link	EADS
		High torque mainshaft spline couplings and fan blade roots	Rolls Royce
		Fuel pump drive spline	Goodrich/AEC
	Sliding wear	Fuel pump thrust ball	Goodrich/AEC
	High speed, high temperature helical transmission gears		Rolls Royce
	Structural aircraft parts (leading edges, landing flaps)		EADS
	Aircraft Engine Fuel System “anti-lacquer” coatings		Goodrich/AEC
Automotive	Cam-tappet		Renault
	Window elevator - magnesium track		Proplast
Manufacturing	Ball-screw drives		Fatronik
	Glaze coater		Proplast

Besides improving wear resistance and reducing friction, the incorporation of fullerene-like nanoparticles can provide **additional functionalities,** e.g. **de-icing, hydrophobic or “self-cleaning” (anti-sticking) behaviour.** Such functionalities have a special relevance in aeronautic and space parts.

Another **important breakthrough** of the project is to **provide industry with modelling data and other design criteria** to make full use of these new materials and systems.

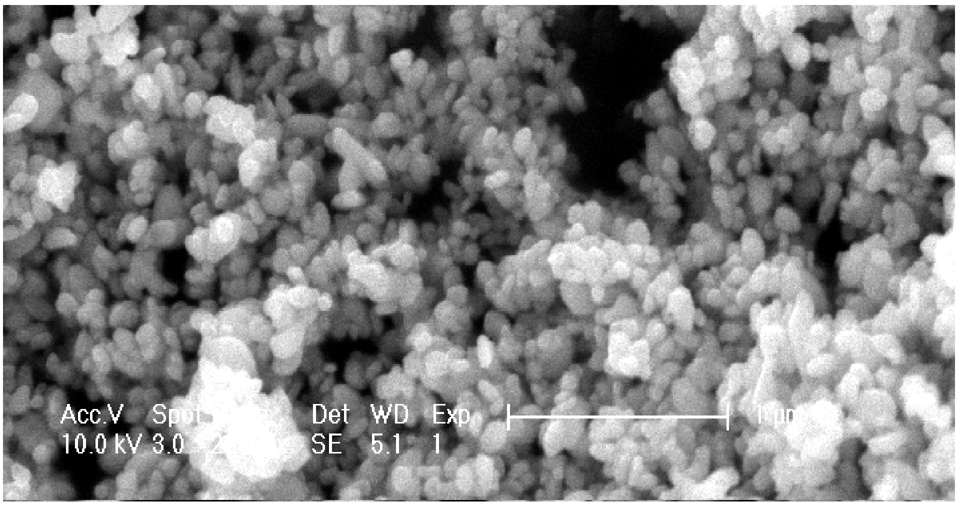

Figure 2: Scanning Electron Microscopy image of WS_2 Fullerene-like particles (IFLMs) synthesised by NanoMaterials Ltd.

4. Overall project structure

The various activities of the project were divided into four SUB-PROJECTS (SP1 to SP4), according to their specific role within the project (figure 3) Sub-Project 1 dealt with the synthesis of coatings and lubricants containing fullerene-like microstructures. Once films and lubricants with promising mechanical properties had been developed in SP1, they were subjected to tribological testing and, where appropriate, detailed performance mapping in Sub-Project 2. The best coatings were then tested at Sub-project 3 in relevant demonstrators for some real industrial applications selected from the aerospace, automotive and manufacturing sectors. Sub-project 4 grouped a variety of other management and cross-sectional horizontal activities.

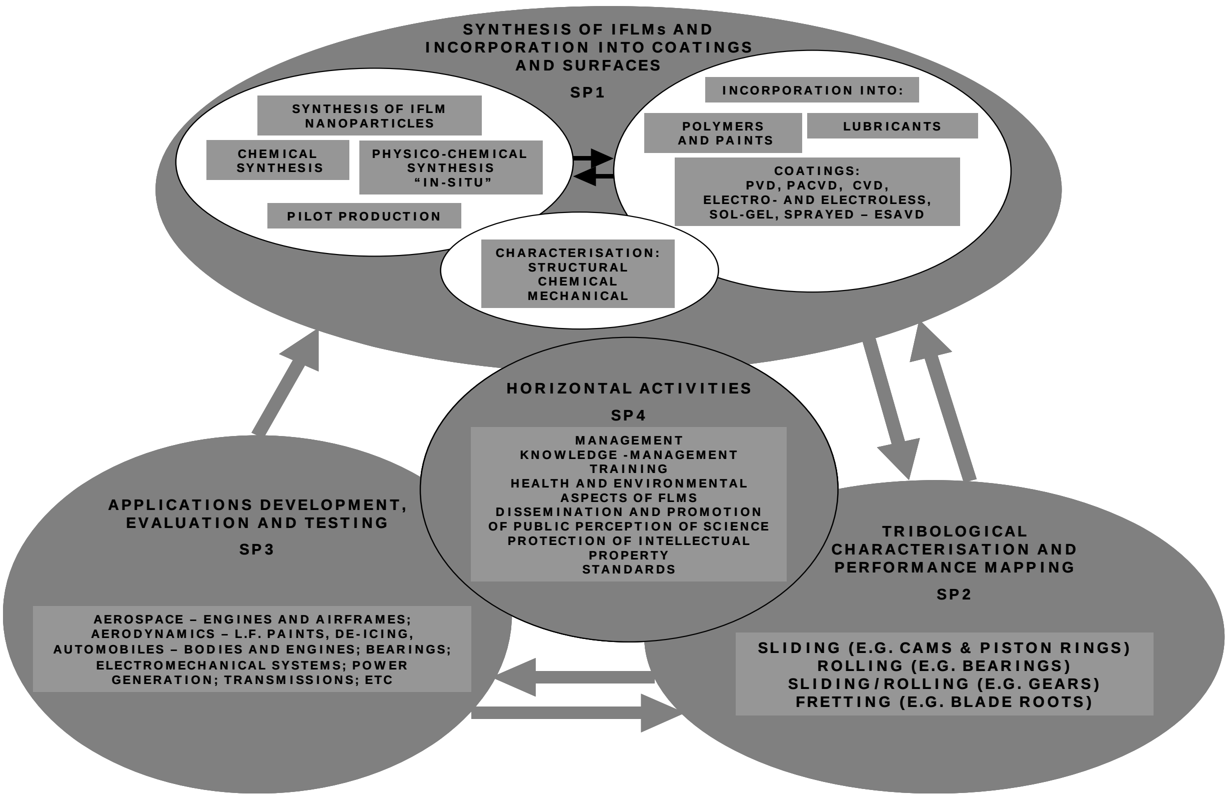

Figure 3: Project structure showing content of, and the relationship and information flow between subprojects

5. Major achievements

From a scientific point of view, important contributions have been made in the synthesis of new kinds of inorganic layered compounds as nanospheres and nanotubes. Thus, new fullerene-like materials have been developed, like MoS_2 "mama"-tubes (MoS_2 fullerenes inside MoS_2 nanotubes) from Jozef Stefan Institute. Fundamental studies about growth mechanisms of inorganic fullerene-like structures were also carried out by JSI and Linköping University. This research led to several new patent applications.

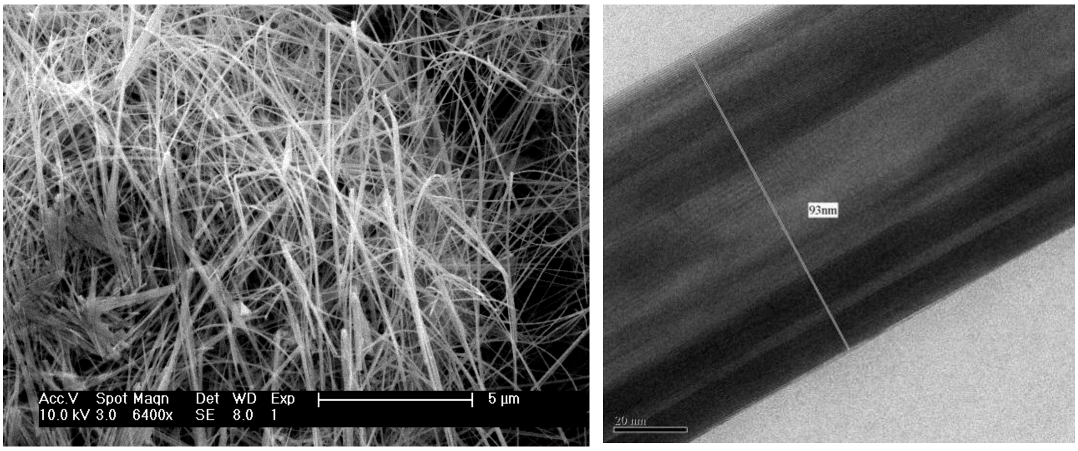

Figure 4: MoS_2 Nanotubes developed by JSI

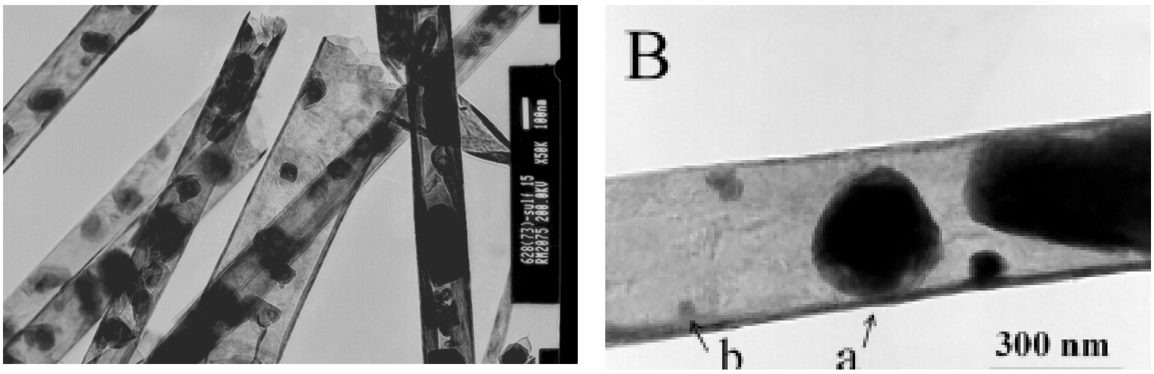

Figure 5: MoS_2 "Mama-tubes" developed by JSI

Reductions in expense, increases in efficiency and production yield of IFLMs are needed to make these materials available to the industry. NanoMaterials successfully achieved these objectives by improving previously existing fluidized bed reactor production processes to produce WS_2 nano-spheres and nanotubes. Thus, as a demonstration activity of the project**,** NanoMaterials completed installation of all process equipment plus infrastructure of a Pilot Unit for cost-effective production of fullerene-like WS_2 nano-spheres with a production capacity of 75 kg/day (figure 6).

