Project no. COOP-CT-2006-032133

STREAM

Novel drilling system for cost effective extraction of ornamental stone blocks in Europe with lower environmental impact

Co-operative research Project

Full activity report

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Project coordinator name: Claudio Bavelli
Project coordinator organisation name: Ripamonti

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1 Publishable executive summary

STREAM project developed an innovative DLC coating deposition by Plasma Assisted Chemical Vapor (PACVD) technique, enabling the design and successful test of a new down-the-hole (DTH) water hammer of small dimension (2 ¼ inches) for quarry applications.

In order to optimize the deposition process and to improve the quality of the coating in term of substrate adhesion and wear resistance, the PACVD technique was modelled using a pre-industrial PACVD plant (Figure 1-1). Laboratory testes allowed to define the most important process parameters and a semi-empirical control system model of the plant.

Figure 1-1: Pre-industrial PACVD plant

Further tests were conducted in order to understand optimal base material, pre-coating and thermal treatment to be used for the elements of a water powered drilling hammer.
Tests's results showed that high wear resistance and low friction are provided by the DLC coating and that the surfaces have a very good corrosion resistance.
In order to optimise the process for the specific application, several base materials and the most suitable surface treatments have been studied obtaining the highest level of compatibility between the substrate and the coating: hybrid diffusion treatment consisting of carburizing and sulfonitriding applied on base steel 16MnCr5 resulted the best solution for thickness uniformity, corrosion resistance and wear resistance.
Regarding the DLC coating two different environmental conditions were considered: clear water and water plus hard dispersed particles Al_2O_3 simulating the fragments of stone in the working conditions. In both cases experimental results confirmed an excellent adhesion properties of coating layer and low presence of cracks.
Once validated the process of laboratory scale, the same treatments and coatings were applied on the surfaces of several STREAM prototypes components (Figure 1-2).

Figure 1-2: Piston with chromising - DLC

The excellent experimental results achieved with the pre-industrial DLC plant, pushed the consortium to design a bigger industrial DLC plant in order to coat larger elements and fully exploit the commercial potential of the optimised coating process. A 3D view of the new plant is shown in Figure 1-3. The plant will have a coating area of 1.0 x 1.0 x 0.7 m^3 and has been designed taking in account the process optimization performed during the project.

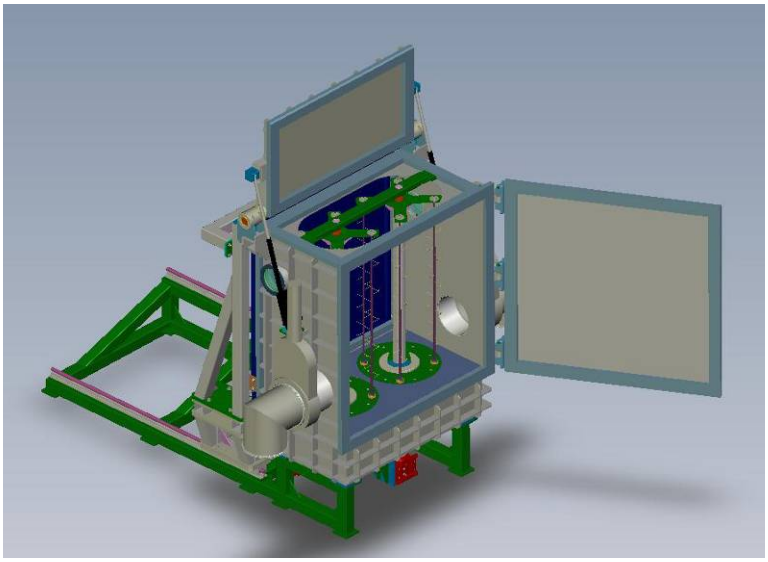


Figure 1-3: Design of the industrial DLC deposition plant with 1,0 X 1,0 X 0,7 m3 coating volume area

The design of a new water down the hole (DTH) hammer is the second innovative result of STREAM project.

In comparison with pneumatic hammer, water powered hammers are more energy efficient, do not generate high hole deviations and do not diffuse microscopic particles in the working environment during drilling. Furthermore water DTH hammer represent a better solution in comparison to hydraulic top-hammers: water top hammers are in fact noisy, characterized by high vibrations and less efficient because percussion is generated far from the drilling bit.

The design of the new water DTH hammer prototype started from the study and analysis of an existing water top hammer. The first manufactured STREAM hammer prototype was a 3 ¼ inches DTH hammer that was successfully tested in different drilling condition always confirming a good penetration rate (Table 1 and Table 2). The success in testing the 3 ¼ inches prototype (Figure 1-4) represented the first important step towards the design of the final STREAM prototype.

Table 1: Tests with white granite

Inclination [°]	90°	0°
Penetration rate [cm/min]	35 ±1.1	39±1.1
Water flow [l/min]	33	33

Table 2: Tests with marble

Inclination [°]	90°	0°
Penetration rate [cm/min]	40±1.2	43±1.1
Water flow [l/min]	33	33

So a second smaller STREAM hammer prototype with an external diameter of 2 ¼ inches was studied.

Figure 1-4: Test of the DTH 3 ¼ inches STREAM prototype

The successful design and prototyping of a 2¼ inches hammer (Figure 1-5) is a very important solution for quarry extraction where actually explosive or wire diamonds techniques follows holes drilling of about 58 mm diameter using pneumatic DTH hammers. Besides, drilling with 2¼ inches pneumatic DTH hammer are commonly used in the mining activities or in the civil construction sector (e.i. tunnel drilling) that represents a big secondary market.

Figure 1-5: The 2 ¼ inches STREAM DTH prototype

The 2 ¼ inches hammer (**Table 3**) was tested in very different conditions varying the type of stones (marble, granite, Serizzo and Serena stone) and the drilling inclination (90°, 0°, 45°).

Table 3: Technical specifications of the 2¼ STREAM prototype

External diameter	2 ¼ inches
Water flow	33 l/min
Water hammer pressure	150 bar
Penetration rate (on granite)	50 cm/min
Piston frequency	73 Hz
Mass	10.2 kg
Length	635 mm

Hammer's penetration rate was measured (Table 4 and Table 5) together with feeding water pressure, inlet water flow and other hammer's technical characteristics using DLC coated elements or standard one. Experimental data showed an improvement up to 15 % of penetration rate if DLC coated components are used confirming the success in the STREAM approach (Table 4 and Table 5).

Table 4: Values for test with granite

Inclination [°]	Piston Coating	Penetration Rate [cm / min]	Water Flow [l /min]
90	without DLC	41±1,2	39,6
	with DLC	50±1.1	33,2
45	without DLC	42±0.8	38,2
	with DLC	52±0.8	32,9
0	without DLC	44±1.3	38,7
	with DLC	54±1.1	33,3

Table 5: Values for test with marble

Inclination [°]	Piston Coating	Penetration Rate [cm / min]	Water Flow [l /min]
90	without DLC	46±1,6	39,3
	with DLC	55±1.2	33,6
45	without DLC	48±0.8	38,9
	with DLC	57±0.8	33,1
0	without DLC	49±1.3	38,6
	with DLC	58±1.3	33,3

Finally a 1¼ inches STREAM prototype was fully designed DTH hammer and a full 3D model of the hammer was made (Figure 1-6). Moreover a parametric model in Matlab-Simulink was developed allowing to simulate the dynamic hammer behaviour and to verify the correctness of the mechanical design and to calculate expected hammer performances.

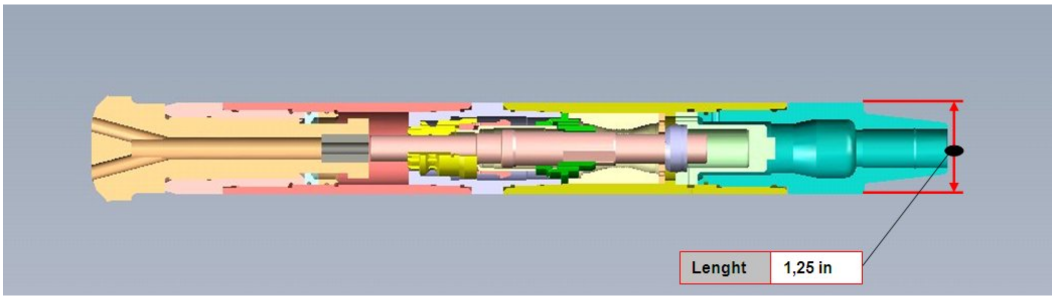


Figure 1-6: The full 3D model of 1 ¼ inches STREAM prototype

2 Project objectives and major achievements during the reporting period

The main aim of the STREAM project was to develop effective coating technologies in order to enable the design and prototyping of a small diameter water Down-The-Hole (DTH) hammer with a high mechanical efficiency and a long working life. STREAM wanted to develop a cost-effective deposition of water and wear resistant Diamond Like Coating (DLC), coupled with specific thermal treatments and pre-coatings.

During the first reporting period activities were concentrated on:

- Industrial requirements and definition of materials and processing parameters;
- Development of the structure of the STREAM software tool;
- Selection and testing of the surface treatment;
- Design of the pilot plant for the DLC deposition;
- Selection of the most suitable test method for the coating evaluation;
- Preliminary selection of a suitable design for the STREAM hammer development.

The activities started with the selection of the best base materials and thermal treatments to develop a high wear and corrosion resistant coating to be used in the heavy duty applications as quarry or mining was began too. Starting from a standard DLC plant and adapting it to the STREAM application, several laboratory tests have been performed in order to optimize the DLC deposition process.
Three hammers (Wassara, Rockbit and Novateck) have been deeply studied both by experimental tests and developing 3D solid and dynamic models in order to select the best starting design for the water DTH STREAM hammer. As a result of these studies an original down-the-hole hydraulic hammer design was undertaken.

During the second reporting period activities were concentrated on:

- Designing, manufacturing, testing and evaluating the STREAM hammer prototypes in order to design of 1¼ inches DHL hammer. As result a 3¼ and 2¼ inches hammer prototypes have been successfully designed, manufactured and tested on different materials and working conditions. The 1¼ inches water DTH hammer has been fully designed and modeled.

- Completing the coating thin film characterisation, defining the PACVD Process Control Methodology and testing at full scale the coating and thermal treatments on the final hammer prototype. As result an optimized deposition process has been defined and an industrial DLC deposition plan has been designed. Moreover full scale hammer components have been coated and tested, demonstrating the improvement of performance and working life in line with the initial project objectives.

- Defining a complete plan for the use and the dissemination of project innovative knowledge. Several scientific papers were presented participating to four International fairs and congresses.

The first step of the design of the STREAM hammer prototype was the manufacturing of a 3 ¼ inches down the hole water hammer.
This hammer was successfully tested and allowed to manufacture the 2 ¼ inches prototype that was performed redesigning the front part and the housing of 3 ¼ inches hammer prototype. In parallel to the design activity of the hammer the study on the coatings and base materials continued. Tribological experiments allowed deciding definitely the base material and coatings to use in the 2 ¼ inches prototype design: chromium-plating and chromium-plating plus DLC deposition (duplex coating) were furthermore tested in laboratory to simulate the condition of the hydraulic parts of the hammer. The 2 ¼ hammer was manufactured and after tested in different conditions varying the type of stones, the drilling inclination and some working parameters of the system.
Project results has been presented to several international conferences ("Interfinish 2008" and "32th National Congress of A.I.M.") and fairs ("Geogluid 2008" and "Research2Business 2008"). The project website has been continuously updated to help the easy communication among partners and disseminate project results.

The results show that all planned milestones have achieved as planned in the DoW and in the letter "Answers to Recommendations in the Review Report RP1" of April 2008:

- Design of reduced performance manufacturing analysis tool;
- System specification;
- Material Selection;
- Design of reduced performance PACVD plant;
- Preliminary test on First Water DTH hammer prototype;
- System performance evaluation;
- Study and optimization of the DLC PACVD process;
- Manufacture of a lab scale DLC plant;
- Design of a new industrial DLC plant;
- Tribological tests to understand the best base material and pre-coating to apply in mechanical components;
- Modelling, design and testing of the first 3 ½ inches STREAM prototype;
- Tribological tests to understand the best base material and coating;
- Modelling, design and testing of the second 2 ¼ inches STREAM prototype;
- Modelling and design of the third STREAM 1 ¼ inches prototype;
- Participation to international fairs and international congresses to disseminate project results.

3 Workpackage progress of the period

The activities performed during all the reporting period, as scheduled by the project plan, are relative to: WP1 – Manufacturing analysis tool; WP2 – Requirements and specification; WP3 – Materials selection and testing; WP4 – Coating plant; WP5 – Process optimization; WP6 – Design and prototyping of demonstrators; WP7 - Testing and system performance demonstration; WP8 – Innovation related activities; WP9 – Project management.

In the following paragraphs the activities performed in the two years of the project are reported as far as activities related to tasks 1.1,1.2, 1.3 of WP 1, to tasks 2.1, 2.2, 2.3 of WP 2, to tasks 3.1, 3.2 of WP 3, to tasks 4.1, 4.2 of WP4, to tasks 5.1, 5.2 and 5.3 of WP5, to tasks 6.1, 6.2, 6.3 and 6.4 of WP6, to task 7.1, 7.2 and 7.3 of WP7, to tasks 8.1, 8.2 and 8.3 of WP8 and to task 9.1, 9.2 of WP9.

3.1 WP 1 Manufacturing analysis tool

The objective of the Workpackage is to develop a Software Tool able to support end-users on estimating the effects of the crucial parameters of the manufacturing process of mechanical components using the STREAM coating process.

Task 1.1: Definition of materials and processing parameters
Partners Involved: DAPP, CROMO, POLIMI, NEUMAC, MARMORES
Related deliverable: D1 – Specification of the materials and production parameters

The existing coating and surface treatments have been reviewed and the STREAM coating process based on Plasma Assisted Chemical Vapour Deposition (PACVD) deposition of Diamond-Like-Carbon DLC films has been defined. The information on coatings and surface treatments has been collected to be used as input to develop the Manufacturing Analysis Tool and to define the coating system specification of STREAM system.
The most suitable surface treatments or coatings able to satisfy requirements of metal parts used in drilling systems have been selected and classified on the base of their influence on the final performance of the base material.
In drilling main parts of are made of metallic materials, which can fulfil the exacting requirements about their properties only after proper surface treatments. This is especially true for water-powered drilling systems, where corrosion phenomena and wear mechanisms may interact each other by exacerbating single effects. Because moving parts exist in drilling systems, also attainment of low friction is quite desirable, to reduce the power dissipation and to decrease the stress level in the contact area. Similar arguments are valid for many others mechanical devices, where corrosion and wear control the overall performance of the system. Therefore, the data collected and analysed in this task could be a useful for many industrial fields, other than drilling equipment.
In particular for mechanical systems surface treatments and coatings aims to improve mainly wear resistance, corrosion resistance, and to allow low friction and self-lubrication.
The most common coatings and treatments able to improve each of these properties have been described giving for each one details of substrate requirements, deposition process and mechanical properties. These are thermochemical treatments (vacuum carburising, gas nitriding), PVD, hard chromium, electroless Ni-P, electrolytic Ni-P, low friction materials (graphite-based materials, MoS_2, PTFE)
A more detailed analysis has been performed for DLC coating as it can provide an improvement of the properties of base materials on all the three aspects (wear, corrosion and self-lubrication).

The several deposition processes of DLC suitable for industrial production has been analysed. An accurate analysis of each deposition method showed that the most suitable for our application is the Plasma Assisted Chemical Vapour Depositon (PACVD).

