Core report of the project

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A. Introduction

The project COTEM titled "Advanced electrical machine manufacturing process implementation and tuning based on composite material process technologies" aims to develop an optimized manufacturing process for the Open-Rotor demonstrator deicing system electrical machine based on organic matrix composite material processing technologies. Labinal Power System technically supervises the project as Topic Manager. The different tasks designed the manufacturing process, selected the resin and optimized its process parameters, and then manufactured a first demonstrator of an electrical machine. This advanced manufacturing has been based on composite material process technologies developed at Nimitech Composites (partner) with optimized process parameters determined at Ecole Nationale d'Ingénieurs de Tarbes (partner and coordinator). ENIT organized and monitored the financial and administrative progress of the project. This involved maintaining practical and economically relationships with all partners. The project secretariat functions were contracts administration, compilation of cost statements and progress reports, organization of meetings, and the co-ordination of the external dimension of the project

ENIT organized and monitored the technical progress of the project to follow the on-going work gathered in milestones and deliverables. The task included the management of the relationship between work packages, the compilation of technical progress reports, and facilitation of technical meetings. The project had a Steering Group that was the decision-making body of the project. Financial statements are gathered in four F7 form C documents, one by partner and period.

COTEM project started on 21/11/2012 and was foreseen to end on 20/11/2014. However, the end of the project was delayed one year. The reasons are detailed in the following part:

The technology chosen for the TFU which is the electrical deicing system studied to supply and transfer the power necessary to the deicing on the SAGE2 Demonstrator is "SATURN" concept. Initially a first prototype manufactured by Nimitech should be proposed to Labinal Power System for November 2014.

Nevertheless, design details evolutions (i.e. hollowed shape of the magnetic links for example) have been discussed between Nimitech and Labinal Power Systems.

These different exchanges done on CATIA V5 files basis have delayed the different milestones and deliverables D3.1, D4.1, D5.1, hence the final report D1.1. ***The last design conception has been sent by LPS in November 2014, the 20th, date of the project end****. So the consortium has sent a letter to Clean sky Joint Understanding to request the Project's extension during one year.*

This request has been refused *because the letter was sent after the end of the project. However, the consortium has decided to come to the end of the project with the deliverable of a first demonstrator (Deliverable D5.1) and with additional ageing tests on materials not initially programmed in the project.*

Consequently, several deliverables were delayed (see table below).

B. Consortium management tasks and achievements

Table 1: Initial Deliverables list

Del.no.	Deliverable name	WP no.	Nature	Initial Delivery date	Delayed delivery date
1	*State of art report*	*2*	*R (Report)*	*month 3*	*Month 4*
2	*Manufacturing process design*	*3*	*R (Report)*	*month 9*	*Month 19*
3	*Resin process parameters report*	*4*	*R (Report)*	*month 18*	*Month 29*
4	*Electrical machine prototype*	*5*	*P (Prototype)*	*month 24*	*Month 35*
5	*Final report*	*1*	*R (Report)*	*month 24*	*Month 46*

The different meetings between the partners are gathered in the following Table 2.

date	place	participants	Main topic
2012/11/21	Tarbes (ENIT)	LPS, Nimitech, ENIT	Kick off meeting
2013/01/22	Bagnères (Nimitech)	LPS, Nimitech, ENIT	Industrial requirements
2013/03/13	Paris (LPS)	LPS, Nimitech, ENIT	First design proposition of the magnetic core by LPS. Presentation of potential composite process by Nimitech (WP2)
2013/04/17	Tarbes (ENIT)	Nimitech, ENIT	Presentation of the different families of materials
2013/07/27	Bagnères (Nimitech)	Nimitech, ENIT	Presentation of the first results on resin choices (WP3)
2013/11/04	ENIT (Tarbes)	LPS/ENIT	WP3 progress
2014/06/12	Bagnères	LPS, Nimitech, ENIT	WP3 end
2015/05/08*		LPS, Nimitech, ENIT	Presentation of resin' ageing
2015/05/11*		LPS, Nimitech, ENIT	Presentation of process and tool design

***two progress meetings after the project's end**

C. Technical Report

1. Introduction

The SAGE2 Demonstrator incorporates two counter-rotating propellers, which should be deiced. An electrical deicing system is studied to supply and transfer the power necessary to the deicing. Regardless of the system design, this electrical machine can be consider as a complex assembly of enameled winding insulated from a magnetic core by layers of fiber glass reinforced thermoset resin composite, finally encapsulated with a high dielectric thermoset resin. This topic aims to develop an optimized manufacturing process for the Open-Rotor demonstrator deicing system electrical machine based on organic matrix composite material processing technologies.

The overall work plan is structured into five work packages, for an initial total duration of twenty four months, where progress of both the work packages and its inter-relationship with the project can be assessed. To achieve the mentioned objectives, different steps and research activities are necessary. First of all a scientific analysis and state of the art of electrical machine manufacturing process have to be investigated (in WP2). This includes detailed investigations concerning all relevant parameters and information about the production process. After, the design of the manufacturing process, based on state of art and specification of the electrical machine, in close relation to the resin selection, has be realised in WP3. The optimisation of the resin process parameters has been investigated in the next WP (WP4) in order to get the most adequate parameters to the process and all environment variables. The technology has been integrated in WP5 to manufacture a first part of the prototype of the electrical machine. ENIT has carried out the financial, administrative and technical coordination described in WP1.