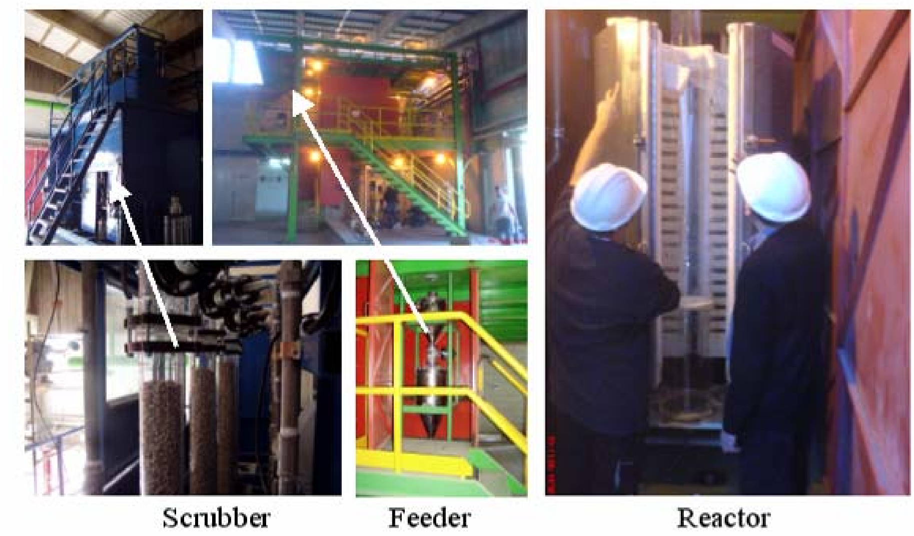

Figure 6: Demonstration Pilot Plant built by NanoMaterials within WP 1.1B

A large variety of techniques were studied to incorporate previously synthesised IFLM nanoparticles into coatings deposited by arc evaporation PVD, RF-PACVD, CVD, Electron-beam evaporation, Magnetron sputtering, Electrolytic deposition, Sol-gel, Aerosol assisted and Atmospheric plasma processes, as well as direct incorporation into polymer - thermoplastics and thermosetting phenolic and polyester resin coatings.

Regarding the incorporation of previously synthesised IFLM nanoparticles into coatings, the main problem encountered was the agglomeration of the IFLM powder. Large clusters of particles were found inside the coatings that were not a problem for the friction behaviour, but for their negative impact on the mechanical properties of the coatings, like adhesion or wear resistance. Ultrasonic bath and agitation were found to be the best methods for the dispersion of IF-WS_2 nanoparticles in organic and hybrid liquids. Re-agglomeration of IF-WS_2 nanoparticles often occurred but stable aqueous dispersions were obtained with appropriate surfactants, especially for low concentration of IF-WS_2 In parallel, modification of the process parameters in the scaled-up demonstration unit enables the production of relatively un-agglomerated IFLM.

IFLM nanoparticles were also successfully incorporated into lubricants. The wide range of applications defined by the end-users of the FOREMOST project led to a variety of lubricant developments in the project: lubricating oils, lubricating greases, solid-film lubricants and lubricating pastes.

As a second approach, some advanced nano-composite films in which the IFLM components were generated *in-situ* during the deposition process, were successfully synthesised in FOREMOST. This achievement should be highlighted, because the *in-situ* growth of fullerene-like structures during the coating deposition was considered as the highest risk in the entire project. These positive results probed the technical feasibility of such an approach. The most energetic deposition techniques were used for this purpose, i.e. Arc evaporation, Ion assisted E-beam evaporation, ECR-CVD, PECVD and Magnetron Sputtering. "In-situ" formed fine crystalline structures with curved closed planes were deposited by combining supersonic cluster beam deposition (SCBD) sources with PVD coating systems, arc evaporation or sputtering (collaboration between Milano University and IonBond-UK).

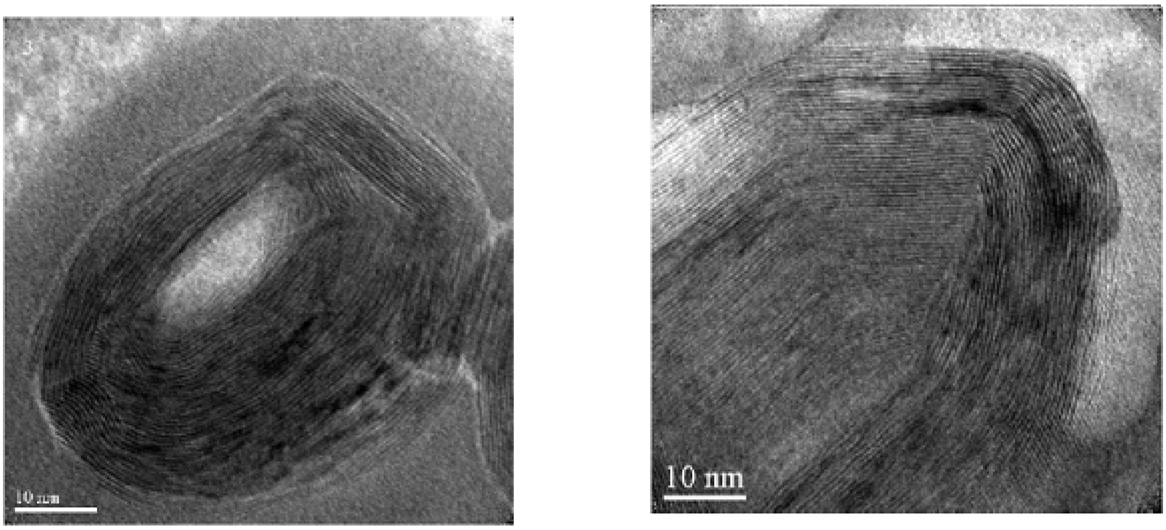

Figure 7: TEM image of WS_2 fullerene (Synthesis by Nanomaterials. TEM analysis carried out by Stockholm University)

Apart from the basic characterization of IFLM-based coatings, undertaken by the respective coating producers, FOREMOST provided non-routine chemical, structural and thermal characterisation on both single IFLM components and on IFLM nanocomposites with a view to elucidating the structure and surface and bulk chemistry of the nanoparticles, and the chemical and physical bonding between IFLMs and the coating matrix. For these analyses, some of the most sophisticated analytical and observational tools available in Europe today were used, e.g. Spatially Resolved EELS, Quantitative HREM (CNRS), XANES analysis by synchrotron radiation (CSIC), TEM in-situ annealing, depth profiling by XPS (Linkoping University), Depth profiling by Ion Beam Analysis (FZD) and HREM, AFM and UHV STM (Jozef Stefan Institute).

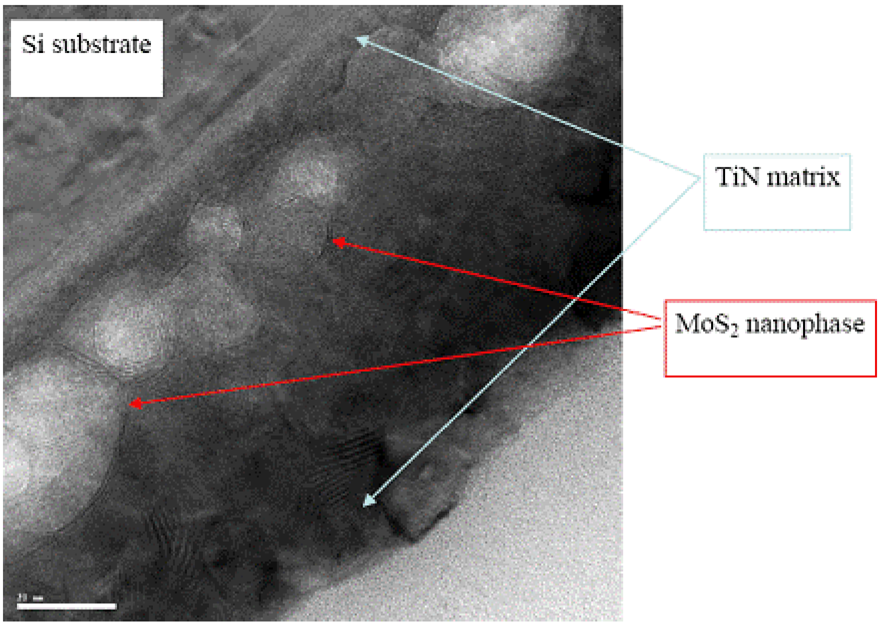

Figure 8: Fullerene-like MoS_2 structures grown "in situ" with a TiN matrix, using SCBD + PVD process (Synthesis by collaboration between University of Milano and IonBond-UK. TEM analysis carried out by MFA).

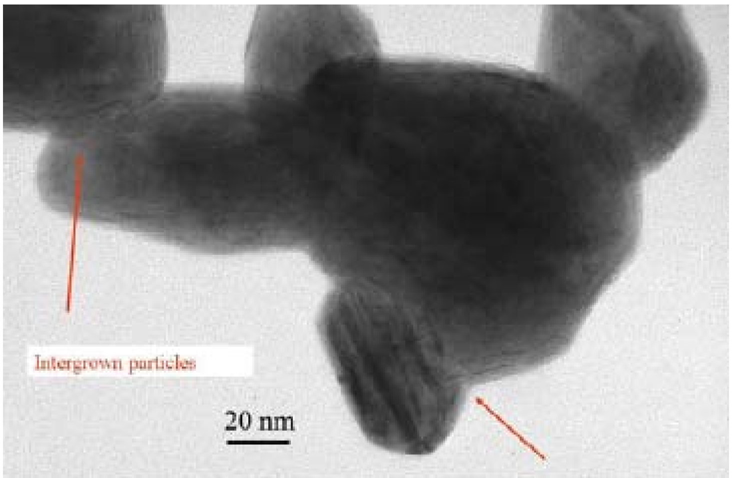

Figure 9: TEM image of WS_2 nanoparticles.