A first description of the deposition process that will be used in the STREAM project has been given. The process is similar to the traditional PACVD technique but differing mainly in the remote-plasma configuration. The limitations about the capability of the system to coat internal surfaces have been critically analysed; the problem to assure a uniform coating on internal surface rise only with hollow slender parts, like a cylinder of a drilling machine, for which other coating or thermal treatments then DLC can be used.

Task 1.2: Development and implementation
Partners Involved: DAPP, CROMO, NEUMAC, POLIMI
Related deliverable: D1 – Specification of the materials and production parameters; D2 – Software tool;

The first reporting period was used to reviews the existing coating and surface treatments for drilling systems components and many other mechanical devices; furthermore the STREAM coating process based on PACVD deposition of DLC films was defined.
The information collected was employed as input to develop a first version of the Design Tool (D2) and to define the coating system specification of STREAM system (D3).
The information on coatings and surface treatments previously collected in Task 1.1 has been used as starting point for the development of the structure of the first Stream Software Tool. The requirements and the expectations for the software tool have been defined as follow:

- Provide the necessary knowledge for the selection of coatings and surface treatments on the base of general requirements (friction, wear, corrosion and fatigue) through a tool service called “Guide To Coating Selection”;
- Guide the user in selecting the most suitable coatings/surface treatments on the base of the required application in the field of mechanical engineering through a tool service called “Solving Your Problem”;

The user will access to the software through the private area of the Stream web portal.

Figure 3-1 shows a partial view of the STREAM software tool architecture.

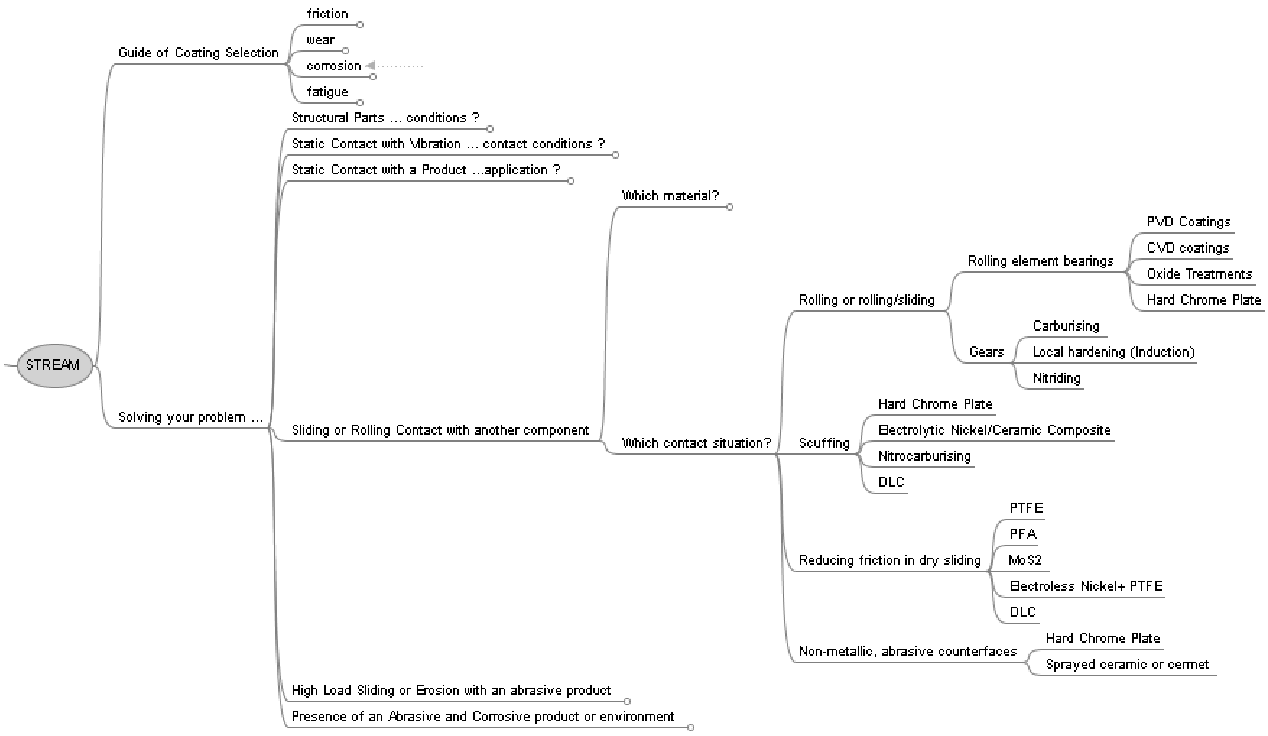


Figure 3-1 Flowchart of the Stream Software Tool

In the second reporting period the final version of the STREAM Design Tool was developed by DAPP with the contribution of CROMO, NEUMAC and POLIMI. The software tool was made with the purpose of facilitating the use of DLC, enhancing the competence of the user in the selection of the best coating and in supporting the optimise design of mechanical components to be used in drilling equipments. The tool helps the user in its decision making and, in the same time, is able to stimulate its inventive capability. This application was built also to exploit the potentiality of the DLC coating in particular in the surface design of hydraulic components of water DTH hammers.
It has a tree-structure that articulates, proceeding in its pages, in cases always more particular. Step by step questions about load, motion and environmental conditions are posed, aspects that help to describe the particular application of interest. In order to arrive to the own solution the user can define his case expressing the values of some parameters like pressure, temperature, entity of loads, and giving information about the chemical composition of the working environment.
The simple structure and easy to use approach of the tool allows unskilled users to exploit the potentialities of the Design Tool. This instrument is able to support the use of DLC in the inventive application process by means of specific examples and effective tutorials. The preliminary design phase could be there accomplished in a straightforward way.
The user-friendly interface has a positive effect of making easier and more intuitive for the user to perform rapid query of the databases finalised to provide him with the information needed.

The STREAM Glossary (see Figure 3-3) is a collection of meaningful words that regards the world of surface design and mechanical design in general, arranged in alphabetical order. The user, after having logged in, can use the “search filter” and write the word he interests. That allows him to access directly to what he/she search. This tool can join to the design tool during the choice of base materials and coatings. All the concepts used in the design tool are commented and explained in the glossary completing the information supplied in the linked page of the same design tool.

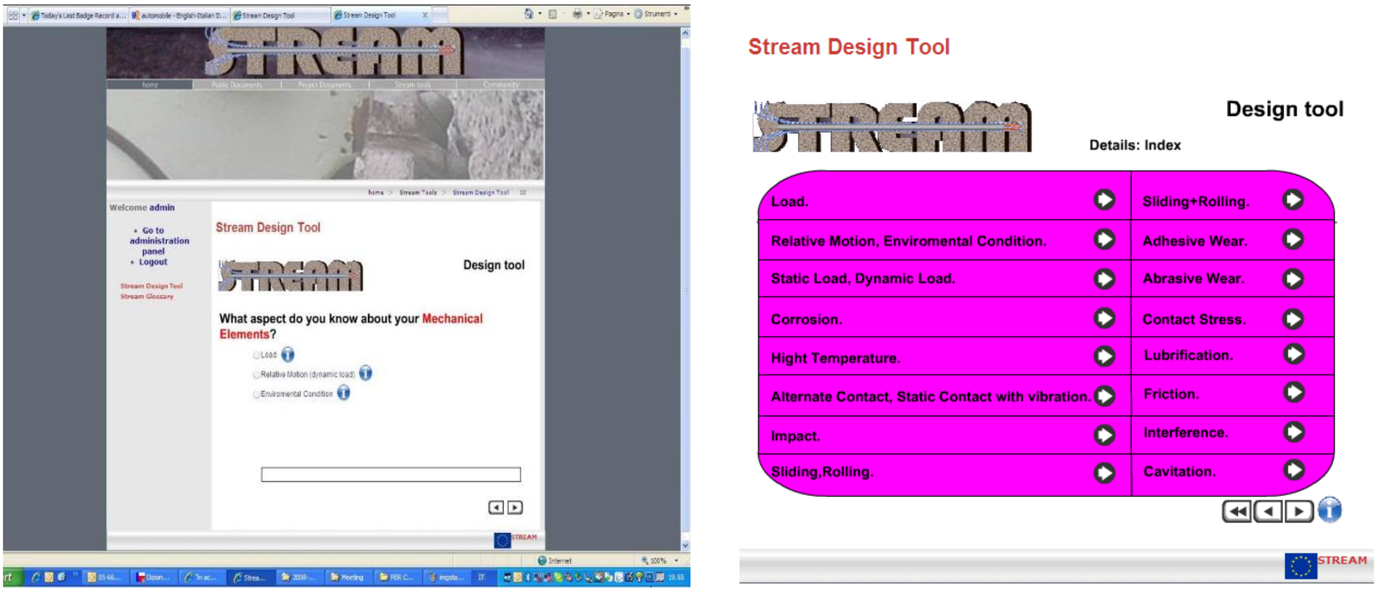


Figure 3-2: STREAM design tool

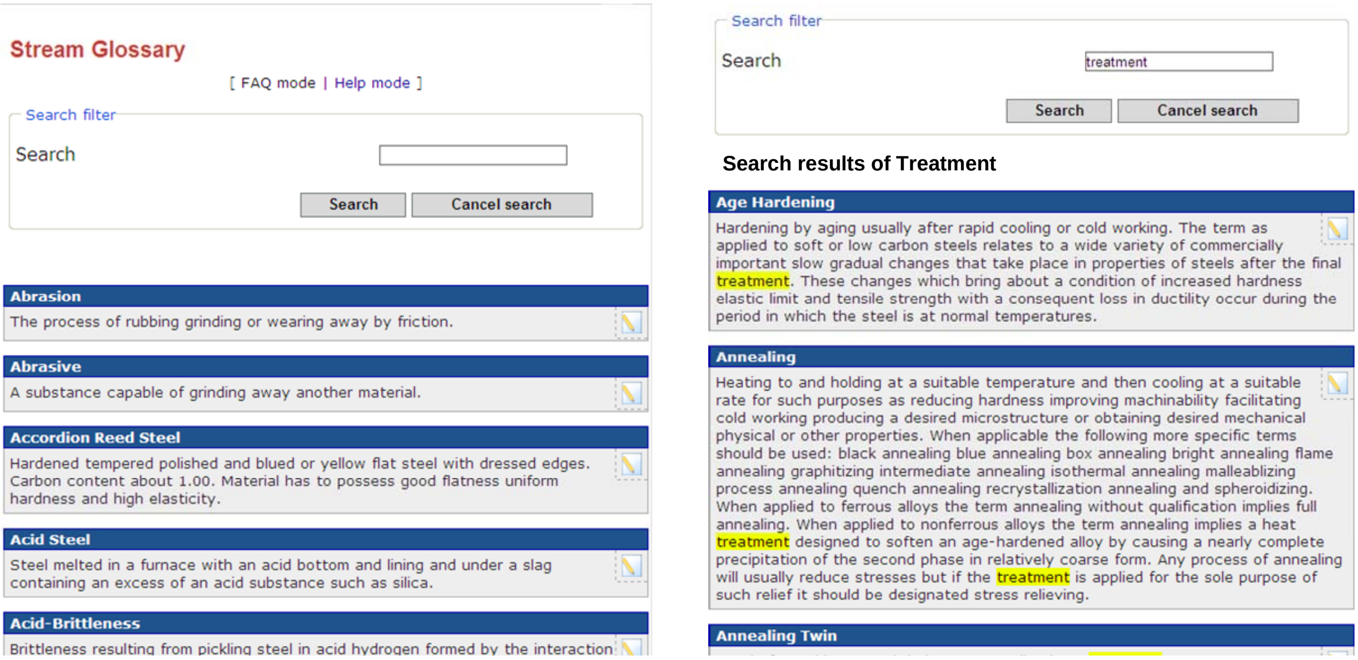


Figure 3-3: STREAM Glossary

The user can access to the software tools through the private area of the Stream web portal www.stream-project.it.

Task 1.3: Validation and testing
Partners Involved: DAPP, CROMO, NEUMAC, POLIMI
Related deliverable: D2 – Software tool

In the first reporting period of the project the information collected about the choice of treatments – coatings and relative base material for surface design of mechanical components were organised with the help of a software creating a tree structure.

In the second period of the project, after judgement of partners, a new design tool was compiled and implemented in the website. The information was rearranged and the study on the DLC applicability was extended. The new design tool is constituted by a series of pages in which questions regarding the particular application of interest are posed. The user can describe and focus his case in its different aspects. In the last page of the software tool the outputs are reported. These are arranged in four categories (see Figure 3-4):

- Suggested treatments and coatings;
- Suggested base materials;
- DLC coating applicability;
- Meaningful examples of applications of the suggested treatments and coatings.

A second validation of the tool followed thank to the collaboration of POLIMI, VTT and CROMO: DLC applicability for the case of fretting was verified, new base materials were added to the case of impact and new coatings were indicated for the protection of nitrated steels by corrosion.

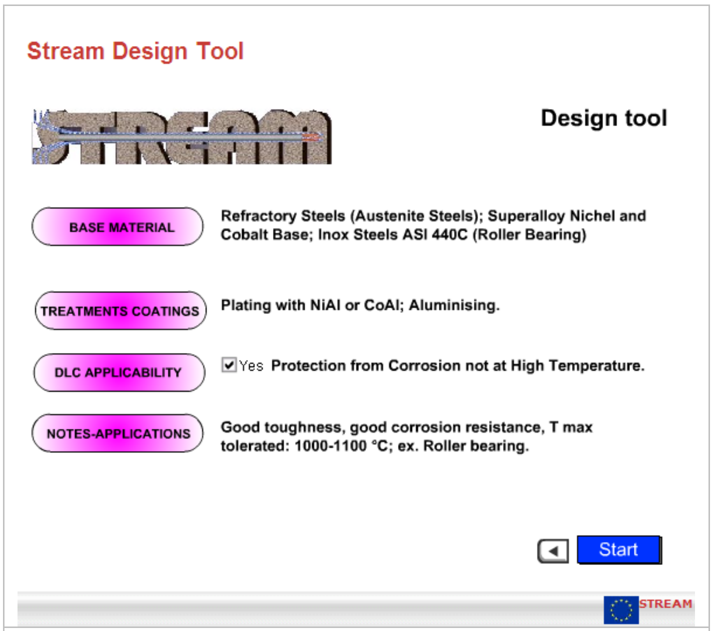


Figure 3-4: Outputs of the validated Design Tool

3.2 WP 2 Requirements and specifications

Task 2.1: Industrial requirements

Partners Involved: RIPAMONTI, CROMO, NEUMAC, MARMORES, ABRA, DAPP, COVER

Related deliverable: D3 – Industrial requirements and definition of the system specification

A review of the existing drilling methodologies and drilling technologies has been performed. Three drilling technologies have been considered: drilling+diamond wire, drilling +explosives and drilling +iron wedges. Among drilling technologies Down the hole (DTH) hammer and Top hammer have been compared in terms of drill performance, energy consumption, environmental and health aspects. The analysis performed highlighted that among drilling methodologies, stitch drilling is the most widely used. Alternative methods do exist but most require specialist equipment and supplies, and

some, such as diamond wire cutting, are too expensive for SMEs to consider when tough materials like granite are concerned. As far as drilling equipment, hand held pneumatic top hammers are still the most diffused since they present good flexibility and easy handling properties but they present many disadvantages (low efficiency, low precision, noise and dust). Looking to pneumatic DTH hammers noise and precision requirements are satisfied but their use is limited to the creation of large holes (90 mm). Furthermore the use of air still led to the presence of dust and low efficiency. Water powered DTH hammers offer a good solution for satisfying both energy and environmental issues. These hammers have been recently developed for deep mining applications and their size allows to drill only large holes (>100 mm).
As a result of the work performed in this task the target industrial specification for drilling hammer has been defined (Table 6).