2. Development

In electrical motor the element that concentrates complexity is the rotor and the stator. This complexity leads to a long and expensive fabrication cycle. Multiple kinds of materials require the manufacturer to use preparation techniques and different implementations that need different equipments. Therefore the product cycles increase by splitting the manufacture steps.

WP2 : State of art of electrical machine manufacturing process

Firstly ENIT and Nimitech (the two partners) have reported a state of art on electrical machines in order to underline the benefits and drawbacks of electrical machine manufacturing, then to reduce the product cycle by integration of the various phases of manufacturing. This integration involved the study of processes of each material constituting the electrical machine and gathered in deliverable D2.1. Then each process was streamlined and adapted to the global process because this is the target: architecting a global process of obtaining the electrical machine. The electric machine assembly is complex because it contains a polymer matrix as the dielectric insulation, anodised aluminum sheets as reinforcements and the interface between these two elements. Two other elements exist in this assembly, the interface between the main insulation and the magnetic core and the interphase between the main insulation and the matrix. Interface optimisation deals with surface treatments to make the adherence maximum. The interphase is another problem; the two polymers have to entangle without mixing. It is possible that the polymers rejects each other and creates porosity because of their thermodynamically incompatibility.

This state of art enabled to identity criteria on which we shall focus to identify the most interesting solution to improve the product cycle. In summary this global process takes into account aspects of adhesion and compatibility of materials, thermal and mechanical stability of the resins and resources for a sustainable and profitable product.
The objective of WP2 is fully reached.

WP3 : Manufacturing process design & resin selection

In this work package, starting from the integration of innovative process technologies issued from composites in the electrical machine manufacturing, impregnation resins were specified and selected to meet with the manufacturing process requirements but also with the application requirements. The second work is to propose design processes.

Therefore the first material parameters were defined and studied in order to conclude on a first resin selection.

A first risk factor identified was the electrical motor insulating materials temperature ageing. Thus, the material selection has also focused on the material ability to withstand high temperature.
Another selection criterion has focused on the motor manufacturing process that is considered as a multi-material assembly with multiple interfaces. It is noted that the importance of impregnation resin viscosity which is the second parameter to select resin. Furthermore, it important to note the impact of the coefficient of thermal expansion that shall be modulated at materials interfaces (i.e. conductor – dielectric interface) due to the differential thermal dilatation.
As a result, the resin parameters necessary to take into account are resin viscosity, thermal stability, weak shrinkage and material health.
After having proposed a list of materials, based on state of art and specification of the electrical machine, physical, thermal and mechanical characterisations of polymers and interfaces were performed in order to quantify the optimisation level of the resin process.
Each impregnation resin was characterised using several experimental techniques in order to methodically define its physical and chemical properties. Nevertheless, the study only focused on the techniques that are relevant regarding the final application.
It was indispensable to rely on polymerisation process optimisation methods of impregnation resin in order to warranty the strong cohesion and adhesion responsible of the interfaces stresses continuity. Indeed thermoset resins often exhibit a complex chemical structure in particular because of the production of secondary species during the curing reaction. The choice of cure temperature is often a compromise between quality of the product and industrial requirements.
This optimisation work based on rheology and thermal analysis enabled to pre-select three resins in a first approach.

Particularly, the polymerisation process of evolutive systems (resins) was investigated with rheology and thermal analyses in order to warranty the strong cohesion and adhesion responsible of the interfaces stresses continuity.
The viscosimetric profile of these systems was analysed in order to adapt the manufacturing process.
Dynamic rheology was applied to characterise the material thermomechanical behaviour in order to identify the characteristic domains and their associated critical temperatures (glass transition temperature, softening temperature). These data were used to define the temperature range in which the material will be safely used. They were completed by differential scanning calorimetry to define the kinetic evolution (curing of resin). The choice of cure temperature was a compromise between quality of the product and industrial requirements.
All the results are reported in the deliverable D3.1. This optimisation work based on rheology and thermal analysis enabled to pre-select three resins in a first approach.

The second part of WP3 deals (deliverable D3.1) with two propositions of design process (Nimitech Proposal).
The first one is based on one-shot impregnation in three steps:
- The subsets (cheeks, links, coils…) are assembled mechanically and separately
- Then the subsets are gathered in an injection mould

- All the interfaces are impregnated in the same time according to a studied vacuum/pressure/temperature cycle
The second one is based on a two-shot impregnation:
- The subsets (cheeks, links, coils…) are impregnated and pre-cured separately in different impregnation or injection moulds
- The pre-cured subsets are gathered in a compaction mould
- The global assembly is cured under hydrostatic liquid resin pressure
The objective of WP3 is fully reached.