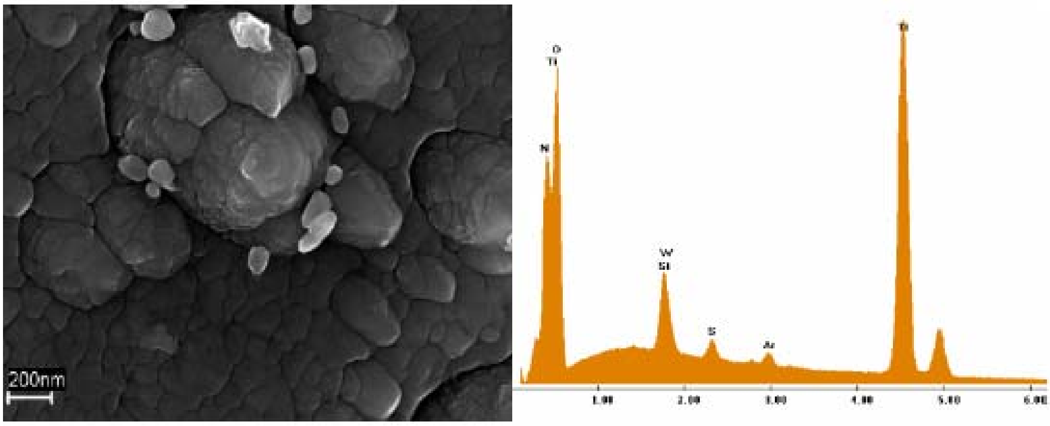

Figure 10: FEG-SEM micrograph of few free standing IF-WS_2 nano particles associated with nodular growth in a TiN matrix. EDS analysis shows a possibility of at most 5% of WS_2 nanospheres embedded inside TiN hard coating matrix.

Additional mechanical property testing support was also provided by BAM and NPL. Such mechanical property testing included adhesion, Young's modulus, internal stress, fracture toughness and surface topography, at macro-micro- and nano-scales. Modelling of the mechanical behaviour of the IFLM nanoparticles and coatings containing IFLMs were carried out by BAM and Linköping University, using different and complementary modelling methods.

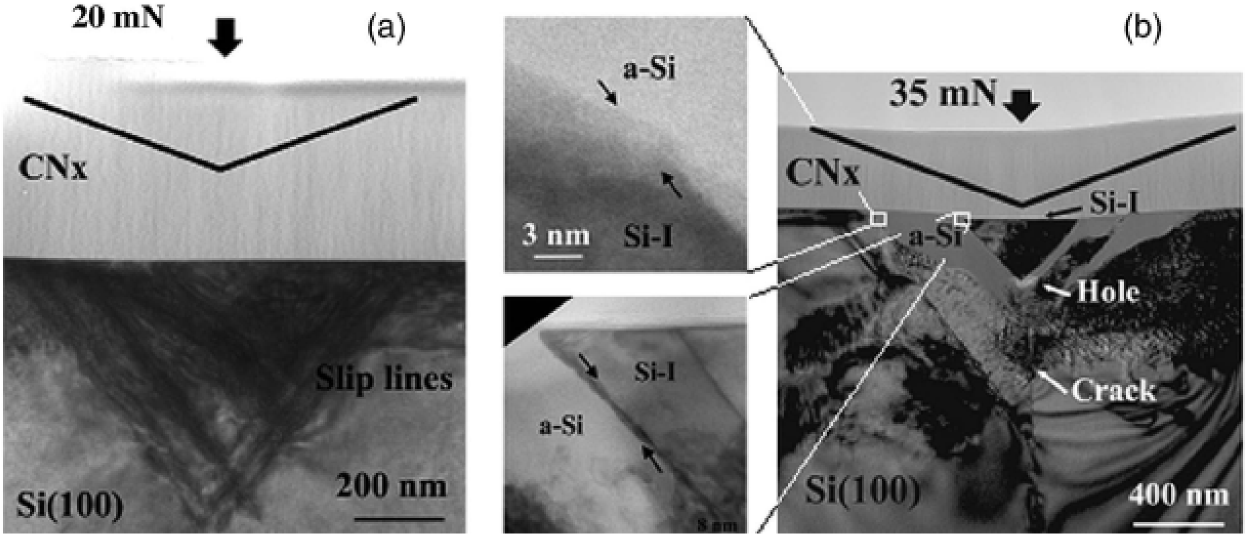

Figure 11: Cross-sectional TEM images of CNx thin films after indentation at (a) 20 mN and (b) 35 mN. High-resolution images of the marked areas in (b) indicate amorphized α-Si around the intact cone of 001 Si. No damage was detected in the films at loads of up to 35 mN and in the Si at loads of <20 mN.

To aid in the selection of suitable coating materials and structures for use in the applications testing stage of the project, an Access database of all FOREMOST coatings was constructed by IonBond-UK. A total of 125 different coating formulations were included in this database. The database contained over forty different data items per sample grouped into different sections i.e. Deposition, Analysis, Mechanical and Other. A number of potential solutions for each end user application were identified on the basis of the coatings-specific requirements of each application. As a general rule, a friction coefficient as low as possible was the most important selection criteria.

Optimization of selected coatings was conducted following an iterative process consisting of providing coatings for screening by tribological testing, further development of those coatings and coating processes providing promising results, followed by further screening.

In order to ensure accurate and consistent preservation of data related to the coatings selected for applications testing, the coatings database, developed for the first selection process, was modified to allow the inclusion of relative performance data and specific file types, allowing additional explanatory information to be stored. This “applications database” was distributed to all partners for further data entry pertinent to their own coatings, and those partners performing the tribological and applications testing to allow them to check that all testing information relevant to coatings of interest had been entered. This database was issued as one of the final deliverables of the project.

Tribological testing was undertaken to determine the coordinates within the contact conditions where the IFLM containing coatings and lubricants offer maximum benefit. Preliminary ranging trials were followed by detailed mapping under pure sliding (as in piston rings), pure rolling (as in cylindrical roller bearings), in sliding/rolling at different ratios (as in gears) and in fretting contacts (as in turbine blade roots). The preliminary ranging trials were carried out under conditions similar to those that would be experienced in the selected commercial applications. Moreover, the tribological mapping evaluated a wider range of parameters to establish the most suitable operating conditions, and other limits, which in turn allow other possible commercial applications to be identified.

In the case of unidirectional movement, the field of use of the coatings was defined in contact pressure versus sliding speed coordinates. Under dry conditions, for medium contact pressure, i.e. 10 to 100 MPa range, the best coatings developed in FOREMOST were the Ni-P-IFLM, MoSeC and WSC, which dispalyed a coefficient of friction in air within the range 0.04-0.10, depending on the degree of humidity and the test conditions. Pure sliding laboratory tests indicate that for some industrial applications, IFLM containing coatings can give significant reductions in wear and friction coefficient when compared to similar coatings containing non-fullerene components of the same material. As an example, excellent results were obtained in pure sliding tests on Ni+P+IF WS_2 based coatings developed by NanoMaterials. In tests performed by Uppsala University at low humidity level (RH 8%) the coefficient of friction decreased to between 0.02-0.04 and remains constant during thousands of cycles. Similar behaviour was also identified in the coatings containing fullerene-like structures grown "in situ". For example, the sputtered WS coating developed by the University of Coimbra, showed very low friction when tested in nitrogen or dry air (coefficient of friction 0.02-0.04). Tests performed on these materials in humid air showed higher friction and clear presence of oxides in the wear track.

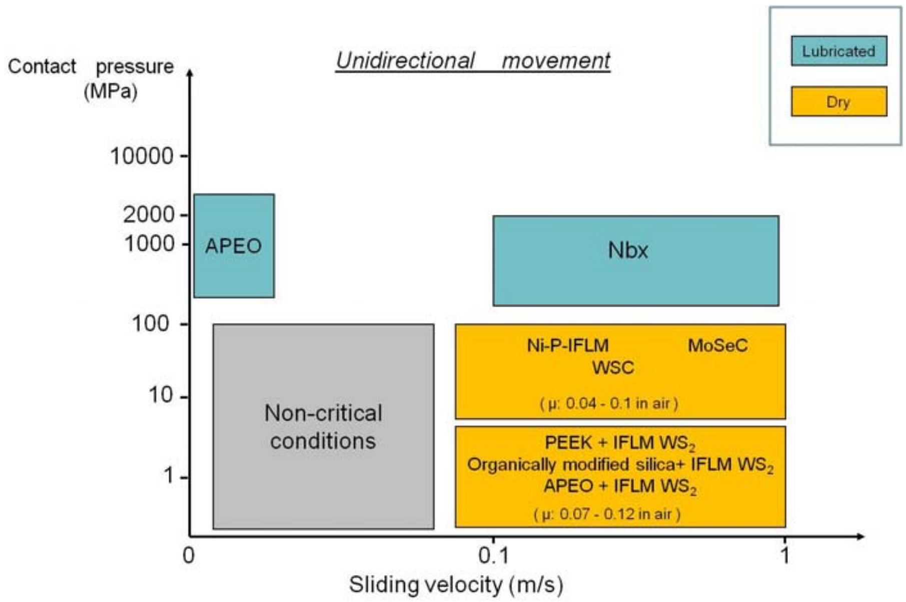

Figure 12: Map to define the field of use for IFLM-based coatings. Contact pressure vs. sliding velocity coordinates