Table 6 General specifications for drilling hammer

PARAMETER	TARGET
Outer Diameter	< 40 mm
Penetration speed in granite (38 mm diameter hole)	Above 1.10 m/min
Water consumption	- Below 30 l/min at operating pressure of 150 bar - Below 10 l/min at operating pressure of 80 bar
Energy consumption	- 8 kW at operating pressure of 150 bar - 1,4 kW at operating pressure of 80 bar
Vibration	2 m/ s^2 (ISO standard)
Noise	85 dB (ISO standard)
Hole deviation	<10 cm over a 10 meter long hole
Total weight (with bit)	< 7 kg
Total length (with bit)	< 1000 mm
Cost	12,000 €, including the DTH hammer and the 11 kW water pumping unit

Task 2.2: Development requirements
Partners Involved: RIPAMONTI, CROMO, VTT, NEUMAC, DAPP, POLIMI, ITE
Related deliverable: D3 – Industrial requirements and definition of the system specification

In order to choose the proper design for the STREAM hammer, six different designs from six different existing drilling machines have been analysed. The aim was to select the best design starting point. The comparison between each hammer has been done focusing on the design of the valve which is the most complex component. The role of valve is to give the continuous back and forth movement to the hammering mass. The valve can be a component apart, in line or offline with the piston or the piston itself can act as a valve (valve-less hammers). The analysis showed that the most promising starting point for the development of the STREAM hammer could be chosen from two different sources: Pneumatic DTH hammer Valve-less and Hydraulic Top hammer. By starting from the former, the needed design work is to change the working fluid from air to water and to reduce the diameter from 3” to 1 ¼”. The design work required by starting from the latter is to change the case and to eliminate the parts related to the rotational movement in order to develop a DTH concept.

In order to minimise friction and wear and maximise overall efficiency and durability, specific requirements for piston and cylinder base material, heat treatments and coating have been selected.
Piston and cylinder base materials have been defined as:

- Piston made of a ferritic steel (X 6 Cr Mo 17 1) carburized or nitrided, or made of high-carbon steel (X 90 Cr Mo V 18) surface hardened by localized heating and quenching
- Cylinder made of a case hardening steel 16 Mn Cr S 5

Coatings treatments have been defined as:

- Piston surface will be coated with a layer of 1 μm of DLC film deposited by Remote Plasma Assisted Chemical Vapour Deposition (PACVD) technique;
- Cylinder inner surface must be chromed since the material is not resistant to corrosion. As regards deposition process, pulsed current reversal will be considered and compared to the conventional procedure.

Task 2.3: Target specification
Partners Involved: RIPAMONTI, CROMO, MARMORES, DAPP, POLIMI, ITE, COVER
Progress: fully completed
Related deliverable: D3 – Industrial requirements and definition of the system specification

In order to define the specification of a 1 ¼" hammer, a scaling down approach has been followed, starting from the specifications of the existing water hammer family named Wassara and considering a valve-less pneumatic DTH hammer produced by Rocbit.

Table 7 summarizes the extrapolated data for a 1 ¼" diameter hammer.

Table 7 Extrapolated target specifications

	Diameter	Length [mm]	Weight [kg]	Water consumption [l/min]	Water operating pressure [bar]
Wassara	1 ¼"	625	7	15-20	140
Rocbit	1 ¼"	545	7	NA	NA

As far as the minimum piston weight it has been calculated that reducing the diameter from 3" to 1 ¼" a weight of 0.85 kg is sufficient to assure the same penetration rate. Therefore, by maintaining a similar geometry of the Rocbit piston the finally selected length is 300 mm. A preliminary drawing of the 300 mm piston has been made highlighting contact surfaces between the piston and the cylinder.

3.3 WP 3 Materials selection and testing

Task 3.1: Surface treatment selection and testing
Partners Involved: CROMO, VTT, NEUMAC, DAPP, POLIMI, ITE
Related deliverable: D4 – Metallographic and residual stress analysis and selected material to be used

The materials for the cylinder were selected as well as the surface treatment technologies that guarantee required surface characteristics were proposed and validated. Several surface treatments, including two-stage hybrid processes were developed by varying the process parameters with the aim of evaluating the influence of the main parameters on the process results and their mutual interaction. The surface layer properties can be modified by different surface treatment methods, e.g.: thermo-chemical diffusion treatment, plasma assisted deposition of anti-wear coatings and hybrid surface technologies, which join both mentioned processes.

Mechanical elements working in the conditions of heavy, cyclic mechanical loads and intensive abrasive wear must have high surface hardness, to restrict tribological wear, and a ductile core ensuring high fatigue strength. Such properties can be obtained by the use of different heat treatment methods, e.g. induction hardening or case hardening. The first method has been already applied by other producers, e.g. Atlas Copco, to the pistons manufactured from the steel grade X90CrMoV18 (AISI 440) and can be also exploited for heat treating of the piston which is being developed within the project. The application of the induction hardening as the heat treatment method of the cylinder can be much more difficult, because in this case an internal surface must be hardened and the wall thickness is only 3mm. For such specific requirements the technologies from the second group can be applied. From among case hardening methods, vacuum carburizing seems to be particularly promising, especially as it can be used for the treatment of the steel grade 16MNCrS5 chosen for the cylinder manufacturing.

On the basis of the existing surface treatment review, the surface treatments of the cylinder have been defined as the hybrid technology consisting of two diffusion treatment processes: the vacuum carburising process as the first stage, and the gas nitriding process as the second one.

Task 3.2: Manufacturing tests and experimental analysis
Partners Involved: CROMO, VTT, NEUMAC, DAPP, POLIMI, ITE
Related deliverable: D4 – Metallographic and residual stress analysis and selected material to be used

The applied methodology of the research work included both simulation of the surface treatment processes and their verification through experiments done on laboratory samples. Investigations were performed in order to evaluate coating properties in terms of coating adhesion, wear friction, residual stress level and other physical and mechanical properties. The available data, both theoretical and experimental, were used to optimise surface/substrate properties.
Experimental tests were performed on laboratory batch samples with the purpose of selecting the material and superficial treatments with the best performance. The performance of the coating in terms of residual stress originated by different thermal expansions was evaluated through stress measurement with the use of the X-ray diffraction method. The experimental analyses performed using the samples resulting from the manufacturing tests comprised:

- analysis of residual stresses in the surface layer;
- measurement of the surface layer thickness;
- microstructure of the surface layer (presence of cracks, uniformity);
- measurement of the hardness profile of the surface layer.

The created hybrid layers underwent investigations aimed at defining their material properties. Optical microscope observations of the surface (Neophot32) were carried out to determine their morphology. The phase structure of the prepared hybrid layers was examined with the use of the X-ray analysis (diffractometer Philips PW1830). The hardness profiles were measured after each stage of hybrid technology with the use of the hardness tester EMCO TEST M4R075.

On the basis of the achieved results the following conclusions were formulated:

1. The hybrid diffusion treatment (carburizing and nitriding) is a good way for the creation of the structure with high surface hardness (57HRC) and low bulk hardness (35HRC).
2. The use of the multi-stage gas nitriding process is necessary for creation of the structure with good hardness parameters, good corrosion resistance and higher level of compressive residual stresses in the basic cylinder material 16MnCrS5 steel grade.

3. The results of the technological processes (carburising and nitriding) executed in the project on the steel grade Ferrium C61 proved that it is possible to apply for the cylinder the one-stage nitriding process for creation of the structure with good hardness parameters and good corrosion resistance.
4. The diffusion treatment processes (carburizing and nitriding) have to be performed for the cylinder with real dimensions in order to check the dimensional stability of the cylinder in both one-stage and two-stage hybrid surface treatment processes.

3.4 WP 4 Coating plant

The objective of the Workpackage is to develop a laboratory plant suitable for the coating of the sliding surface.

Task 4.1: Pilot plant design
Partners Involved: CROMO, POLIMI
Related deliverable: D5 – Labscale plant

Pilot plant for DLC deposition consists of the following main parts:

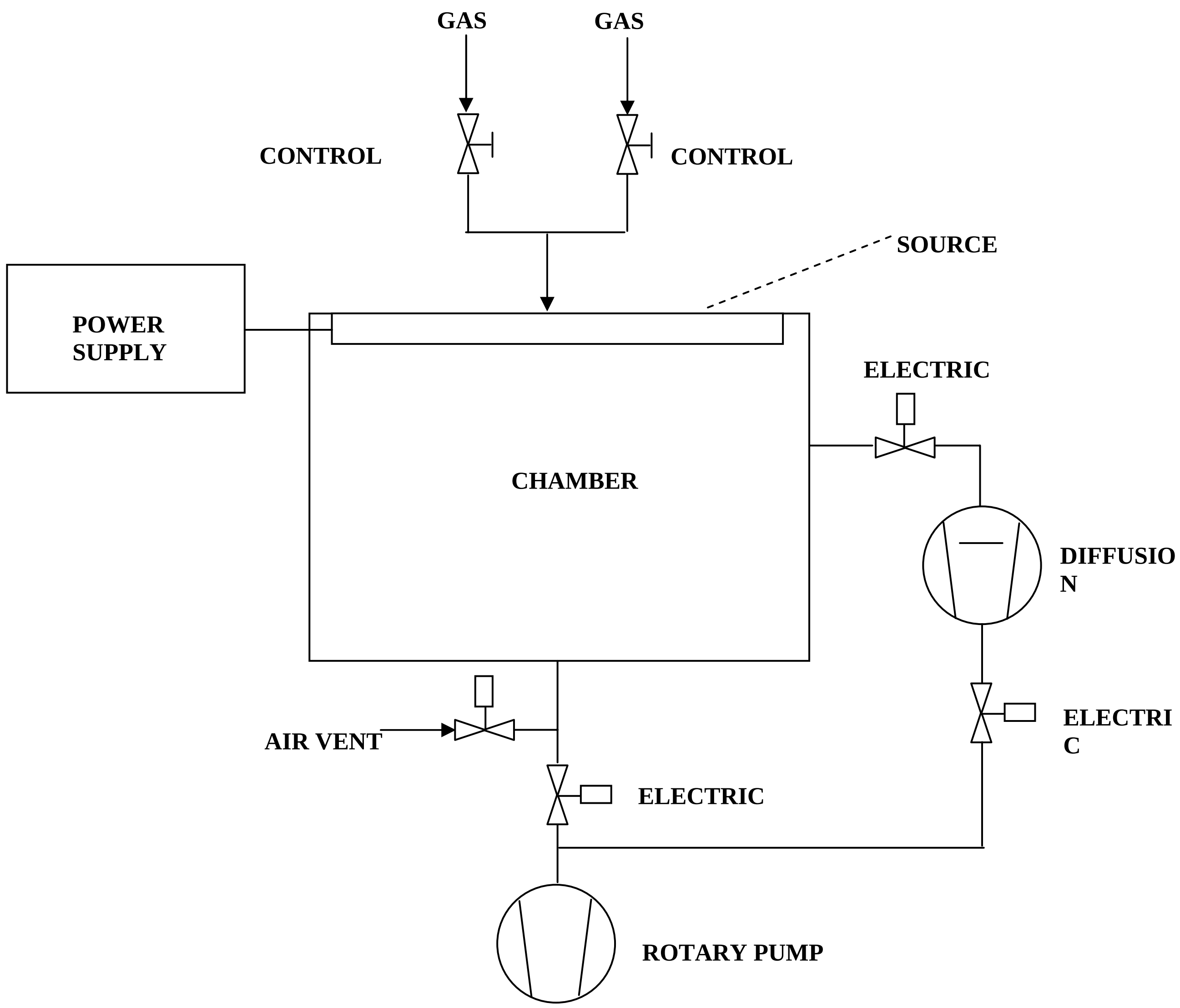
a. gas lines with control valves
b. deposition chamber
c. rotary pump (fore vacuum)
d. diffusion pump (high vacuum)
e. plasma source
f. source power supply

The rotary pump produces preliminary evacuation of the chamber (medium vacuum) and keeps the diffusion pump in the operating range of pressure. High vacuum, necessary for deposition, is obtained by the diffusion pump.

Operating pressure inside the chamber is controlled by regulating the gas flow rate and the source parameters (voltage and current) are set by the power supply unit. Deposition parameters are selected according to research activity developed in WP 5.

The vacuum chamber is equipped with an electric motor that allows to keep the substrate in rotation during deposition. This movement is very important to obtain a uniform coating, especially on cylindrical parts as those forming the drilling hammer.

The deposition run, including chamber evacuation and coating growth, has a total duration of approximately two hours; this time is fully adequate for the industrial implementation of the process. Plant layout is shown in the following diagram.



Plant layout

Task 4.2: Plant integration
Partners Involved: CROMO, POLIMI, VTT, ITE
Related deliverable: D5 – Lab scale plant

In the first reporting period of the project CROMO used a pre-industrial plant for DLC deposition with PACVD technique. This allowed to study at laboratory scale the best coating process and, by the experimental data acquired, tuning the process.
The pilot plant works properly to deposit DLC coatings on the parts of the drilling hammer. Only one limitation might arise about the size of the parts to be coated.
The deposition chamber is cylindrical in shape, with inner diameter of 34 cm and length of 21 cm.
One end of the chamber is closed by the plasma source and the other end was originally equipped with a sample holder that allows the substrate to rotate around an axis perpendicular to the source plane. This holder is fit for plates or flat substrates, but it is not convenient for cylindrical pieces, like the piston in the drilling hammer. Moreover, the holder occupies a significant volume and reduces the available space inside the chamber. Therefore the holder has been replaced by a steel plate, that

allows to exploit the full capacity of the vacuum chamber. The substrate rotation is ensured by the electric motor mounted on the top of the chamber.
The internal dimension of the deposition chamber has been decided considering the design of the preliminary version of the first STREAM hammer prototype. Since the length of the piston exceeded the size of the vacuum chamber, it was conceivable to divide the piston in smaller parts, just for manufacturing the demonstrator hammer. One half of the piston was screened and the other discovered half was treated.

In the second reporting period, the pre-industrial plant was used to coat several full-scale hammer components and to further optimise the coating process parameters.
Therefore the good results obtained during the manufacturing of hammer components and samples for tests, achieved with the lab scale DLC plant, pushed CROMO and VTT, with the support of the other consortium members, to design a bigger industrial DLC plant in order to coat larger elements and fully exploit the commercial potential of the optimised coating process. A 3D view of the new plant is shown in Figure 3-5. The plant will have a coating area of 1,0 X 1,0 X 0,7 m^3 and has been designed taking in account the process optimization performed during the project.

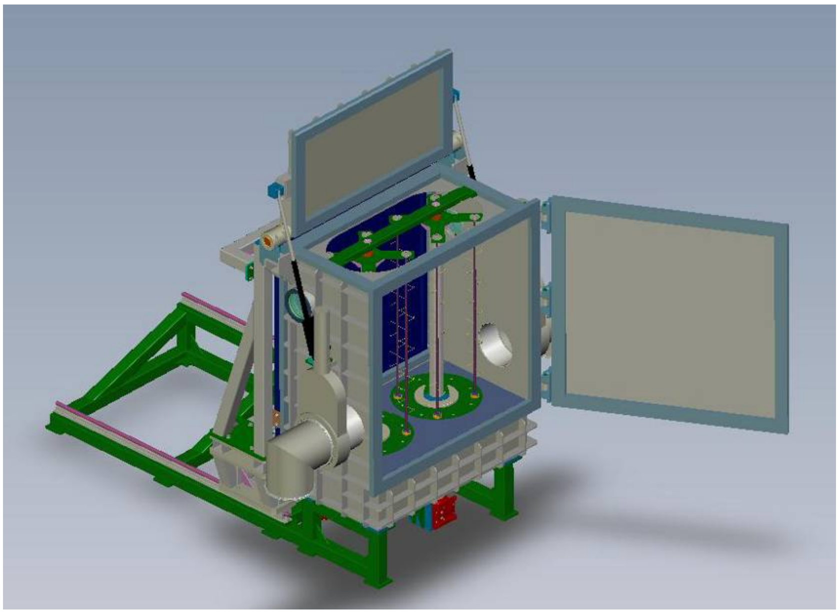


Figure 3-5: Design of the industrial DLC deposition plant with 1,0 X 1,0 X 0,7 m^3 coating volume area

3.5 WP 5 Process optimisation

The objective of this WP is to analyse in detail the Plasma Assisted Chemical Vapour Deposition Process in order to control each sequence of the industrial process and to optimise the overall process with respect to the predicted performance of the final products.

Task 5.1: Tests methods
Partners Involved: CROMO, VTT, DAPP, POLIMI, ITE
Related deliverable: D6 – Film testing methodology

DLC layers are wear-resistant coatings synthesized by plasma-assisted deposition techniques. In principle, testing techniques which are commonly employed to characterize thin films are suitable for

measuring properties of DLC coatings as well. Nevertheless, these films have peculiar features which make necessary a proper selection of the testing techniques and a correct definition of the measuring procedure and parameters.
Structural properties and pertinent characterization methods were analysed. Although atomic structure is tightly related to mechanical properties, reliable relationships which enable mechanical performance to be predicted from structural examination are still not available. The main reason is that structural parameters to be considered would be a lot and assessing all of them is usually an unworkable task. Therefore, direct evaluation of mechanical properties is regarded as the most reliable approach.
Mechanical performance of DLC coatings is particularly important for the present project and therefore the DLC film characterisation was focused on this topic. In addition to hardness measurement, test methods for internal stresses and adhesion to the substrate were analysed.
Composition and mechanical properties of DLC, dependent on the deposition parameters and the coating synthesis, should be optimized by searching a suitable compromise between high hardness and low internal stress.
The process control will be developed by the following tests:

- elemental analysis by combustion (hydrogen fraction)
- microindentation (hardness)
- substrate bending (internal stress)
- scratch test (adhesion)

When proper deposition conditions are defined, final tests (task 5.2) deal with the evaluation of the tribological performance by block-on-ring experiments. These tests include the observation of the worn surfaces by optical and electronic microscopy, in order to acquire complementary information. If adhesion failure would be recognized as the main wear mechanism, the deposition process would be investigated further, especially including the growth of an intermediate layer.
The block-on-ring tests will be performed both in air and in water: air is regarded as a reference environment and water is representative of the conditions existing in the final application.

Task 5.2: Final tests
Partners Involved: CROMO, VTT, DAPP, POLIMI, ITE, ABRA
Related deliverable: D7 – Thin film characterisation.

In the first reporting period of the project deposition and testing of DLC films prove that coatings with relatively low hydrogen content (around 28 %) can be produced from non-toxic hydrocarbons. These coatings exhibit high hardness and moderate compressive residual stress, which ensure high mechanical stability and strong adhesion to the substrate.

Preliminary tests were performed to investigate the effect of the process parameters (gas composition and plasma source variables) on the final properties of the DLC coatings.
The deposition technique used in this project is an unconventional plasma-assisted CVD process, which is fed by a gaseous hydrocarbon. Four gases have been tested: methane (CH_4), cyclohexane (C_6H_{12}), benzene (C_6H_6) and acetylene (C_2H_2). The results of these tests show that acetylene provides the most favourable combination of properties of the coatings: a content of hydrogen ranging from 25 to 35 %, high hardness (30-35 GPa), adhesion to the substrate. As regards environmental issues and exposure risks, it is noted that acetylene is not recognized as a toxic gas.

DLC coatings have been deposited from acetylene, with different process parameters (gas pressure and current or voltage in the plasma source). The most favourable conditions provide deposition rates

in the range 1 to 1.5 μm/h, which is quite acceptable in perspective of industrial implementation of the process. Each run includes chamber evacuation, substrate activation, coating growth and chamber filling up to atmospheric pressure. The whole deposition step takes about one hour, while the duration of the evacuation stage is largely dependent on the configuration of the pumping system. In the industrial practice, chamber evacuation and backfilling take usually less than half an hour.
DLC coatings have been prepared with the most promising deposition parameters and have been tested by laboratory experiments to evaluate their tribological behaviour.
Block-on-ring wear tests have been performed both in air and in tap water and the block scars have been examined after the test, to evaluate the worn volume and to investigate the failure mechanism. The DLC coating has been deposited only on the block and two different materials have been selected for this piece, in order to investigate the effect of the substrate hardness. The soft material is a martensitic stainless steel (X30Cr13) in the annealed condition, with hardness of 240 HV, and the hard material is a cemented carbide (WC 94% - Co 6%) attaining hardness of 1500 HV. For each combination of block material and environment (air or water), a comparison has been made between coated and uncoated blocks, with the same counterbody (tool steel X210Cr12). On the other hand the coating improves very slightly the wear resistance of a soft substrate.
A good solution could consist by depositing DLC on a hard chromium-plated substrate and exposing this part to a chromium-plated counterbody.

In the second period of the project ITE and VTT selected the steel constituent material of sliding components, and conducted some tribological tests to verify the application of some thermal tretments: hybrid diffusion treatment, consisting of carburizing and sulfonitriding, resulted the best solution for thickness uniformity, corrosion resistance and wear resistance.

POLIMI continued the study on DLC coating: they conducted microidentation tests on samples coated with DLC, prepared by CROMO, in order to verify indentation depth, elastic behaviour and adhesion properties.

POLIMI conducted other tribological tests in order to simulate the working conditions of the hammer components surfaces. The base material selected was a low-alloy steel covered with the following surface treatments: sulfo-nitriding, chromium plating, DLC, and chromium+DLC. In particular the surfaces used in the tests for the block were: nitrided steel, nitrided+Cr+DLC. Chromium plated steel and PTFE (a fluoropolymer) were also tested in order to simulate the contact of plastic o-rings with the piston. Two different environmental conditions were considered: clear water and water + hard dispersed particles Al_2O_3. The alumina was employed to simulate the presence of fragments in the water during the working of the hammer. All these tests suggested (see Table 3.8) that chromium plating plus DLC deposition is the best solution because it guarantees low friction coefficient, high surface hardness and so high abrasive wear resistance, good corrosion resistance. These treatments and coatings were applied on the surfaces of the piston (Figure 3-7) and other internal components of the hammer characterized by sliding.

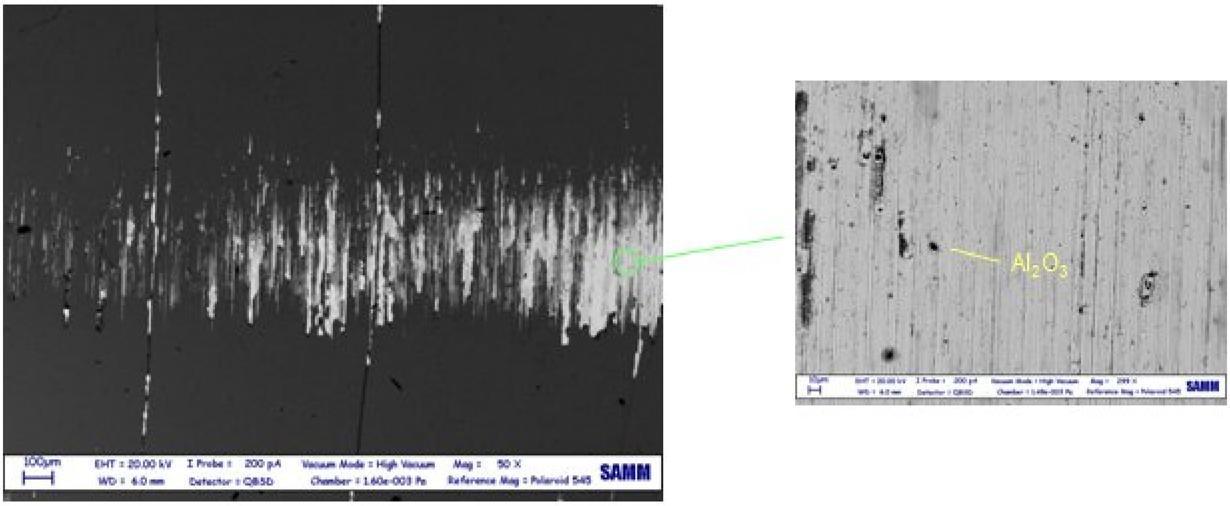


Figure 3-6: Results on surface optical analysis: Nitr.+Cr+DLC vs. Cr in water with Al_2O_3

Table 3.8: Results of the tribological tests that simulated the working condition of hammer components surfaces

Block	**Ring**	**Wear rate (mm3 N-1 m-1)**	**COF**
Nitrided steel	Cr-plated steel	8.3·10-5	0.44
Nitrided steel	PTFE	4.6·10-6	0.18
Nitr.+Cr+DLC	Cr-plated steel	4.8·10-6	0.09
Nitr.+Cr+DLC	PTFE	8.5·10-8	0.09

Figure 3-7: Piston with chromising – DLC

Task 5.3: Process control system
Partners Involved: CROMO, VTT, DAPP, POLIMI, ITE, ABRA
Related deliverable: D8 – PACVD process control methodology

During the first period of the task the DLC PACVD was described, by a semiempirical model, considering the effect of heating of the substrate of base material, caused by the action of the plasma.

That allowed to design a first version of the system control of the pilot DLC plant able to avoid excessive surface temperatures responsible of undesired structural modifications of the substrate.
DLC coatings have been deposited by a PACVD process that works in a remote-plasma configuration, i.e. a plasma source emits ions which travel to the substrate and collide with it. These fast particles transfer kinetic energy that is mainly converted into sensible heat and causes a temperature increase of the substrate. This effect must be controlled to avoid unwanted structural modifications in the substrate and in the coating. In particular, temperature rise promotes coating graphitization, with reduction of hardness.
Process control has been developed by starting with temperature measurements. Thin plates of stainless steel have been used as substrates and a thermocouple was held in contact to their back face during deposition. Temperature rises rapidly when the plasma source is switched on, later it increases more slowly and approaches a steady value. When the plasma source is switched off, temperature starts to decrease and its dependence on time is well described as Newtonian cooling of a plate by convective heat transfer.

A model has been developed to predict the temperature profile versus time and the adjustable parameters of the fitting curve have been determined by interpolating the experimental data.
Substrate temperature has been measured during deposition runs performed with different operating parameters and the following quantities have been calculated by interpolation:

- power density transferred by fast particles
- heat transfer coefficient

In addition, the maximum temperature has been recorded in each deposition run: the values are in the range 70° to 150°C. The model anticipates that a steady temperature is reached when the convective flux is equal to the heat flux transferred by the colliding particles. This steady value represents the maximum temperature attainable during deposition and results to depend on power density and heat transfer coefficient. These quantities have been correlated to the deposition parameters and the model predictions show that the temperature increase (above room temperature) can not exceed 135°C. Moreover, time required to attain the steady temperature increases with the substrate thickness, then massive parts are expected to reach an even lower temperature within the deposition duration.
Modelling of the deposition process will be integrated by acquiring experimental data about internal stresses, which are produced by the peening effect of the colliding fast particles and the mismatch in thermal expansion of coating and substrate. Maximum temperature during deposition and power density of particle flux will be quite useful to find out correlations between process parameters and coating properties.

In the second period of the project the entire process was optimized considering the different phases. Starting from the pilot DLC plant and adapting it to the STREAM application several laboratory tests have been performed in order to optimize the DLC deposition process. The consortium work enabled to increase the deposition speed of DLC by optimizing the plasma path length and increasing the ionization efficiency. The temperature deposition was reduced further on allowing to keep the substrate materials below 160 °C without effecting previous heat treatments. As a result, there is an increase of coating strength from typical values of 10-20 GPa up to 40 GPa by optimization of hydrogen inclusion.
Therefore the system regulation was designed in order to control (see Figure 3-8) the rotative pump for the evacuation of the deposition chamber, the micrometric regulation valve V2 relative to the argon flow, the micrometric regulation valve V1 relative to the fluoride flow, the electric valve EV, the micrometric regulation valve V3 relative to acetylene flow and the electric valve EI relative to the air flow.

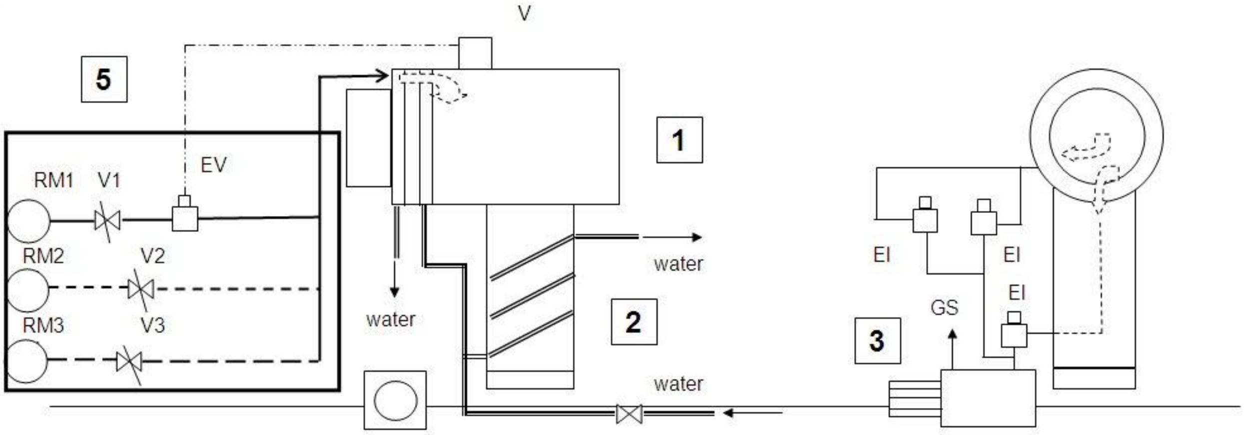


Figure 3-8: DLC plant scheme with control system

3.6 WP 6 Design and prototyping of demonstrators

The objective of the Workpackage is to design and manufacture the prototypes of the drilling demonstrator implementing the STREAM system according to the industrial requirements defined in WP 2.