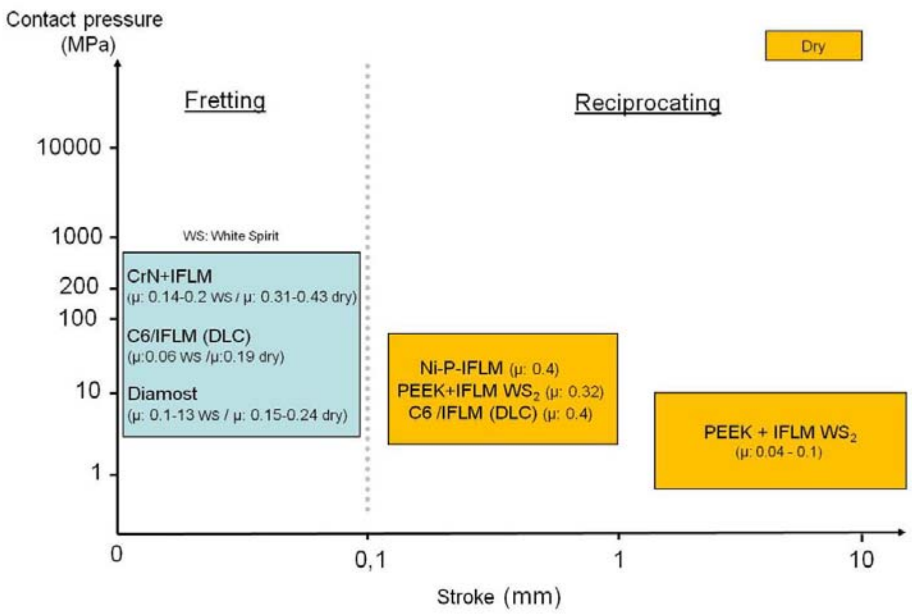

Figure 13: Map to define the field of use for IFLM-based coatings. Contact pressure vs. reciprocating stroke coordinates

In the range of lower contact pressure, PEEK+IFLM from Nottingham University, APEO from VITO, and the organically modified silica +IFLM from BAM seems to be the most appropriate coatings, which coefficient of friction in air was found within the range 0.07-0.12.

In lubricated tribological contacts, one of the most critical fields of applications is that involving large contact pressure (1-2 GPa) and relatively high sliding velocity, in the range of 0.5 m/s or larger. In this case, the best results obtained in gear tests performed by Newcastle University were for the NbX coatings from IonBond-UK.

For pure rolling applications, the contact pressure can be larger than 2 GPa, but although the total contact speed is normally high, its sliding component is very low. According to the ball-on-rod pure rolling tests carried out by Tekniker, the APEO coating was the most appropriate for these working conditions.

In the case of reciprocating movements, for dry large amplitude reciprocating movement under relatively low contact pressure, up to 20 MPa, the PEEK+IFLM coating was the best FOREMOST coating. For reciprocating movement with amplitude between 0.1 and 1 mm, under dry conditions and medium contact pressures, up to 100 MPa, Ni-P-IFLM, PEEK+IFLM and C6+IFLM (IonBond-CH) coatings exhibit the best results, although in all cases the coefficient of friction was around 0.3-0.4.

Within the pure fretting conditions, low or moderate contact pressure (2-200 MPa) high frequency and short stroke, for both dry and lubricated contacts, the best coatings were C6+IFLM and Diamost from Kenosistec. Also CrN+IFLM, from IonBond-UK, can be considered for this use in lubricated applications.

Surface texturing experiments were done by Tekniker using pulsed Nd:YAG lasers to produce controlled textures on the surface prior to coatings. Then load carrying tests were performed at progressively increased load to determine the seizure resistance of the IFLM-based coatings. Texturing increased significantly the seizure resistance of NbX coatings from Ionbond-UK, the seizure failure load of which increased from 1000

N on the untextured surface up to the maximum test load (2000N) when this coating was tested on a previously textured surface.

The very good performance of lubricants and coatings containing IFLM particles in sliding/rolling applications was confirmed through FZG scuffing tests and Brugger tests. The FZG scuffing test uses spur gears at the highest Hetzian pressures and tip sliding speeds IFLM proves to be efficient in reducing scuffing in spur gears. This allowed the maximum Hertz'ian pressure to be raised from 1960 N/mm² to 2500 N/mm² - a raise of 25 % The Brugger test uses crossed cylinder geometry to study the load-carrying capacity of EP-oils. The Brugger test results showed a very big benefit of the IFLM-particles in this test. The wear area was reduced by approximately 50%. The comparison of lubricating greases in a SRV line-contact friction test showed a significant improvement for IFLM over MoS_2 and conventional WS_2 However, all results obtained from the tribotesting of IFLM containing lubricants were not as good as those reported above. In some cases, IFLM containing oils did not show significant improvement against the state-of-the-art reference lubricants or the scattered data gave no indication of improved performance of IFLM containing lubricants.

Elucidating the lubrication mechanisms through which the fullerene-like structures improve friction and prevent wear, was another of the most relevant scientific challenges of the FOREMOST project. TEM analyses of the wear tracks after tribological testing of IFLM-based coatings and lubricants, carried out by Stockholm University, revealed that the lubrication mechanism of IFLM materials involves pressure induced exfoliation of the IFLM structure (figure 14), adhesion of the exfoliated crystallographic planes to the contact surface and formation of IFLM tribofilms (figure 15)

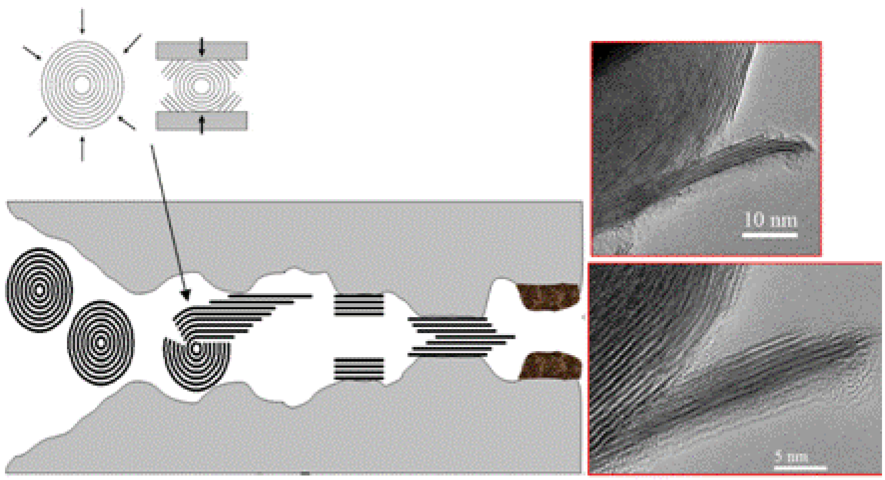

Figure 14: Scheme of lubrication mechanisms of IFLMs. Pressure induced exfoliation of the IFLM particle (Stockholm University)

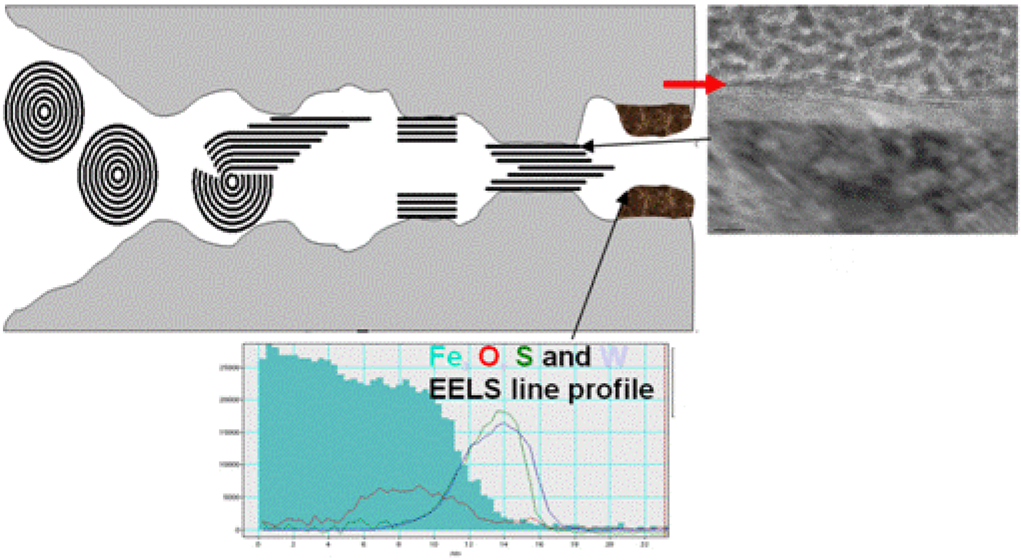

Figure 15: Scheme of lubrication mechanisms of IFLMs. WS_2 tribofilm and oxidation (Stockholm University)

IFLM-based coatings and lubricants were tested according to the requirements for some real industrial applications selected as demonstrators to evaluate the industrial feasibility of FOREMOST materials.

Improving lubrication of gears is a common problem of the aerospace, automotive and manufacturing sectors. However, in order to avoid overlapping of activities, it was agreed that only one type of gears would be tested in FOREMOST as demonstrator. Materials and working conditions of the high speed helical transmission gears from Rolls-Royce were selected by the University of Newcastle, the partner in charge of performing these validation tests. The best results were obtained with the NbX coatings. For high speed high loaded gears this FOREMOST coating was significantly better that all the state-of-the-art presently available coatings. For NbX coatings wear lower than 5 µm was measured after 90 million cycles at maximum pressure (figure 16). Moreover, most of this wear measured takes place during the running in of the tests, after some thousand of cycles the gear profile deviation remains constant till the end of the test. This confirms that the protective mechanism provided by the fullerene-like structures need for the generation of a WS_2 tribofilm on the gear surface. This is an outstanding result that demonstrates the beneficial effect of the fullerene-like structures for improving lubrication and wear resistance in combined sliding-rolling tribological contacts.

Consistently, the lubricant oils containing IFLM nanoparticles showed very good performance in FZG scuffing tests, which also involve gears.