Task 6.1: Design and simulation model
Partners Involved: DAPP, CROMO, VTT, ITE, NEUMAC, RIPAMONTI, ABRA, MARMORES, COVER
Related deliverable: D9 – Parametric hammer model

During the first period of the project the consortium investigate the possibility to use a pneumatic hammer as starting point for the development of the STREAM hammer. Then it was decided to start from an existing water top-hammer and to first develop a 3 ¼ inches DTH hammer design.
Design work was initially carried out following two possible existing designs selected as starting points as indicated by the analysis performed in task 2.2. Work was done in parallel by studying the working principle and by developing a parametric simulation model for a pneumatic DTH hammer, ROCBIT RH3 330IR, and for a hydraulic top hammer produced by a South African company.
The parametric models was developed using the software of SIMULINK of Matlab where the equations describing the working fluid behavior are implemented and solved. The model allows a better understanding of the hammer performance, and gives characteristic results of impact frequency, velocity, energy and power, as well as the working fluid (air or water) consumption.
Figure 3-9 show the model of the pneumatic DTH hammer. The model considers four chambers in the hammer: input chamber, front chamber, accumulator chamber and output chamber, and evolution of pressure and temperature are calculated in all of them (except from the output chamber, where pressure and temperature are considered as constants). Figure 3-10 shows the calculated pressure-displacement diagram of the pneumatic DTH hammer obtained as result of the hammer simulation.
The model of the hydraulic top hammer was made. The model considers six chambers in the hammer: front return chamber, middle return chamber, rear return chamber, front drive chamber, middle drive chamber and rear drive chamber, and evolution of pressure are calculated in all of them.
Several simulations of the pneumatic hammer were performed by changing the working fluid from air to water. The results showed that hammer could theoretically work if accumulators are placed in both the front and the rear chamber. Nevertheless hammer performance were still bad and only introducing significant changes on hammer design, for example by placing a special valve in the

front part, it is possible to obtain better results. On the other side the Hydraulic top hammer showed more promising results, thanks to the advantage of being designed to work with an incompressible fluid.

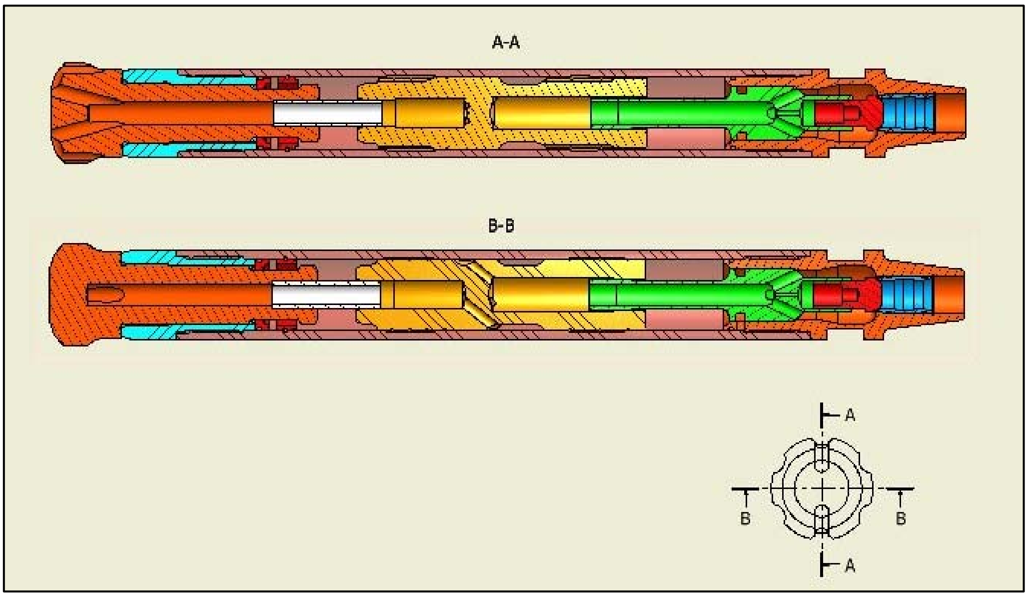


Figure 3-9: Model of the pneumatic DTH hammer

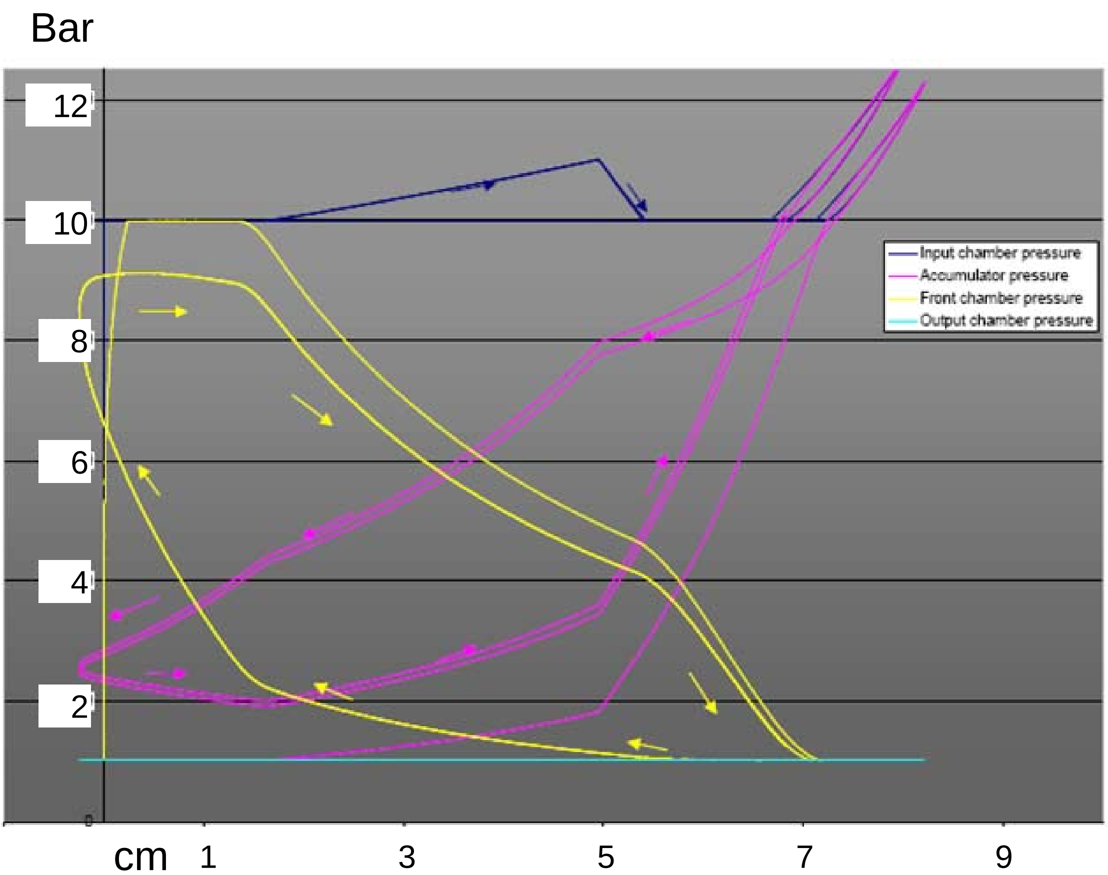


Figure 3-10: Pressure vs. Displacement of the pneumatic DTH hammer

In the second period of the project, tests were conducted on the developed 3 ¼ inches prototype and after on 2 ¼ inches prototype. These allowed to collect experimental data about the principle working parameters. Therefore this information was used to develop and validate the dynamic model compiled for the first two STREAM prototypes.

Finally, based on the experience of the 3¼ and 2¼ inches prototypes, a full parametric model of the 1¼ inches STREAM hammer has been developed in Matlab-Simulink environment. This model allows simulating all its working conditions, as well as the analysis of all the relevant system variable. A fully 3D model was made and the final version of the dynamic parametric model was used to complete the design of the internal components. By the simulation it was possible to find out the performance of each mechanical element as well as the pressure trend in each chamber.
The parametric model allowed to verify the most important characteristics of working and to intervene in the design modifying some geometrical parameters.
The different parts of the hammer were considered: chambers, valves, channels geometry of the piston. The principles of working of this alternative machine were studied. The diverse phases of working were analysed highlighting the subsequent positions of the piston in the most important instants of the working cicle; the dynamic of the piston was studied and modelled too (Figure 3-11).
Each block of the model was created to represent the single component of the hammer. In the Figure 3-12 is possible to view the mathematic model of the internal chamber of the hammer: the rear wall chamber. By this concentrated parameter model it was possible to calculate the most important working parameters like pressure, water flow, piston frequency and piston impact force.
E.g. the model results allowed to observe the piston displacement, water consumption and pressure in the main chambers of the hammer (see Figure 3-13).

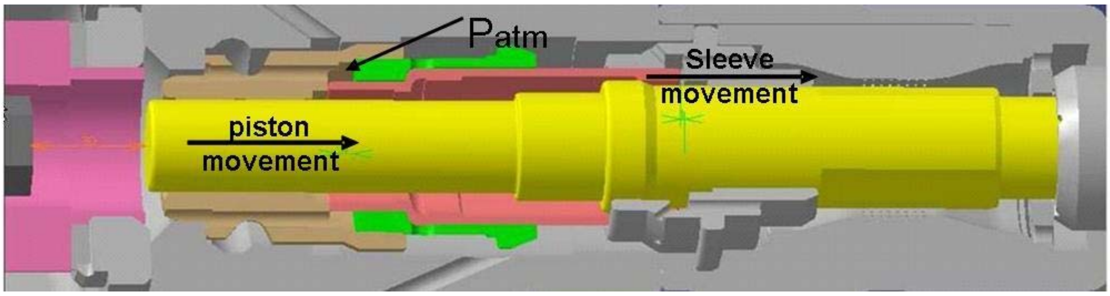


Figure 3-11: Study of the dynamic of the piston

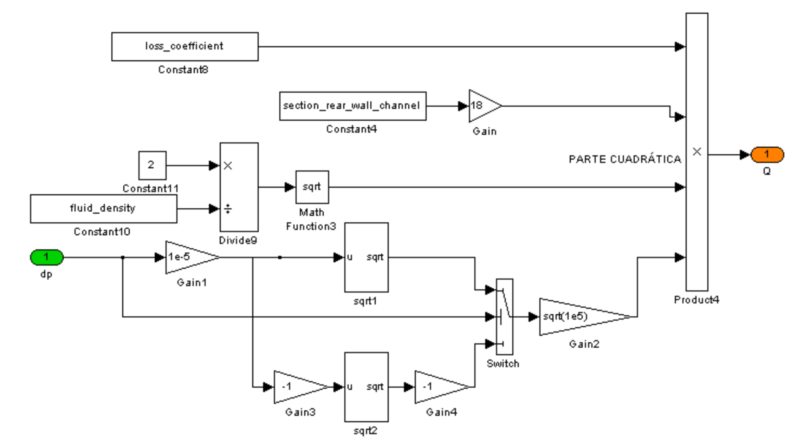


Figure 3-12: Rear wall channel

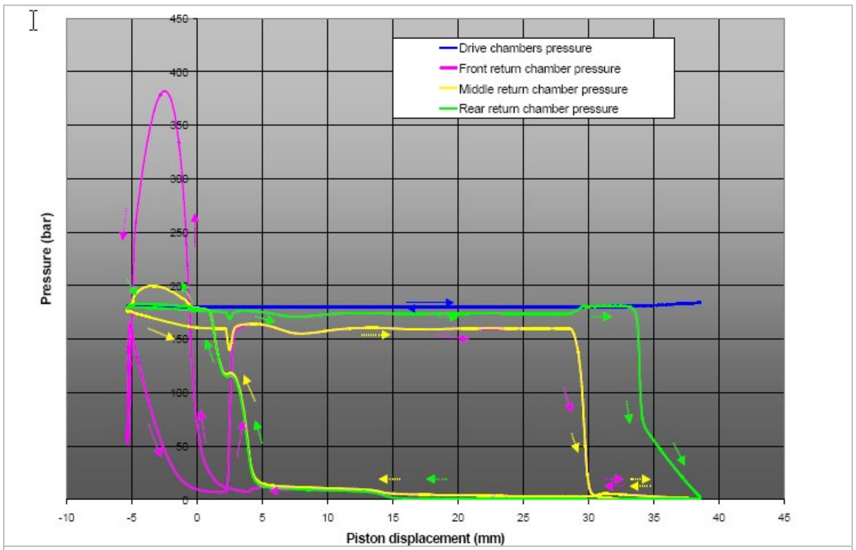


Figure 3-13: Chamber pressures

Task 6.2: First prototyping and testing of a Water DTH
Partners Involved: DAPP, CROMO, VTT, ITE, NEUMAC, RIPAMONTI, ABRA, MARMORES, COVER
Related deliverable: D10 – First Water DTH hammer prototype

A preliminary test was organised at Ripamonti premise Febraury 8th 2007. The test was performed using a small pneumatic down the hole (DTH) hammer (30 mm diameter) fed with water instead of air. For performing this test an accumulator was settled in the rear part of the hammer to allow water compressibility. The aim of this test was to see if the pneumatic DTH hammer, which has a simple valve-less design, is able make impacts on the bit using water instead of air. Figure 3-14 shows the test rig which has been set up at Ripamonti premises.

The test demonstrated that the piston inside the pneumatic hammer is not able to move with water. This result was subsequently confirmed also by the model developed for simulating the pneumatic hammer working with water. The piston is not able to hit the bit because of the incompressibility of the water that fills the volume between the piston and the bit.

Figure 3-14: Water test on a pneumatic DTH hammer

Therefore after having studied the state of the art of drilling hammers, the consortium decided to design a new DTH prototype starting from the “Novatek” water top hammer.

In order to begin the conversion in DTH hammer of the Novatek hammer, the piston motion and its rear parts were studied. The components and ducts related to the rotation actuation were not considered because in case of STREAM DTH rotation will be provided by the drilling head were the hammer will be mounted.

Its rear part was isolated and its geometry modelled with a 3D model. A parametric model in Matlab/Simulink environment was compiled to understand the dynamic of the piston and the principle hydrodynamic phenomena. A preliminary prototype was designed with a full 3D model (see Figure 3-15) and subsequently manufactured. A test followed to verify the correctness of piston motion and to measure some important parameters like piston frequency (see Figure 3-16). These experimental data were used to perform a first validation of the parametric model.

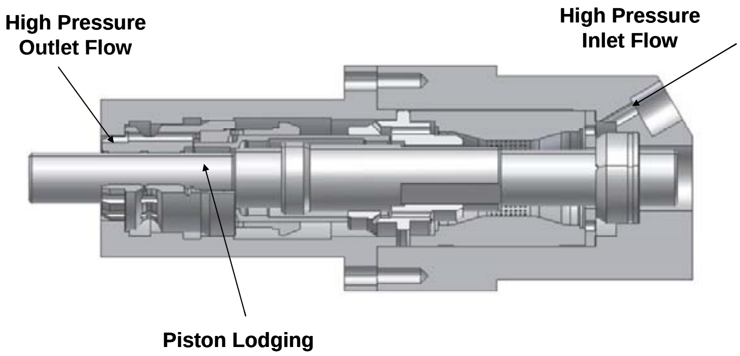


Figure 3-15: Preliminary prototype – 3D model

Figure 3-16: The manufactured preliminary prototype and functional testes

A second STREAM 3 ¼ inches prototype was developed: using a 3D model (see Figure 3-17), the rear part of the hammer was redesigned to allow the water inflow along longitudinal direction and a new case adapted for the down the hole drilling was redesigned, too. This second prototype was manufactured and then tested using different types of stones in order:

- to verify the correctness of working and performances;
- to perform a second validation on the parametric model;
- to understand the most promising design route to make a new 2 ¼ inches DTH hammer.

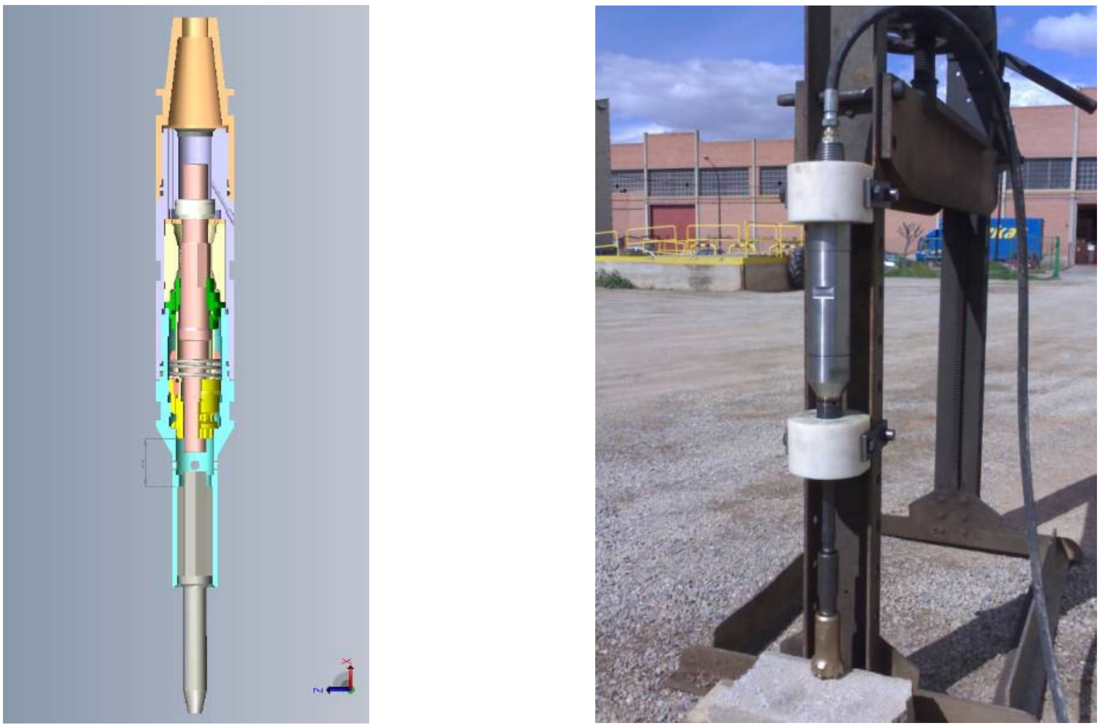


Figure 3-17: 3D model and hammer prototype

The results were very positive and the parametric model was validated a second time with the experimental measures of the blow energy. In order to arrive to the final version of the 2 ¼ inches hammer in the full DTH configuration, it was needed to redesign some hammer components. The front part was modified to place the components necessary to assemble a 3 ¾ inches bit. The parametric model, validated in the previous tests, was used during all this phase to choose the best geometry on the basis of the technical specifications (see Table 3.9). Therefore the full 3D model of the definitive 3 ¼ STREAM prototype was made and finally the hammer was manufactured and assembled (see Figure 3-19).

After the manufacture of the prototype, several tests were performed to verify the working of the STREAM 3 ¼ inches DTH hammer with several drilling bits thanks to the input provided by ABRA. Further tests were performed to measure water DHT prototype performances in different conditions varying the type of stone and the drilling inclination as suggested by the MARMORES and COVER. The hammer had not working problems in any conditions and showed a good penetration rate and good mechanical efficiency.

Table 3.9: Technical specifications of 3 ¼ inches STREAM prototype

External diameter	3 ¼ inches
Water flow	33 l/min
Water hammer pressure	150 bar
Penetration rate (on granite)	40 cm/min
Piston frequency	53 Hz
Mass	23.7 kg
Length	700 mm

Even if the overall goal of the project is to further reduce this diameter, this intermediate step was needed to validate for the first time the STREAM design and because any change in dimension as a strong influence on the hammer behaviour and mode of operation.

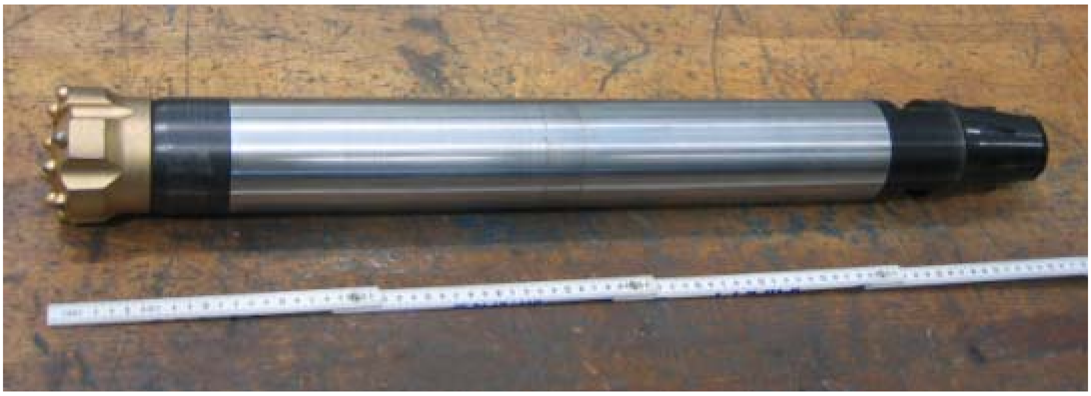


Figure 3-18: 3 ¼ inches DTH STREAM prototype

Nevertheless the 3 ¼ inches prototype represents a very interesting hammer for the drilling in quarries.

Figure 3-19: Test of the 3 ¼ inches DTH STREAM protoytpe

Task 6.3: Design and prototyping of STREAM hammer
Partners Involved: DAPP, CROMO, VTT, ITE, NEUMAC, RIPAMONTI, ABRA, MARMORES, COVER
Related deliverable: D9 – Parametric hammer model; D17 – STREAM prototype

The initial studies that brought to the design of the first STREAM prototype helped to understand the technical barriers to arrive to the final 1 ¼ inches prototype. Therefore the consortium decided to follow a gradual procedure. The experiences developed so far during the project of 3 ¼ inches STREAM prototype showed that it was necessary to proceed by small steps in order to apply successful modification to the hammer design.
Therefore the consortium decided to design a second STREAM prototype reducing the dimensions up to 2¼ inches integrating the result from the coating and surface treatments activities.

Figure 3-20: Comparison between 3 ¼ and 2 ¼ inches STREAM hammer prototypes

The design of a 2 ¼ inches hammer, performed mainly by NEUMAC, RIPAMONTI and DAPP, represented an important solution for quarry extraction where actually explosive or wire diamonds techniques follows holes drilling of about 58 mm diameter using pneumatic DTH hammers. Besides, drilling with 2 ¼ inches pneumatic DTH hammer are commonly used in the mining activities or in the civil construction sector (e.i. tunnel drilling) that represent a big secondary market.

The activity conducted in the two years of the project regarded also the development of an industrial effective process for DLC coating of steel surfaces that, coupled with specific thermal treatments, enables the manufacturing of components with very high wear and corrosion resistance. The conclusion of these tests was that a duplex coating, consisting of electroplated chromium and DLC, combines valuable tribological properties with corrosion protection, even in water containing hard abrasive particles. These treatments and coatings were applied on the surfaces of the 2 ¼ inches STREAM prototypes components.

At the same time starting from the prototypes with an external diameter of 3 ¼ and 2 ¼ inches, a new DTH hammer with external diameter of 1 ¼ inches was developed. The geometry has been defined scaling and adapting the previous hammers design.
The new prototype, complete with bit, has been modelled using SolidWorks by DAPP.
In the Figure 3-21 , some section views of the hammer are shown.

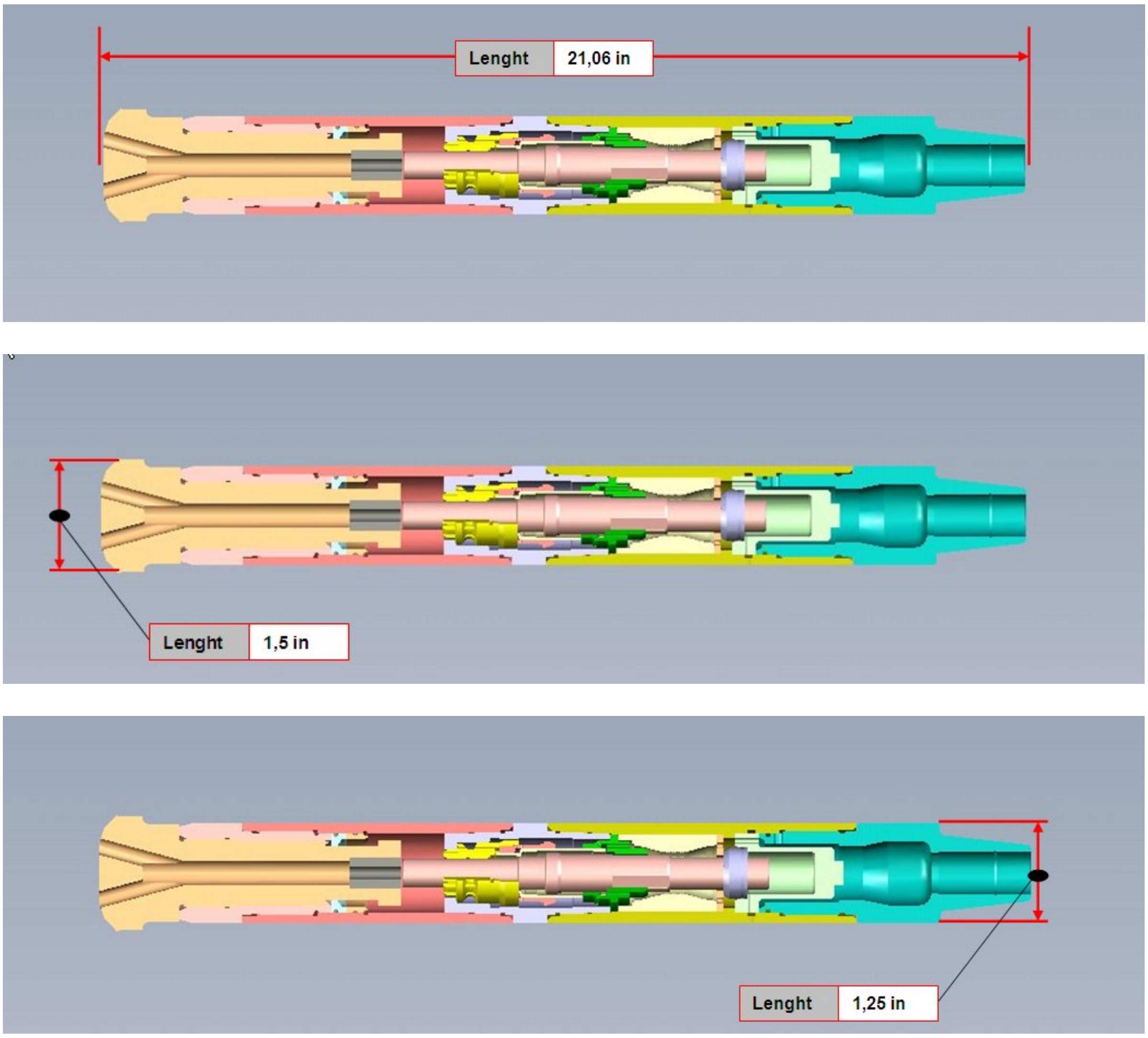


Figure 3-21: 3D model of 1 ¼ inches hammer

The simulation with the concentrated parameters model has been performed, subsequently, in order to validate the model geometry.

Task 6.4: Prototype integration
Partners Involved: DAPP, CROMO, VTT, ITE, NEUMAC, RIPAMONTI, ABRA, MARMORES, COVER
Related deliverable: D17- STREAM prototype

Preliminary tests conducted on the 3 ¼ inches prototype helped to understand that a configuration with an external accumulator was not feasible.
In order to minimize the hammer dimension a new case was designed enabling to reduce the external diameter to 2 ¼ inches. So the external wall of the air chamber coincides with the housing of the hammer (see Figure 3-22).
A 3D model was made and the parametric model was used to verify the respect of technical specifications (see Table 3.10).

Table 3.10: Technical specifications of 2 ¼ inches STREAM prototype

External diameter	2 ¼ inches
Water flow	33 l/min
Water hammer pressure	150 bar
Penetration rate (on granite)	50 cm/min
Piston frequency	73 Hz
Mass	10.2 kg
Length	635 mm

Therefore the 2 ¼ inches prototype was manufactured by NEUMAC and assembled by RIPAMONTI with the components coated previously by CROMO and VTT (see Figure 3-23).

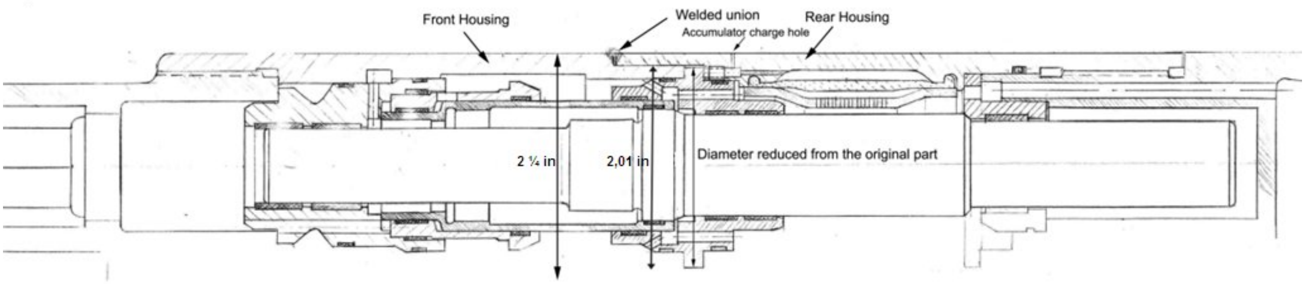


Figure 3-22: 2D drawing of the 2 ¼ inches prototype

Figure 3-23: The 2 ¼ inches prototype manufactured by NEUMAC

3.7 WP 7 Testing and system performance demonstration

The objective of the Work Package is the development of trials of the optimised demonstrators for the evaluation of their characteristics.

Task 7.1: Prototype optimization
Partners Involved: VTT, RIPAMONTI, CROMOSTAMP, NEUMAC, MARMORES, ABRA, DAPP, POLIMI, ITE, COVER
Related deliverable: D11: Demonstration of the system performance

In order to simulate rock drilling in quarry and to verify the correctness of working and the performances of 2 ¼ inches STREAM prototype a drilling test rig was prepared by ABRA, RIPAMONTI and DAPP.
The hammer was mounted on a drilling tracked machine and then connected to the feeding pumping rig. Manometers were connected in three different sections of the plant in order to monitor the water pressure. The hammer flow was observed too.
The 2 ¼ inches hammer was tested in very different conditions varying the type of stones and the drilling inclination. The types of stones tried were provided by MARMORES and COVER : marble, granite, Serizzo and Serena stone (Figure 3-24).

Serizzo Serena Granite Marble

Figure 3-24: Stone's types used during testes

Three different drilling angles were tested for all the stones: normal (90°), horizontal (0°) and 45°. The hammer did not show any problems in each working configurations. The analysis of the performances allowed verifying the success of the design.

Hammer's penetration rate was measured together with feeding water pressure, inlet water flow and other hammer's technical characteristics using DLC coated elements or standard one. Experimental data showed an improvement up to 10 % of penetration rate if DLC coated components are used confirming the success in the STREAM approach. These result confirmed the success in the design of the internal components and the optimal treatment of surfaces in terms of low friction and high wear resistance.