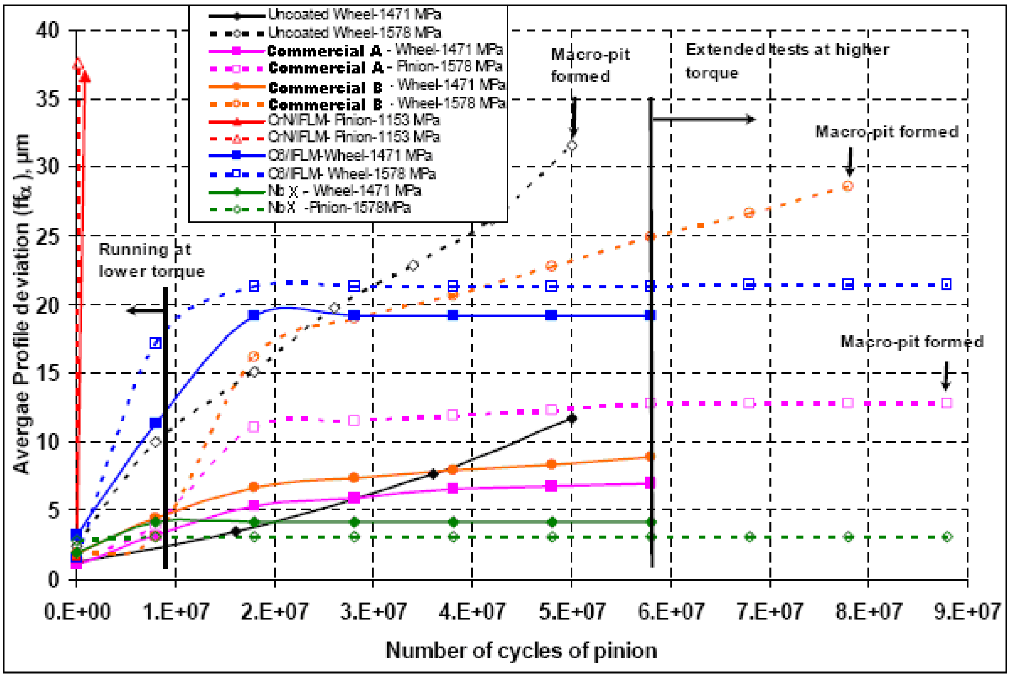

Figure 16: Gear profile deviation (tests by Newcastle University)

Under aeronautic conditions some bolts are prone to fretting (fretting corrosion or fretting fatigue), induced by micro motions due to vibrations. This is an adhesive wear phenomena that makes the bolt severely stick to the mating counterpart; thus, causing problems in maintenance checks, functionality and life time of the corresponding joint. The selection of coatings to be tested for this application was carried out by EADS through reciprocating pin on disc tests and specific ring-ring fretting tests. Although the fretting test at EADS IW on bolts is a qualitative test, it is quite near to the application where fretting may cause damage in service life: at the bolt / protective coating / bushing interfaces. Different types of protective coatings of inorganic fullerene like materials (IFLM) incorporated in different matrices´ materials (nickel phosphorous, polyetherethyketone, PEEK and MoSeCH) were focussed in this test program. Stepwise the maximum pressure is increased up to 100 MPa, where some coatings failed in adhesion. At 20 and 50 MPa no coating failed under the given test conditions.

Aero Engine Controls collaborated with Imperial College to simulate the fretting wear conditions encountered in fuel pump drive shaft spline applications using a High Frequency Reciprocating rig (HFRR). Regarding the friction coefficient for each coating at 0.2 GPa contact pressure in a dry environment, all the six FOREMOST coatings performed better than benchmark Cr coating. Lowest friction throughout the test ($\mu<0.3$) was obtained with Diamost from Kenosistec, Ni-P+WS_2 from NanoMaterials and Co-W-WS_2 from Nottingham University. Comparison of the friction coefficient obtained in white spirit liquid for each, only two coatings, namely Diamost and Ni-P+WS_2, were able to demonstrate very low stable friction under the test specific conditions applied. On the basis of average wear scar sizes, three FOREMOST coatings showed better wear resistance in this application: CrN+WS_2, Diamost and Co-W-WS_2.

The third aerospace application concerning fretting considered in FOREMOST was the mainshaft spline coupling and fan blade roots of the Rolls-Royce aero engine, which suffer surface damage associated with fretting due to delamination (alternating stresses), adhesion and abrasion by trapped oxide debris. Nottingham University designed a

Fretting Fatigue of Spline Couplings tests using a Multiaxial Representative Specimen (MRS) which gives similar fretting fatigue lives to those real data. Fretting fatigue tests at Nottingham on DLC+WS_2 coatings from IonBond-CH have demonstrated a 50% improvement in performance over steel components. Similar tests on CrN+WS_2 from IonBond-UK have shown a 10% improvement. Duplicate tests are being carried out on two spline samples with DLC+WS_2 coatings. These coatings showed the best performance as demonstrated by the S-N plots under fretting fatigue conditions**.** The results of these tests could have significant effect on the life and maintenance of Rolls Royce splines.

Aero Engine Controls collaborated with the National Physical Laboratory to simulate the sliding wear conditions encountered in variable displacement fuel pump applications using a pin on disc tribometer test. In these experiments the Diamost coating from Kenosistec, NiP+WS_2 from Nanomaterials and BCN developed at CEA were the most promising coatings for the Goodrich/AEC variable displacement pump application. A coated thrust ball / auxiliary cam plate pair has been run for 58 hours at ambient temperature and maximum service operating conditions (fuel pressure, pump speed) for current piston pump designs. Further testing is required to demonstrate operating temperature capability at maximum pressure/speed and endurance capability.

Another relevant aerospace application considered in the project was the anti-abrasion anti-icing coatings for structural aircraft parts. Three coatings were tested by EADS: an epoxy varnish + nanoSiO_2+IFLM and enamel + nanoSiO_2+IFLM from Spolchemie, and the PEEK+IFLM from Nottingham University. No evidence on improvement of anti-icing effect due to IFLM incorporated in organic topcoat prepared at Spolchemie, while significant reduction in friction coefficient was found for IFLM incorporation in PEEK.

The last aeronautic application, proposed by Goodrich/AEC, concerns the control fuel filter mesh, which suffer relatively quick lacquering during its lifetime, due to the deposition of fuel break-down products. Low surface energy self-cleaning coatings are needed to inhibit this phenomenon. AEC developed a simulative test rig to compare performance of different filter mesh samples at 150°C in aircraft fuel. Two FOREMOST coatings, the PTFE+IFLM from Nottingham University, and the APEO Siloxane + IFLM from VITO showed promising results. Nevertheless, a commercially available product, which also demonstrated a significant reduction in rate of fuel break-down product deposition in rig testing, in comparison with the uncoated mesh.

Moving to the automotive applications, friction and wear resistance of the cam-tappet system have a relevant influence on the fuel consumption and CO_2 emissions of automotive engines. According to the results recorded in the FOREMOST coatings database, five coatings were selected by Renault for the final testing on the cylinder-head test bench. After performance evaluation, three FOREMOST solutions were better than serial one (figure 17), namely, WSC from Coimbra, NbX from Ionbond-UK, Ni-P+IFWS_2 from Nanomaterials. Nevertheless, the durability of these solutions is still a question point, which must be improved with the best selected coatings, retained by Renault in a future study, with the industrial and costs approach.

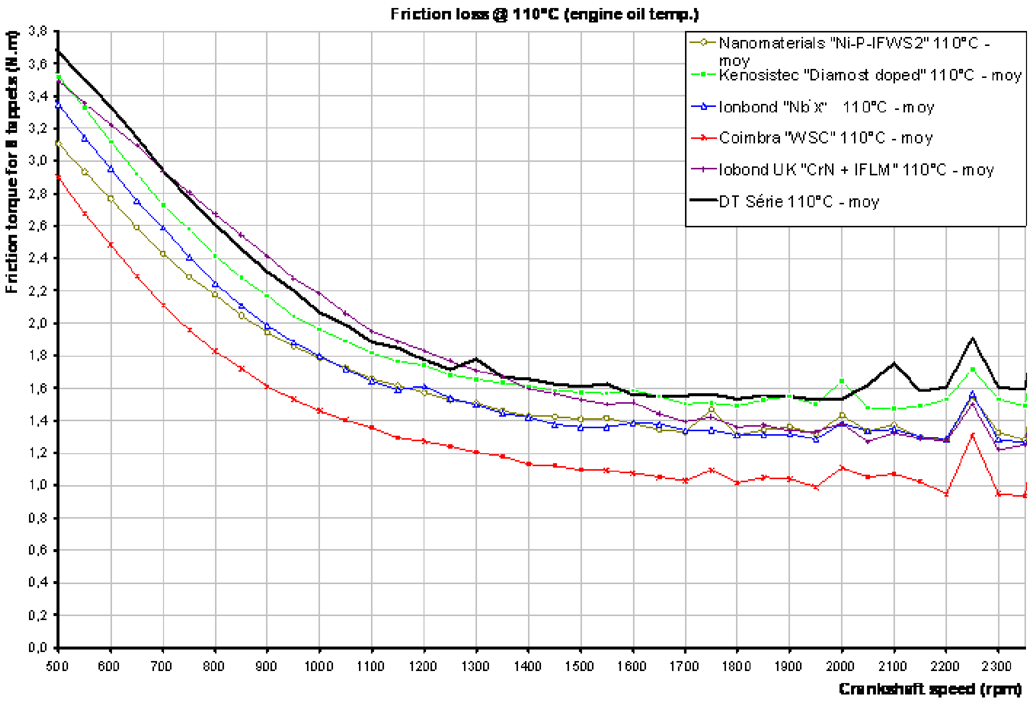

Figure 17: Cam/tappet test bench results. Torque comparative results. 110 °C (Renault)

Also for the automotive sector, the second application considered in FOREMOST was the window elevator-magnesium track. This research was conducted by Proplast. Preliminary selection was done considering the Ni-P+IFLM based coating developed in NanoMaterials, and the PEEK+3.3% IFLM from Nottingham University. The preliminary results of the corrosion tests done on the small samples showed that in bad environment, the two selected coatings cannot be applied on the magnesium based substrate. According to these results, Proplast decided to use the epoxy-phenolic blend (30:70) filled with IF-WS_2 (from masterbacth) on the magnesium track. At the date of writing this report the coated real prototype is still on testing for verification of the requirements (abrasion and corrosion resistance).

Among the applications for the manufacturing sector, Fatronik designed the test bench where the ball screw, rack and pinion and liner guidance systems can be tested, but in order to limit the large number of industrial applications contemplated in the project, it was decided that only the ball screw will be tested. The ball screw was sent to VITO for coating with their APEO coating that has shown promising results in the ball-on-rod pure rolling tribological tests performed by Tekniker. Testing was performed monitoring such parameters as energy consumption, heat generation and vibration levels during different operating conditions. The results obtained were not conclusive in the sense that it was not possible to point out a definite improvement in performance. Similar results have been obtained from the tests performed on the IFLM containing greases supplied by Fuchs.

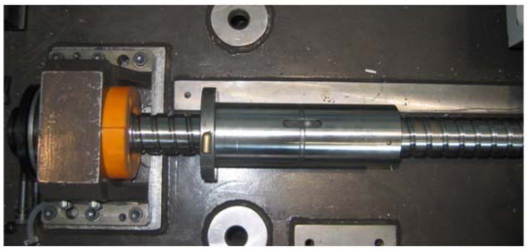

Figure 18: Test bench with ball-screw drive set up by Fatronik

Figure 19: Coating of the Fatronik demonstrator with atmospheric plasma torch (VITO)

Also interesting results were obtained with the glaze coater application conducted by Proplast. The glaze coater is a piece of a painting system for paper that works in contact with chemical abrasive products such kaolin and carbonates contained in the polymeric slurry used for the coating of paper. The central body and the external heads are made of stainless steel AISI 316. Proplast is interested to substitute the metallic substrate with a composite material, to do it, it was necessary to reduce wear due to the erosion of kaolin particles in the paint. Hydroabrasion tests were done, in order to verify the abrasion resistance of the carbon based epoxy composite used for the glaze coater. The APEO-siloxane coating by VITO showed the best performance, in terms of abrasion resistance. It seems that the "rubber" state of the coating itself prevents the abrasion of the coated surface.

Apart from the activities dealing with the day to day correct running of the project, like financial and administrative management, technical coordination, dissemination, knowledge and IPR management, Horizontal Activities of FOREMOST included other relevant actions on Gender Equality, Training, Health and Environmental aspects concerning fullerene-like materials, and Standardization.

The FOREMOST project has provided relevant contributions on health, safety and environmental aspects concerning inorganic fullerene-like nanoparticles and their use in coatings and lubricants. Thus, a document on *"safety measures for handling of IFLMs* *in production and processing stage"* was issued and updated during the project. An important objective for this task was to evaluate the sampling procedures for airborne nanoparticles and the setting up and operating the monitoring tools to detect IFLM nano-particles in the workplace of participants, contribute to the registering of the IFLM and working with relevant EU regulatory agencies for obtaining safety and health approval of IFLM. Therefore, a Scanning Mobility Particle Sizer detector 3034 SMPS was purchased by Tekniker and used to monitor nanoparticle size and density in the atmosphere at different places, in the laboratories and production plants of IonBond-UK, Vito, Milano University and NanoMaterials. Technical reports of these activities were issued. Dissemination of health and safety aspects of IFLMs was another important activity of the project, mainly borne by Jozef Stefan Institute.

In order to obtaining safety and health certification via toxicological evaluation of the IFLM compounds used in FOREMOST, before starting the project NanoMaterials asked for independent inhalation toxicity studies of IFLMs, which were shown to be non-toxic in acute oral ingestion and in skin sensitization toxicology tests. IFLM's are pre-registered in REACH.

Concerning standardisation, two possible standards have been identified that would build on work undertaken during the FOREMOST project. These are: "*Guidance on characteizinging low friction dry sliding contacts*"; and **"***Guidance on determination of distribution function for nano-objects in composite structures*", which will be proposed to the appropriate European standards technical committee.

Outstanding success had also the training courses organized in FOREMOST. Coordinated by Stockholm University, six courses on different subjects relevant for the project were organized during the project duration.

6. Conclusions

Innovative coatings lubricants and paints based on the incorporation of nanoparticles of inorganic fullerene-like materials (IFLMs) have been developed in the project. Two alternative routes have been explored for this purpose: introducing preformed IFLMs into the deposition process/lubricant/paint or by forming the IFLM components in-situ during the deposition process. Both methods have been demonstrated to be technically feasible, depending of the nature of the coating matrix or the desired fullerene-like structure.

Thus, after solving the problem of the de-agglomeration of the IFLM powder, a large variety of techniques were studied to incorporate previously synthesised IFLM nanoparticles into hard and polymeric coatings. IFLM nanoparticles were also successfully incorporated into lubricants.

Following the second approach considered in the project, some advanced nano-composite films in which the IFLM components were generated *in-situ* during the deposition process, were successfully synthesised. This achievement should be highlighted, because the *in-situ* growth of fullerene-like structures during the coating deposition was considered as the highest risk in the entire project. These positive results probed the technical feasibility of such approach.

An Access database of all FOREMOST coatings, containing a total of 125 different coating formulations, was issued at the middle of the project. A number of potential solutions for each end user application were identified on the basis of the coatings-specific requirements of each application. This coatings database was modified at the end of the project, adding information about the tribological testing and applications performance of the selected coatings.

The main industrially focussed objective of this project was to provide industry with radically new coatings and lubricants to significantly reduce and control friction and wear in rolling and sliding contacts to: extend operational life, reducing maintenance requirements and environmental impact.

This objective has been successfully achieved for some of the industrial applications considered in the project. Thus, according to the gear tests performed by the University of Newcastle, the best results were obtained with the NbX coatings developed by IonBond-UK. For high speed high loaded gears this FOREMOST coating was significantly better that all the state-of-the-art presently available coatings. The very good performance of lubricants and coatings containing IFLM particles in sliding/rolling applications was confirmed through FZG scuffing tests and Brugger tests carried out by Fuchs. Improving lubrication of gears is a common problem of the aerospace, automotive and manufacturing sectors. Therefore, this outstanding result obtained in FOREMOST for the specific requirement of the Rolls-Royce high speed, high temperature helical transmission gears could be reasonably extrapolated to other applications and industrial sectors.

Very good results have been also obtained for the mainshaft spline coupling and fan blade roots of the Rolls-Royce aero engine. Fretting fatigue tests made by Nottingham University showed excellent behaviour of DLC+WS_2 coatings from IonBond-CH, which have demonstrated a 50% improvement in performance over standard components.

Another successful result has been obtained in the case of the cam-tappet system of Renault. After performance evaluation in the Renault cylinder-head test bench, three FOREMOST solutions were better than serial one, namely, WSC from Coimbra, NbX from Ionbond-UK, and Ni-P+$IFWS_2$ from NanoMaterials.

For the EADS helicopter control link application, three different types of protective coatings of inorganic fullerene like materials (IFLM) incorporated in different matrix´ materials (nickel phosphorous and PEEK) or in situ grown IFLM structures (MoSeCH) showed positive results at the bolt-bushing fretting tests.

Also interesting results have been obtained with the glaze coater application conducted by Proplast, where the APEO-siloxane coating by VITO showed the best performance, in terms of abrasion resistance.

For other group of applications excellent results were obtained with the FOREMOST new materials in tribological laboratory tests. However, the performance of these coatings could not be fully validated in real parts within the duration of the project. That was the case of the fuel pump drive shaft spline application, where Aero Engine Controls collaborated with Imperial College to simulate the fretting wear conditions encountered in fuel pump using a High Frequency Reciprocating rig (HFRR). Regarding the friction coefficient Diamost from Kenosistec, Ni-P+WS_2 from NanoMaterials and Co-W-WS_2 from Nottingham University were the most promising coatings.

For the variable displacement fuel pump application, AEC collaborated with NPL, and the most promising coatings were Diamost, Ni-P+WS_2 and the BCN/C developed by CEA.

In the case of the window elevator-magnesium track best results were obtained with the epoxy-phenolic blend (30:70) filled with IF-WS_2 developed by Proplast.

There is a third group of applications where the IFLM containing coatings and lubricants did not show significant improvement against the state-of-the-art references or the scattered data gave no indication of clear improved performance of these new materials. Such was the case of the ball screw drive studied by Fatronik, where results obtained with the APEO-siloxane coating and the IFLM containing greases were not conclusive.

Concerning the control fuel filter mesh, two FOREMOST coatings, the PTFE+IFLM from Nottingham University, and the APEO Siloxane + IFLM from VITO showed promising results, but not better than the state-of-the-art PTFE-based commercially available products.

For the anti-abrasion anti-icing coatings for structural aircraft parts, tested by EADS, no evidence on improvement of anti-icing effect was found due to IFLM incorporated in organic topcoat prepared at Spolchemie (epoxy varnish + nanoSiO_2 + IFLM and enamel + nanoSiO_2 + IFLM).The PEEK+IFLM from Nottingham University showed significant reduction in friction coefficient through IFLM incorporation in PEEK.