Figure 3-25: Drilling test on marble and granite

The DLC coating is then the keystone of the project because of its exceptional surface properties. The very low friction coefficient guarantees low dissipation of energy and the high surface hardness involves a longer working life.

The hydraulic DTH hammer of 2 ¼ inches is a very interesting solution for ornamental stone blocks drilling as it increases the performances in comparison with the air hammers actually in the market.

Figure 3-26: Some STREAM project partners during the tests

Task 7.2: Final demonstration and training
Partners Involved: VTT, RIPAMONTI, CROMOSTAMP, NEUMAC, MARMORES, ABRA, DAPP, POLIMI, ITE, COVER
Related deliverable: D11: Demonstration of the system performance. D12: System validation and final reporting

For the demonstration of the system performance several on-field drilling testes were organised by RIPAMONTI. The most interesting hammer parameter observed during the tests was its high drilling capacity compare to standard pneumatic hammer and top-hammers

Table 3.11: The most important mechanical properties of stones used in the tests

	White granite[1]	Marble[2]	"Serizzo"[2]	"Serena" stone[2]
Compressive strength σ_c (MPa)	229	82	141	90
Compressive strength Young's modulus E (MPa)	30200	44141	20199	27342
Knoop microhardness (MPa)	5445	2269	4576	2549

The penetration rate relative to each configuration was measured for two 2 ¼ inches hammers: one with components treated with DLC coating and another with components devoid of DLC coating. All the values were collected in Tables 3.5 and Table 3.13 are relative to two cases. These data were interpreted considering the mechanical properties of the stones selected (Table 3.11).
The inclination of the hammer influences the rate penetration because it influences the velocity of the flushing. The flushing is facilitated if the hole inclination is less that 90° degrees. The penetration rate is in fact higher in the cases with inclination of 45° degrees or 0° degrees. Furthermore the flushing velocity is influenced by the dimension of fragments; this dimension depends on the grain dimension of each type of stone. The penetration velocity decreases with the growing of the surface hardness (Knoop micro hardness).

[1] For these data refer to http://www.biancomontorfano.it
[2] For these data refer to http://www.pietredelvco.it

Table 3.7: Values for test with granite

Inclination [°]	Piston Coating	Penetration Rate [cm / min]	Water Flow [l /min]
90	without DLC	41±1,2	39,6
	with DLC	50±1.1	33,2
45	without DLC	42±0.8	38,2
	with DLC	52±0.8	32,9
0	without DLC	44±1.3	38,7
	with DLC	54±1.1	33,3

Table 3.13: Values for test with marble

Inclination [°]	Piston Coating	Penetration Rate [cm / min]	Water Flow [l /min]
90	without DLC	46±1,6	39,3
	with DLC	55±1.2	33,6
45	without DLC	48±0.8	38,9
	with DLC	57±0.8	33,1
0	without DLC	49±1.3	38,6
	with DLC	58±1.3	33,3

Furthermore the collected values showed how the DLC coating increased sensibly the penetration rate: the mechanical efficiency was improved by a maximum of 15 %.

Task 7.3: Validation
Partners Involved: VTT, RIPAMONTI, CROMOSTAMP, NEUMAC, MARMORES, ABRA, DAPP, POLIMI, ITE, COVER
Related deliverable: D12: System validation and final reporting

In order to know the frequency of the 2 ¼ inches STREAM prototype it was calculated the displacement of the piston respect the time. This was performed by the parametric model validated during the previous tests conducted with the first two STREAM prototypes.
In order to verify experimentally the piston frequency, the noise of the hammer recorded during the test was analysed using a software able to calculate the Fourier transform. The distribution of frequencies respect the time was displayed (see Figure 3-27). The frequencies with higher intensity are represented with a more marked line. It can be observed a marked curve below the level of 0.1 kHz. This frequency corresponds with the calculated working frequency of the hammer.
The sonorous signal plotted in the domain of frequencies confirmed the calculated frequency of 76 Hz for the impact of the piston on the bit, being one of the most important noise sources.

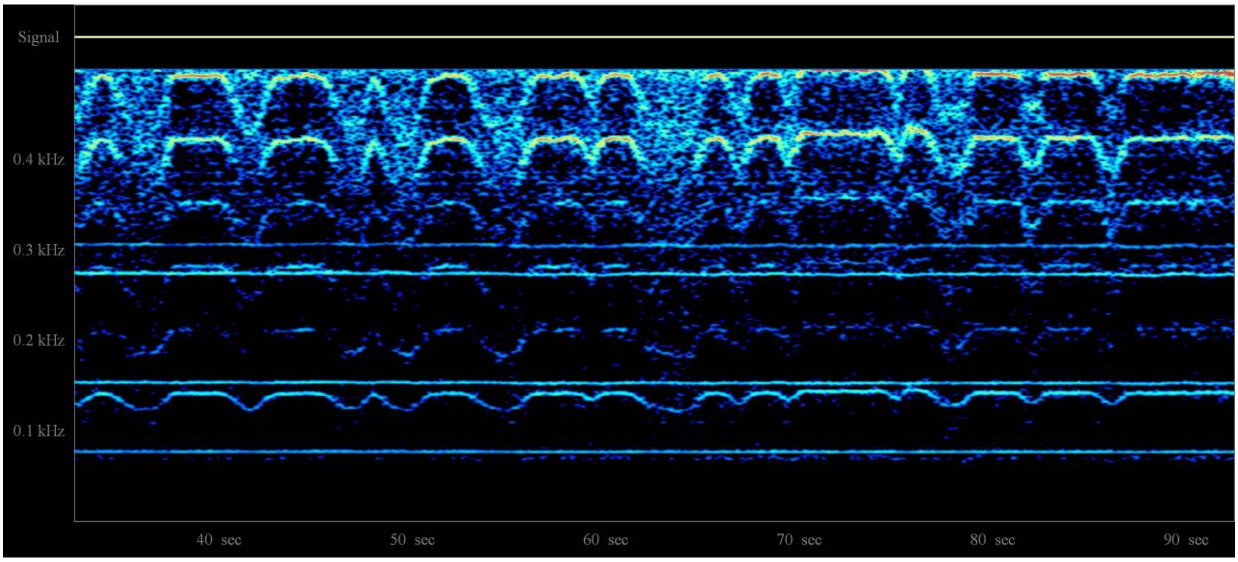


Figure 3-27: Signal in the time domain

The effective of the coatings applied to the sliding surfaces of the hammer was the other aspect analysed during the tests. In particular starting from the surface properties reported in the Table 3.9 the experimental data collected during the tribological tests (see Table 3.10) were interpreted observing the surface of the components of the tested hammer and the formulas for the calculation of the coefficient of friction and the wear rate. The surfaces coated with DLC were compared with those of a previous tested hammer devoid of DLC coating.

Table 3.9: Properties of the studied surfaces

	Thickness (μm)	**Hardness** (GPa)	**Roughness Ra** (μm)	**Roughness Rmax** (μm)
Chromising	50	11	0.054	0.781
Chromising + DLC	1	35	0.040	0.661

Table 3.10: Tribological test in environment with water and alumina

	k$_i$ [$mm^3 N^{-1} m^{-1}$**]**	*COF*
Chromising vs. Chromising	3.8 e-5	0.35
Cr+DLC vs. Cr	4.9 e-6	0.04

3.8 WP8 Innovation and related activities

The objective of the Work Package is to facilitate and encourage the industrial and commercial exploitation of the results and define the measure to ensure that the SME proposers will be able to assimilate and exploit the results of the project as well as the dissemination of the results. A plan for using and disseminating the knowledge will be developed to transfer specific knowledge from the RTD performers to the SME participants to enable them to rapidly apply and embed the technology onto specific products.

Task 8.1: Protection IPR

Partners Involved: VTT, RIPAMONTI, CROMOSTAMP, NEUMAC, MARMORES, ABRA, DAPP, POLIMI, ITE, COVER

Related deliverable: D13: International patent application for the STREAM system

The general aim of this task was to analyse the best methodology to protect the principal innovations of the STREAM project:

- A novel process for the DLC deposition based on PACVD technique;
- A new design for a water Down-the-hole hammer of small diameter.

In order to evaluate the possibility to patent such innovation, the consortium performed a deep analysis in all major patent databases worldwide.

Regarding the new PACVD technique for DLC deposition, the worldwide patent analysis demonstrated that :

- o DLC is a well know coating that it used to produce wear resistant pieces, as cutters or bits, in different markets and applications (E.g. milling, tools for medical sector, production of information storage items);

- o PACVD is still an innovative process to produce DLC. Only in 1991 it was submitted the first patent mentioning it. The number of patent found (22) in all major worldwide patent databases is quite small with maximum five patents submitted per year.

- o Only two European companies (Bekaert and SECO) are active in using PACVD for DLC, especially to improve substrate adhesion and wear resistance: Bekaert is proposing solutions based on fluorine-doped coatings while SECO is proposing a coating comprising layers containing h-MeX phase.

Compared to patents analysed, STREAM deposition process and control system is still innovative because STREAM process is able to increase the adhesion properties of DLC by using a low-temperature plasma source in order to keep the maximum temperature of coated element lower than 110°C. Low temperature of the substrate and proper kinetic energy of the incident particles can produce DLC coatings with high hardness and moderate internal stress, then having high intrinsic adhesion properties. For these reason the SMEs are in the process of writing a patent application protecting the STREAM result regarding the innovative PACVD process control methodology for the production of water hammer.

Regarding the STREAM new design for a water down-the-hole hammer, the worldwide patent analysis demonstrated that :

- o SANDIVIK, the only company now producing a large diameter water DTH hammer, is by large the first company with patents regarding DHL hammer;

- o NOVATECK does not submit any patent regarding DTH hammer;

- o a preliminary check with a patent attorney confirmed that it is possible to patent the STREAM hammer design in order to protect it.

The consortium aims to submit one patent covering both 2¼ and 1¼ inches STREAM hammer design and order to not protect both. For this reason the consortium decide to first develop a working prototype of 1 ¼ STREAM hammer before starting the process of submitting a patent because, even if a full design and modelling was done, it could be that during the manufacturing and test of the prototype some important upgrade should be made.

Task 8.2: Marketing strategy and feedback
Partners Involved: VTT, RIPAMONTI, CROMOSTAMP, NEUMAC, MARMORES, ABRA, DAPP, POLIMI, ITE, COVER
Related deliverable: D16: Plan for using and dissemination knowledge (M24)

The main innovative results obtained in the STREAM project with the contribution of all partners of the consortium were two:

- A novel process for the DLC deposition;
- A new water DTH hammer of small diameter.

These results will be exploited by the STREAM partners and in particular by the SME's of the consortium.
The primary commercial exploitation routes for the output of this project will be through the quarry and mining industry.

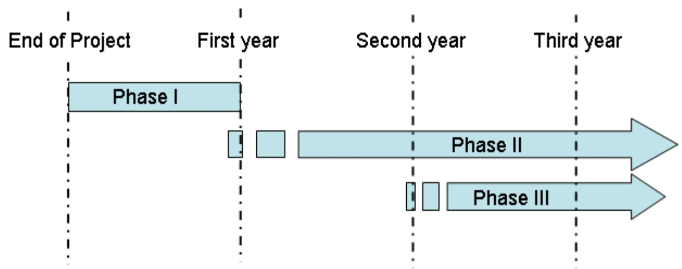


Figure 3-28: Exploitation phases

The exploitation has been organised in three phases (Figure 3-28) as described below:

I. During the first phase, long one year, the consortium will further develop the final 2¼ inches prototype into a complete industrial system ready to be fully exploitable. In particular all the components (pump, distributors, connectors) of the support hydraulic system will be defined in order to develop the full STREAM industrial system. In parallel with this work the consortium will also prototype the 1¼ inches hammer. The consortium has the capability of carrying out such additional development that will mainly consist in the optimisation of the hammer elements and in performing the required actions for the industrialisation.

II. At the end of phase I, a first industrial version of the STREAM system will be used by MARMORES during their extraction works using the hydraulic components provided by ABRA. This will build up a consistent and large record of successful application of the system and also generate the first revenues from the use of the system. During this phase, RIPAMONTI, in conjunction with all the partners, will be in charge of updating the original business plan and the Economic Impact Assessment, including market analysis and sales forecast.

III. After two year from end of project, it will start the commercialisation of the STREAM 2¼ inches hammer system and hydraulic system. As a deep experience on the field is needed to push the new system on the market, NEUMAC will provide training and demonstration to potential users. RIPAMONTI will be responsible for system commercialisation and marketing through its world-wide net of agents well introduced in the reference market.

In parallel with these phases the exploitation of the acquired knowledge in DLC coating will be organized in as many phases:

I. In the first year VTT will provide the base materials treated with hybrid diffusion consisting of carburizing and sulfonitriding to CROMO that will use the pre-industrial DLC plant to optimize furthermore the industrial process.

II. CROMO with the collaboration of VTT will collect a record of successful DLC applications of industrial interest; VTT and CROMO will offer the services to produce high resistant and low friction components to all the other STREAM SMEs in order to enlarge their market of mechanical components of drilling systems. At the same time they will manufacture the new large scale plant;

III. CROMO and VTT will collaborate with firms active in the rock drilling market and interested in the production of mechanical elements coated with DLC. It will exploit the validated large scale plant.

Task 8.3: Training, exploitation and dissemination
Partners Involved: VTT, RIPAMONTI, CROMOSTAMP, NEUMAC, MARMORES, ABRA, DAPP, POLIMI, ITE, COVER
Related deliverable: D14: Project Brochure and website; D16: Plan for using and dissemination knowledge (M24)

Several dissemination activities have been performed to spread to the international community both scientific and technological results, with the final aim to help the effective exploitation of project results.
The STREAM website (see Figure 3-29) represents the first vehicle in raising awareness of the project and includes the most important information, being currently updated: list of partners, the main objectives, project conferences, fairs, news and other related events.
The website is the key factor for quick dissemination and provides the SMEs within the project results. This allowed a quick update on the project outcomes.

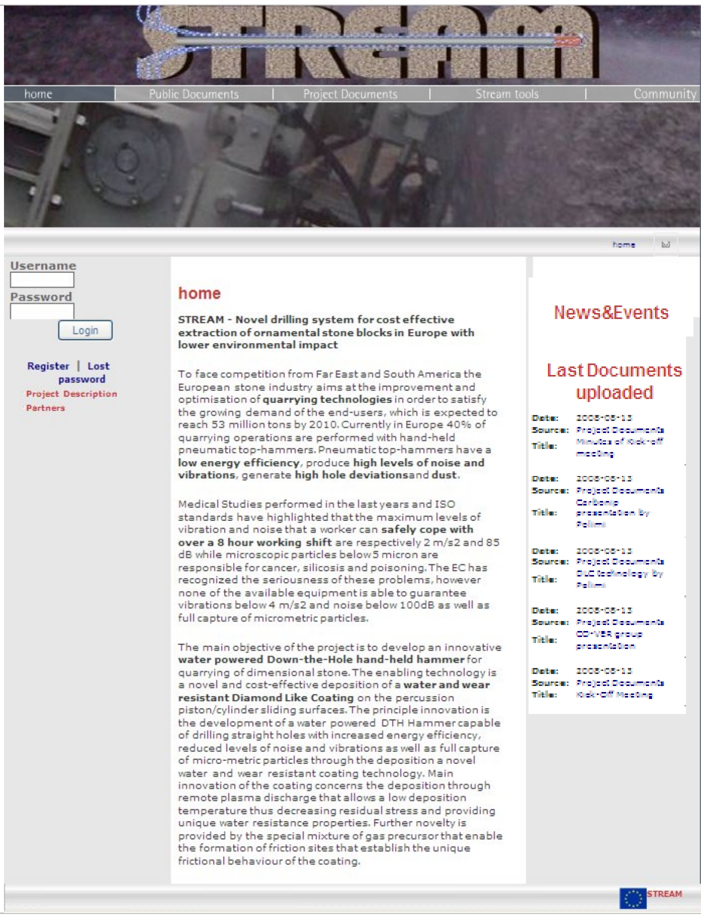


Figure 3-29: Screenshot of the STREAM website

A project brochure (see Figure 3-30) has been designed and used by the partners during international fairs and congresses to spread out STREAM objectives and goals. The STREAM project was presented in four different fairs: Research2Business R2B, Interfinish 2008, 32° National Congress of A.I.M. and Geofluid 2008.