Table 1: Summary of applications testing results

Application	Coatings / Lubricants	Results / Comments
Helicopter fuselage control link (EADS)	PEEK+IFWS$_2$ (Nottingham) Aerosol assisted	Tested up to 100 MPa, At 20 and 50 MPa no coating failed
	Ni-P+IFWS$_2$ (NanoMaterials) electroless	
	MoSeCH (Coimbra) Magnetron sputtering	
High torque mainshaft spline couplings and fan blade roots (Rolls Royce)	C$_6$+WS$_2$ (IonBond-CH) PACVD	Fretting fatigue tests (Nottingham): 50% improvement Scaled Spline tests. The results of these tests could have significant effect on the life and maintenance of Rolls Royce splines
	CrN+WS$_2$ (IonBond UK) PVD-Arc	Fretting fatigue tests (Nottingham): 10% improvement
Fuel pump drive spline (Goodrich/AEC)	Diamost (Kenosistec) PVD-Arc	The three coatings improve the present Cr coating used by AEC COF <0.3 Fretting wear tests have been carried out by Imperial with application specific wear test samples and the performance of the chosen coatings compared with Industry standard coatings. The Diamost coating gave comparable performance to the Industry standard coatings and further simulative testing is now planned with Imperial College outside of FOREMOST.
	Ni-P+IFWS$_2$ (NanoMaterials) electroless	
	Co-W+WS$_2$ (Nottingham) electroplating	
Fuel pump thrust ball (Goodrich/AEC)	Diamost (Kenosistec) PVD-Arc	A coated thrust ball / auxiliary cam plate pair has been run for 58 hrs at ambient temperature + maximum service operating conditions (fuel pressure, pump speed) for current piston pump designs. Further testing is required to demonstrate operating temperature capability + maximum pressure/speed + endurance capability.
	Ni-P+IFWS$_2$ (NanoMaterials) electroless	Very promising results in laboratory tests (NPL)
	BCN/C (CEA)	
High speed, high temperature helical transmission gears (Rolls Royce)	NbX (IonBond-UK.) PVD-Arc	Clear improvement against the state of the art Wear <5µm after 90 million cycles (gear tests by Newcastle)
	Oil + 1-3% IFWS$_2$ (Fuchs)	FZG test 25% improvement
		Brugger test 50% improvement

Application	Coatings / Lubricants	Results / Comments
Structural aircraft parts (EADS)	Epoxy varnish + nanoSiO_2+IFWS_2 (Spolchemie)	No evidence on improvement of anti-icing effect
	Enamel + nanoSiO_2+IFWS_2	
	PEEK+IFWS_2 (Nottingham) Aerosol assisted	Significant reduction in friction coefficient
Aircraft Engine Fuel System "anti-lacquer" coatings (Goodrich/AEC)	APEO-siloxane+IFWS_2 (VITO)	Improve the uncoated AEC reference, equivalent to state of the art PTFE-based product
	PTFE+IFWS_2 (Nottingham) Aerosol assisted	
Cam-tappet (Renault)	WSC (Coimbra) Magnetron sputtering	The three coatings improve the present Renault solution. Future studies of thermal stability needed
	NbX (IonBond-UK.) PVD-Arc	
	Ni-P+IFWS_2 (NanoMaterials) electroless	
Window elevator and magnesium track (Proplast)	Epoxy-phenolic filled with IF-WS_2 (Proplast)	Abrasion and corrosion resistance tests
Ball-screw drives (Fatronik)	APEO-siloxane (VITO)	No clear improvements at the Fatronik's test bench
	Grease+IFWS_2 (Fuchs)	
Glaze coater (Proplast)	APEO-siloxane (VITO)	Good results
	Organically modified Silica + IFWS_2 (BAM)	

To make these materials available to the industry, NanoMaterials completed installation of all process equipment plus infrastructure of a Pilot Unit for cost-effective production of fullerene-like WS_2 nano-spheres with a production capacity of 75 kg/day.

Another important objective of FOREMOST was to provide guide lines to assist in the industrial take-up of these new materials and concepts. Therefore, the tribological testing was undertaken not only to perform the preliminary ranging trials to select the most promising coatings for each application, but also to determine the coordinates within the contact conditions where the IFLM containing coatings and lubricants offer maximum benefit. The tribological mapping evaluated a wide range of parameters to establish the most suitable operating conditions, and other limits, which in turn allow other possible commercial applications to be identified.

From a scientific point of view, important contributions have been made in the synthesis of new kinds of inorganic layered compounds as nanospheres and nanotubes. like MoS_2 "mama"-tubes (MoS_2 fullerenes inside MoS_2 nanotubes) from JSI. Fundamental studies about growth mechanisms of inorganic fullerene-like structures were also carried out by JSI and Linköping University. This research led up to several new patent applications.

Another project objective successfully achieved was to provide full chemical, structural and mechanical characterization of IFLM coatings. Within these studies IFLM lubrication mechanisms were elucidated, being by pressure induced exfoliation of IFLM structures and further formation of a self-lubricant tribofilm.

The FOREMOST project has also provided relevant contributions on health and safety aspects concerning inorganic fullerene-like nanoparticles. Independent inhalation toxicity studies of IFLMs concluded that these particles are non-toxic in acute oral ingestion and in skin sensitization toxicology tests. IFLM's are pre-registered in REACH.

7. References

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8. Publishable results of the Final plan for using and disseminating the knowledge

Partner name:	**Rolls Royce**		**Author**: **M Mountney**
Result Description (Products envisaged, functional description, main advantages, innovations)	Test Requirement documents issues and bought off by appropriate partners Test results published on interim results- baseline material tests and initial ILFM test pieces Final test results published (possible PhD study at University of Nottingham would result in doctoral thesis) Ballot and Publication of Rolls-Royce design standard for the use of IFLM coatings in anti-fretting, reduced friction couplings Ballot and publication of material specification for use with design standard Ballot and publication of process specification for application of material to aerospace steels and titanium		
Possible Market Applications Sectors, type of use….	**Aerospace Gas Turbine Drives** **Industrial Power Gas Turbine Drives** **Marine Gas Turbine Drives**		
Stage of development	**By close of project, successful outcome would be RR TRL (Technology Readiness Level) 4 requirement is met , ie successful component rig test, ideally level 6 is successful engine test**		
Collaboration sought or offered.	✓ Further research or development ✓ Establish a joint enterprise or partnership ☐ License agreement ☐ Marketing agreement ✓ Manufacturing agreement ☐ Development Financing ☐ Private-public partnership ☐ Venture capital/spin-off funding ☐ Available for consultancy ☐ Information exchange/ Training ☐ Other		
Collaborator Details	**Material supplier (NanoMaterials), process supplier, (Ion Bond, University of Nottingham)**		
Intellectual Property rights granted or published	**IPR patent for application of specific nano-material to gas turbine drive shaft couplings**		
Contact details	**Scott Wood** **Email- scott.wood@rolls-royce.com**		

Partner name:	Goodrich		Author: T. Hirst
Result Description (Products envisaged, functional description, main advantages, innovations)	**Aircraft Engine Fuel System Piston Pump Unit.** Kinematic model developed produced to describe the processive movement taking place between the auxiliary cam plate and piston slipper tops which drives the rolling/sliding relative movement between the cadmium plated thrust ball & auxiliary cam plate counter face. Ni-P-WS2 coated Thrust Ball pump tested at ambient temperature to assess potential vs toxic cadmium plating process currently specified. **Aircraft Engine Fuel System Gear Pump Unit** Simulative fretting wear tests carried out on a range of coatings to assess capability to replace current flash chrome plate currently specified **Aircraft Engine Fuel System Metering Unit Filter.** Rig testing of PTFE + WS2 coated filter mesh carried out to assess capability to reduce or eliminate the nucleation + deposition of fuel breakdown products.		
Possible Market Applications Sectors, type of use….	Aircraft Gear Pump & Piston Pump based Fuel Systems		
Stage of development	☐ Scientific and/or Technical knowledge (Basic research) ☐ Guidelines, methodologies, technical drawings ☐ Software code ✓ Experimental development stage (laboratory prototype) ☐ Prototype/demonstrator available for testing ☐ Results of demonstration trials available ✓ Other (please specify.)		
Collaboration sought or offered.	✓ Further research or development ☐ Establish a joint enterprise or partnership ☐ License agreement ☐ Marketing agreement ☐ Manufacturing agreement ☐ Development Financing ☐ Private-public partnership ☐ Venture capital/spin-off funding ☐ Available for consultancy ☐ Information exchange/ Training ☐ Other		
Collaborator Details	**Imperial College:** further fretting test work planned external to FOREMOST Nottingham University: further work on Low Surface Energy Coatings planned external to FOREMOST		
Intellectual Property rights granted or published	**n/a**		
Contact details	Terry.Hirst@goodrich.com		

Partner name:	**LiU**		**Author: Lars Hultman**
Result Description (Products envisaged, functional description, main advantages, innovations)	FL-CN_x coatings made by magnetron sputtering methods developed at Linköping University are of technological interest because of its outstanding elasticity and fracture toughness making it a compliant material. Also, the way it can dissipate contact stresses, suppress brittle fracture, and exhibit smoother surface *by chemical etching* during deposition makes it favourable for tribological applications on, e.g. components,		
Possible Market Applications Sectors, type of use….			
Stage of development	✓ Scientific and/or Technical knowledge (Basic research) ☐ Guidelines, methodologies, technical drawings ☐ Software code ☐ Experimental development stage (laboratory prototype) ☐ Prototype/demonstrator available for testing ☐ Results of demonstration trials available ☐ Other (please specify.)		
Collaboration sought or offered.	✓ Further research or development ☐ Establish a joint enterprise or partnership ☐ License agreement ☐ Marketing agreement ☐ Manufacturing agreement ☐ Development Financing ☐ Private-public partnership ☐ Venture capital/spin-off funding ☐ Available for consultancy ☐ Information exchange/ Training ☐ Other		
Collaborator Details			
Intellectual Property rights granted or published			
Contact details	**Lars Hultman Linköping University** **larhu@ifm.liu.se**		

Partner name:	**Nottingham**	Author:	X.H. Hou and K.L. Choy
Result Description (Products envisaged, functional description, main advantages, innovations)	Inorganic fullerene-like tungsten disulfide (IF-WS_2) nanoparticles have been successfully incorporated into Cr_2O_3 coatings via a modified aerosol-assisted chemical vapour deposition (AACVD) process. A Preliminary ball-on-flat test shows that the coefficient of friction is significantly reduced with the incorporation of IF-WS_2 nanoparticles in the nanocomposite coating.		
Possible Market Applications Sectors, type of use….	Tribological components for automotive and aerospace industries		
Stage of development	□ Scientific and/or Technical knowledge (Basic research) □ Guidelines, methodologies, technical drawings □ Software code ✓ Experimental development stage (laboratory prototype) □ Prototype/demonstrator available for testing □ Results of demonstration trials available □ Other (please specify.)		
Collaboration to be sought or offered.	✓ Further research or development ✓ Establish a joint enterprise or partnership ✓ License agreement □ Marketing agreement ✓ Manufacturing agreement ✓ Development Financing □ Private-public partnership □ Venture capital/spin-off funding □ Available for consultancy □ Information exchange/ Training □ Other		
Collaborator Details			
Intellectual Property rights granted or published	____________		
Contact details	Prof Kwang-Leong Choy, kwang-leong.choy@nottingham.ac.uk		