Figure 3-30: Reproduction of STREAM flyer, outer pages

Regarding the optimised DLC coating deposition process, POLIMI have presented two scientific papers presenting the scientific approach, the improved deposition process and the main characteristics of the obtained coating. Both papers have been reviewed and accepted, and they clearly refer to the research activities developed into the STREAM project.

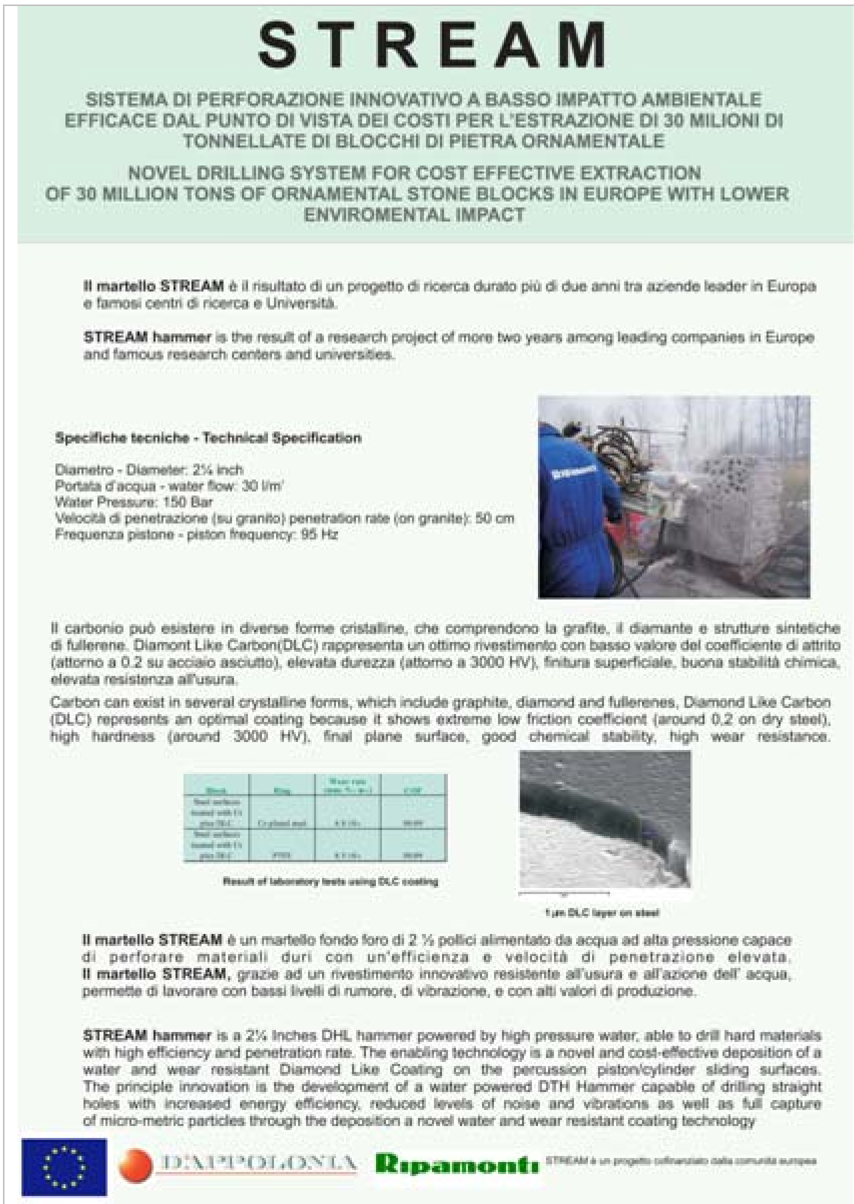


Figure 3-31: The STREAM poster

4 Consortium management

Consortium managements falls under the activities described within the WP 9 (Project Management). The project objective consist in the optimal management of the project resources in order to affect an optimum transfer of the expertise generated and the information gathered to the members of the project.

4.1 The performance of the consortium

The collaborative work has been characterized by a high level of commitment from the Team Leaders and the participating organizations to the successful outcome of the Project. A good balance has been achieved between the individual contribution of each partner and joint review and decision making with respect to the overall direction of the Project.
Consortium manager keep all partners always and frequently updated on the progress achieved in each WPs to assure a unique view on the development of the different modules and increase the efficiency of the R&D activities carried out by each project team. Several emails and phone calls have been exchange between coordinator and partners weekly. The project website has been used as document repository and as tool to exchange information.

4.2 Milestone Achievements

The progress of the project towards its objectives has been assessed as planned in the work programme and all milestone has been achieved. The role and the activities performed by each partners of the STREAM consortium are reported in the Table 4.1.

Table 4.1: Activities performed by the STREAM partners in the diverse WPs

RIPAMONTI	Support to the critical review of the drilling technologies. Provider of technical data and mechanical parts for the study of hammer design. Support in the definition of the base steels to be used. Contribution to the design of the DHL hammer prototypes supplying materials and bits. Organise the tests and performance demonstrations. Presentation of project result to international fair R2B. Management of the project.	WP2,WP6 WP7,WP8 WP9
CROMO	Preparation of samples with different hard cromium coating deposition techniques. Hardness and wear tests on coated samples Contribution on designing the DLC coating plant implementing the new PACVD. Contribution to the design of hammer components. Production of DLC coated elements to be tested at laboratory and on-field.	WP2,WP3 WP4,WP5 WP6,WP7 WP8
VTT	Contribution on defining and testing thermal treatments and base materials for the hammer components. Manufacturing of the cylinders parts. Contribution on testing the hammer.	WP2,WP3 WP4,WP5 WP6,WP7 WP8
MARMORES	Support in the definition of the target industrial requirements from the end user point of view. Contribution on the design of the hammer prototypes. Supply of stone materials and definition of test plan for performance demonstrations.	WP1,WP2 WP6,WP7

ABRA	Support in the definition of manufacturing aspects concerning the hammer prototyping especially regarding hydraulic circuit. Process optimisation of hydraulic components. Contribution in the definition of hydraulic circuit for tests and performance demonstrations.	WP2,WP5 WP6,WP7 WP8
DAPP	Definition of the hammer design requirements. Development of the structure of the Software Tool and process optimisation for coating. Leader in the design activities for the hammer prototyping and testing. Development of dynamic models and simulation of the hammers. Hammer performance analysis and testing. Development of poster, brochure, web site and R2B presentation of the project.	WP1,WP2 WP3,WP5 WP6,WP7 WP8
POLIMI	Definition of coating and surface treatment process parameters and classification on the base of their main application field. Design of the lab scale plant for DLC. Definition of process parameters for the new PACVD process. Design of the new coating plant. Laboratory tests to evaluate the wear, corrosion performances of materials sample DLC coated . Contribution in the design of the different hammer prototypes and test validation. Scientific papers on STREAM project.	WP1,WP2 WP3,WP4 WP5,WP6 WP7,WP8
ITE	Selection of the most suitable surface treatments and definition of the process parameters. Development of innovative knowledge on the best base materials, thermal treatments and surface finishing coupling with DLC coating. Contribution in the production of test components.	WP2,WP3 WP4,WP5 WP6,WP7 WP8
COVER	Analysis of design aspects for the hammer development. Support in the definition of the demonstration activities and supply of stone materials for tests.	WP2,WP6 WP7
NEUMAC	Study of the design and working principle of the hydraulic top hammer. Strong contribution of STREAM hammer design. Manufacturing and assembly of the three hammer prototypes and laboratory testing. Strong contribution in system performance evaluation testes.	WP2,WP3 WP4,WP5 WP6,WP7 WP8

4.3 Meetings

In the first reporting period the 6th Month progress meeting has been successfully held in Italy at RIPAMONTI premises (April 2007) and then, 3 technical meeting has been held between representatives of RTD performers. Finally, the 12th Month meeting has been successfully held in Poland at ITE premises.
In the second reporting period most of the meeting has been used to perform on-field drilling tests and system evaluation and validation activities. The use of internet services allowed to minimise the travel of the person involved into the tests and allow to exchange information among the partners. Two general meeting have been organised at month 18th and at the end of the project to discuss regarding the overall status of the project and the exploitation and dissemination strategy.
The list of meeting organized in the second reporting period is shown in Table 4.2.

Table 4.2 Meetings

Meeting	Date	Place	Present
Kick-off	13th October 2006	Ornavasso, Italy	All
Technical Meeting	8th November 2006	Ornavasso, Italy	RIPAMONTI, DAPP
Technical Meeting	18th January 2007	Milano, Italy	DAPP, POLIMI, CROMO
Technical Meeting	8th February 2007	Ornavasso, Italy	RIPAMONTI, DAPP
6th month meeting	12th April 2007	Ornavasso, Italy	All
Technical Meeting	15th June 2007	Milano, Italy	DAPP, CROMO
12th month meeting	11th September 2007	Radom, Poland	All
Technical Meeting	21th November 2007	Ornavasso, Italy	RIPAMONTI, DAPP, NEUMAC
Laboratory tests	19th February 2008	Saragozza, Spain	NEUMAC, DAPP
18th month	11th March 2008	Saragozza, Spain	All
On-field testes	19th March 2008	Ornavasso, Italy	RIPAMONTI, DAPP
On-field testes	8th May 2008	Ornavasso, Italy	RIPAMONTI, DAPP
Final Meeting	25th September 2008	Ornavasso, Italy	All

4.4 Contractors contribution

Due the complexity of the system and the tight interaction among the different components, partners worked always in cooperation during the development of activities. In general RTD performer led the activities but SMEs were always deeply involved providing the input requirements for each component, validating the work performed by RTD, developing and manufacturing system elements.

In particular CROMO, VTT, ITEE, DAPP and POLIMI worked together to optimize the innovative DLC coating deposition by Plasma Assisted Chemical Vapor (PACVD) technique.
RIPAMONTI, NEUMAC, ABRA, MARMORES, COVER and DAPP worked jointly to design, test and validate the new water down the hole (DTH) hammer that is the second innovative result of STREAM project.
All partners contribute to the consumables and other costs expenses needed to carry out the laboratory and full-scale coating, to adapt the PACVD control, and to design and prototyping of the STREAM hammer prototypes. This confirms again the high commitments of all contractors in the project objectives.

4.5 Project timetable

The main activities during the first reporting period were the development of a pre-industrial DLC plant and a first study of the PACVD process. Tribological tests were conducted in order to select the base material and to obtain the first information about the most suitable thermal treatments and coatings. The state of art of the existing drilling hammers was studied and the design route of the first STREAM hammer prototype was chosen.

In the second reporting period were the development of the 2 ¼ inches hammer prototype, the design of 1 ¼ inches hammer prototype, their integration and the drilling system, evaluation using laboratory and on-field tests about the DLC coating and the performances of the new prototypes. Even if several laboratories and on-field were performed among all second year, during 18 month project meeting (May 9th) it was agreed among partners an aggressive schedule to complete all final development, test and integration activities for the scheduled end of the project, September 30st. Therefore with the contribution of all partners the times were respected in accordance with the programme (Figure 4-1).

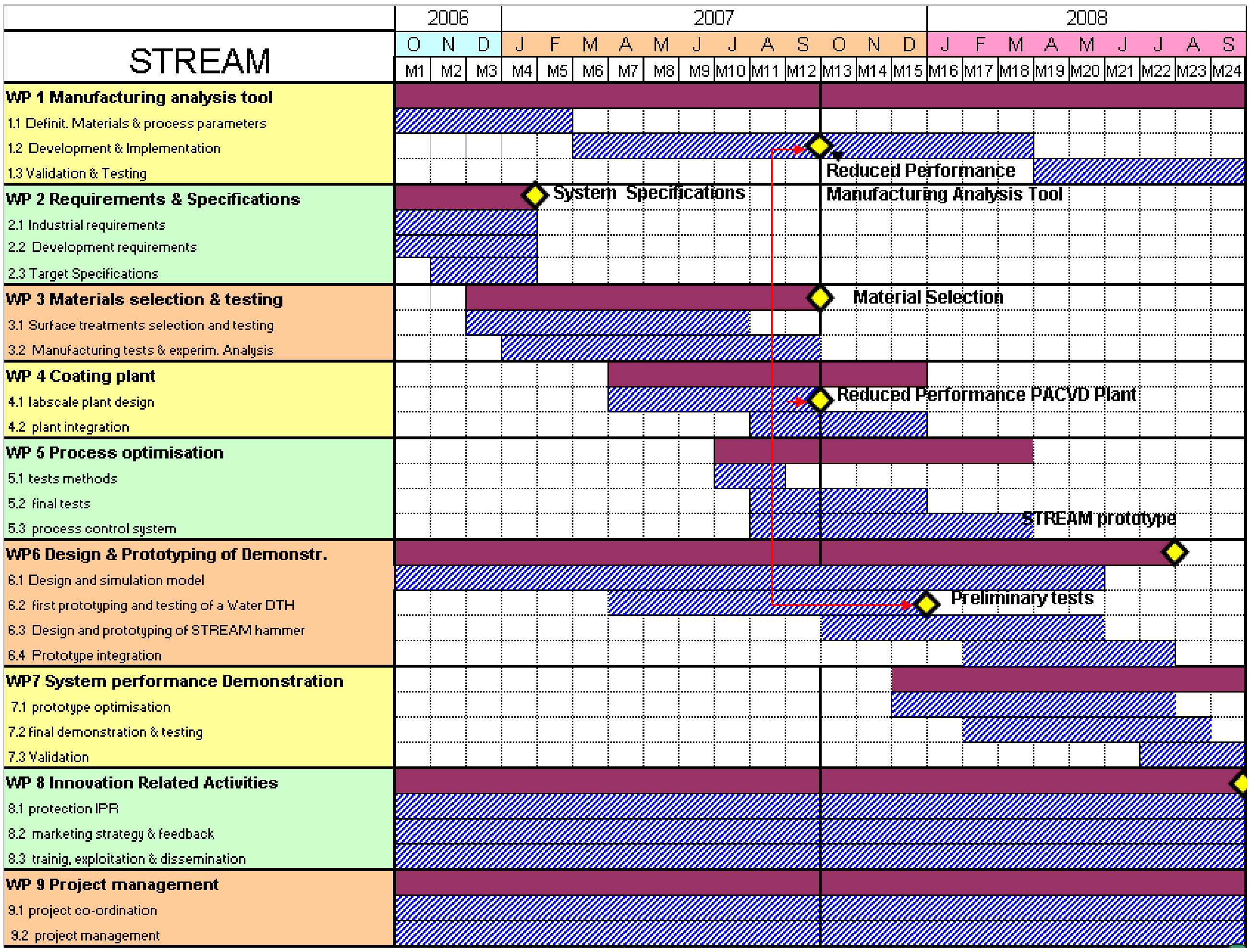


Figure 4-1: Gantt Chart of the activities