Partner name:	**Nottingham**		**Author**: Xianghui Hou, Chongxin Shan and Kwang-Leong Choy
Result Description (Products envisaged, functional description, main advantages, innovations)	Studies on microstructures and tribological properties of PEEK-based nanocomposite coatings incorporating inorganic fullerene-like nanoparticles. IF-WS_2/PEEK nanocomposite coatings have been successfully produced using our aerosol-assisted deposition process. The coefficient of friction of PEEK has been reduced significantly by incorporating IF-WS_2 nanoparticles.		
Possible Market Applications Sectors, type of use….	Tribological components for automotive and aerospace industries		
Stage of development	Coated samples have been sent to SP3 partners for application evaluation, and more coated samples will be prepared for such purpose.		
Collaboration sought or offered.	✓ Further research or development ✓ Establish a joint enterprise or partnership ✓ License agreement ☐ Marketing agreement ☐ Manufacturing agreement ☐ Development Financing ✓ Private-public partnership ✓ Venture capital/spin-off funding ✓ Available for consultancy ☐ Information exchange/ Training ☐ Other		
Collaborator Details			
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Contact details	Prof Kwang-Leong Choy, kwang-leong.choy@nottingham.ac.uk		

Partner name:	**BAM**		**Author**: M. Griepentrog, H. Hattermann
Result Description (Products envisaged, functional description, main advantages, innovations)	A sol-gel route was established to prepare coatings based on either alumina or organically modified silica with embedded fulleren-like WS_2 particles. Due to the embedded nanoparticles the coefficient of friction is reduced significantly compared to coatings without nanoparticles.		
Possible Market Applications Sectors, type of use….	Tribological components		
Stage of development	Coated samples have been sent to SP3 partners for application evaluation, and more coated samples will be prepared for such purpose.		
Collaboration sought or offered.	✓ Further research or development ☐ Establish a joint enterprise or partnership ☐ License agreement ☐ Marketing agreement ☐ Manufacturing agreement ☐ Development Financing ✓ Private-public partnership ☐ Venture capital/spin-off funding ✓ Available for consultancy ✓ Information exchange/ Training ☐ Other		
Collaborator Details			
Intellectual Property rights granted or published			
Contact details	Michael.Griepentrog@bam.de		

Partner name:	**BAM**		**Author**: M. Griepentrog,
Result Description (Products envisaged, functional description, main advantages, innovations)	Special methods for testing thin nanocomposite coatings using Instrumented Indentation Testing. The methods include test procedures, data acquisition and evaluation.		
Possible Market Applications Sectors, type of use….	Mechanical testing of thin coating.		
Stage of development	Ready for use.		
Collaboration sought or offered.	✓ Further research or development ☐ Establish a joint enterprise or partnership ☐ License agreement ☐ Marketing agreement ☐ Manufacturing agreement ☐ Development Financing ✓ Private-public partnership ☐ Venture capital/spin-off funding ✓ Available for consultancy ✓ Information exchange/ Training ☐ Other		
Collaborator Details			
Intellectual Property rights granted or published			
Contact details	Michael.Griepentrog@bam.de		

Partner name:	**Nottingham and CNRS**		**Author**: Xianghui Hou, Kwang-Leong Choy, C.X. Shan and Virginie Serín
Result Description (Products envisaged, functional description, main advantages, innovations)	Studies on the deposition mechanism of Aerosol-Assisted Chemical Vapor Deposition (AACVD) for fabrication of Nanocomposite Coatings.		
Possible Market Applications Sectors, type of use….	To provide a guideline for the fabrication of nanocomposite coatings by AACVD method		
Stage of development	Fundamental research		
Collaboration sought or offered.	✓ Further research or development ✓ Establish a joint enterprise or partnership ✓ License agreement ☐ Marketing agreement ☐ Manufacturing agreement ☐ Development Financing ✓ Private-public partnership ✓ Venture capital/spin-off funding ✓ Available for consultancy ☐ Information exchange/ Training ☐ Other		
Collaborator Details	Nottingham carried out the processing study of AAVCD mechanism, while CNRS performed TEM characterisation. Other partners to be confirmed.		
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Contact details	Prof Kwang-Leong Choy, kwang-leong.choy@nottingham.ac.uk		

Partner name:	**Nottingham, CNRS, Nanomaterials**		**Author**: X Hou, KL Choy, V Serin, and N Fleischer
Result Description (Products envisaged, functional description, main advantages, innovations)	***Processing of nanocomposite coatings using aerosol-assisted chemical vapor deposition (AACVD) method:*** The flexibility of atomizing precursor solution or suspension in the AACVD process makes it possible for the incorporation of pre-formed nanoparticles in the precursor solution and to co-deposit the particles and matrix concurrently on the substrate surface to form the desired nanocomposite coatings. Our recent results have demonstrated that AACVD is a promising method for the synthesis of nanocomposite coatings with the incorporation of nanoparticles into ceramic matrices. The synthesis of inorganic fullerene-like tungsten disulfide (IF-WS_2) nanoparticles, as well as the processing and deposition mechanism of IF-WS_2/Cr_2O_3 is presented.		
Possible Market Applications Sectors, type of use….	***Processing of nanocomposite coatings using aerosol-assisted chemical vapor deposition (AACVD) method***		
Stage of development	R&D		
Collaboration sought or offered.	✓ Further research or development ☐ Establish a joint enterprise or partnership ☐ License agreement ☐ Marketing agreement ☐ Manufacturing agreement ☐ Development Financing ☐ Private-public partnership ☐ Venture capital/spin-off funding ☐ Available for consultancy ☐ Information exchange/ Training ☐ Other		
Collaborator Details	Nanomaterials produces IF-WS_2 nanoparticles; Nottingham synthesizes nanocomposites using Aerosol-assisted techniques; CNRS performs TEM for microstructure analysis.		
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Contact details	Prof. Kwang-Leong Choy Department of Mechanical, Materials, and Manufacturing Engineering Faculty of Engineering, The University of Nottingham, Nottingham, NG7 2RD, United Kingdom Tel/Fax: +44-1159514031 Email:kwang-leong.choy@nottingham.ac.uk		

Partner name:	**PROPLAST**		**Author**: Debora Puglia, Prof. J.M. Kenny
Result Description (Products envisaged, functional description, main advantages, innovations)	Studies on the incorporation and dispersion of IFLMs in thermosetting polymeric matrices with high resistance to erosion and temperature for fabrication of Nanocomposite Coatings.		
Possible Market Applications Sectors, type of use….	To provide a guideline for the realization of nanocomposite coatings by ultrasound and high shear mechanical mixing methods		
Stage of development			
Collaboration sought or offered.	✓ Further research or development ✓ Establish a joint enterprise or partnership ☐ License agreement ☐ Marketing agreement ✓ Manufacturing agreement ☐ Development Financing ☐ Private-public partnership ☐ Venture capital/spin-off funding ☐ Available for consultancy ☐ Information exchange/ Training ☐ Other		
Collaborator Details			
Intellectual Property rights granted or published			
Contact details	Prof. Josè Maria Kenny jkenny@unipg.it		

Partner name:	**NPL**		**Author**: Mark Gee
Result Description (Products envisaged, functional description, main advantages, innovations)	New micro-tribology test system incorporating innovative flexure system for force generation.		
Possible Market Applications Sectors, type of use….	**Tribological testing**		
Stage of development			
Collaboration sought or offered.	✓ Further research or development ✓ Establish a joint enterprise or partnership ✓ License agreement ☐ Marketing agreement ☐ Manufacturing agreement ☐ Development Financing ☐ Private-public partnership ☐ Venture capital/spin-off funding ☐ Available for consultancy ☐ Information exchange/ Training ☐ Other		
Collaborator Details			
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Contact details	**Professor Mark Gee** **National Physical Laboratory** **Hampton Road** **Teddington** **TW11 0LW**		

Partner name:	**Imperial College**		**Author**: Ales Kratky + others
Result Description (Products envisaged, functional description, main advantages, innovations)	New results on tribological performance of various coatings in relation to fretting and other forms of reciprocating sliding.		
Possible Market Applications Sectors, type of use….	**General tribological applications across many sectors**		
Stage of development	**Research and Development**		
Collaboration sought or offered.	✓ Further research or development ☐ Establish a joint enterprise or partnership ☐ License agreement ☐ Marketing agreement ☐ Manufacturing agreement ☐ Development Financing ☐ Private-public partnership ☐ Venture capital/spin-off funding ✓Available for consultancy ✓ Information exchange/ Training ☐ Other		
Collaborator Details			
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Contact details	**Ales Kratky or Dr R S Sayles** **Tribology Section** **Mechanical Engineering Dept.** **South Kensington Campus** **Imperial College** **London, SW7 2BX,** **UK**		

Partner name:	**Imperial College**		**Author**: Dr Amir Kadiric + others
Result Description (Products envisaged, functional description, main advantages, innovations)	Modelling of coated tribological contacts to predict local contact mechanics and stresses, both at the surface and within the sub-surface, and also predict thermal effects under frictional sliding conditions. The models can also deal with surface roughness effects within the contact based on real measurements of topography.		
Possible Market Applications Sectors, type of use….	General tribological applications across many sectors, but also very useful as a design tool for coatings, in terms of optimising materials and layer thickness effects to cope with different contact pressures, surface roughness's and particularly the frictional heating effects these combinations might create under design operational conditions.		
Stage of development	Modelling can be for 2-dimensional multi-layer coatings analyses and several 3-dimensional nominal geometries. Continued research and development is extending the range of applications of the methods.		
Collaboration sought or offered.	✓ Further research or development ☐ Establish a joint enterprise or partnership ☐ License agreement ☐ Marketing agreement ☐ Manufacturing agreement ☐ Development Financing ☐ Private-public partnership ☐ Venture capital/spin-off funding ✓Available for consultancy ☐ Information exchange/ Training ☐ Other		
Collaborator Details			
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Contact details	**Dr A Kadiric or Dr R S Sayles** **Tribology Section** **Mechanical Engineering Dept.** **South Kensington Campus** **Imperial College** **London, SW7 2BX,** **UK**		