WP4 : Resin process parameters optimization

This optimisation work based on rheology and thermal analysis enabled to pre-select three resins in a first approach. In a first part of WP4 the thermal and mechanical properties before ageing tests have been completed to inform the whole materials parameters for the three preselect resins. Then the material mechanical and thermal properties evolutions of the chosen cured resin were studied during ageing in order to understand the material failure mode in their future application. Ttwo ageing mediums (humidity and oil) representative of harsh environment were defined. The most of degradation mechanisms in humidity and oil are accompanied with weight changes, that's why in first approximation gravimetric study is a good guess of stability. Silicone resins are chemically degraded with decrease of mechanical properties (elastic and loss shear moduli) and thermal stability (glass temperature), out of industrial requirements. Only the epoxy resin with relevant properties after ageing tests was retained.
But the mechanical aspect makes no sense if the polymers adherence properties are forgotten. These adhesion aspects appear as very strategic to provide an insulation function. So the variation of the surface tension and topology of aluminum sheets have been measured as a function of surface treatment which is an anodisation. Adherence measurements after curing were performed in order to comply with the different types of materials to be tested and to ensure an interface adherence optimization.
The whole results on optimisation of resin parameters for composite process are gathered in Deliverable D4.1.

The objective of WP4 is fully reached.

WP5: Electrical machine prototype

The goal was to achieve a demonstrator which is closest possible to the final application in terms of geometry, composition and functions.
The final objective of this research work was to manufacture a demonstrator using innovative and if possible, "one-shot process" electrical winding machinery using carefully selected materials.
As previously detailed, the main changes are the integration of new insulated wire technologies (such as anodized aluminum wires or ceramic platted wires) and the assembly of magnetic material sheets to form the machinery magnetic core.
For a first approach, NIMITECH suggested to demonstrate the previous work package choices viability by manufacturing one test vehicles. To make this prototype, it is necessary to use tools special designed by NIMITECH. Resin Transfer molding process was studied. Reinforcement mat or woven roving was placed in the mold, which is then closed and

clamped. Low-viscosity resin is pumped in under pressure, displacing the air and venting it at the edges, until the mold is filled. Vacuum inside has permitted to equally divide the resin between the sheets while it fills the mold. In order to the demonstrator magnetically work, each magnetic sheet had to be covered by a thin defined resin layer which has an insulating function.
The main changes have been the integration of new insulated wire technologies (such as anodised aluminum wires or ceramic platted wires) and the assembly of magnetic material sheets to form the machinery magnetic core. The results proved that the employed technology is suitable for producing magnetic parts. Additional tests on demonstrators permitted to adjust parameters in order to vary quality and thickness of the layers.

This work reached completion and led to additional studies on the concrete application (magnetic rotor). The injection process will be adapted to more complex shape parts and new complex tools will be manufactured. These results are gathered in the Deliverable D5.1.
The objective of WP5 is partially reached.

3. Conclusion

The innovation was at the center of this project. Nowadays no electrical device is manufactured by using the both composite materials and processes. The first part of the demonstrator is encouraging. This work enables to prove the suitability of composites processes to magnetic device such as rotor. Moreover, we have demonstrated that commercial resins are adapted to the industrial and process requirements.

D. Project Effort by Activity type per Beneficiary

	ENIT/ expected PM	ENIT/performed PM	Nimitech/ expected PM	Nimitech/performed PM
Innovation activities				
WP2	1.3	1.1	1.1	1.3
WP3	2.3	2.3	2.2	2.8
WP4	5.4	5	0	0
WP5	0.3	0,15	4.9	4.9
Consortium Management activities				
WP1	1.2	1	0	0

As one can see in the table above, there are very marginal deviations in terms of PM between the grant agreement and the final use of resources.

E. Project efforts and costs

ENIT	Initial Budget	Actual cost (Year 1)	Actual cost (Year 2)	Total actual cost	**Variation**
Personnal qualification an cost	40 000,00	13 816,85	26 245,51	40 062,37	62,37
Other direct Costs	60 000,00	32 243,32	31 378,50	63 621,82	3 621,82

Nimitech	Initial Budget	Actual cost (Year 1)	Actual cost (Year 2)	Total actual cost	**Variation**
Personnal qualification an cost	55 000,00	28 150,00	27 685,32	55 835,32	835,32
Other direct Costs	10 000,00		11 255,03	11 255,03	1 255,03

For Nimitech, the difference between actual and expected costs is due to audit costs.
For ENIT the difference is due to audit costs and use of more consumables during ageing experiment performed in WP4.

F. Impact

The innovation is at the center of this project. Nowadays no electrical device is manufactured by using the both composite materials and processes. This project would improve the competitiveness of the SME-Participant NIMITECH in its country and also at European level by the demonstration of its knowledge in manufacturing process technology of composite materials and its ability to bring and adapt this technology to the manufacture of electrical machine, a new market.
Beyond the success of the project COTEM, NIMITECH will launch a recruiting and training strategy to meet its needs of growth opportunities. It will continuously develop its recruitment and selection practices to increase its number of employees, contributing to the European effort to reduce the unemployment rate.
ENIT has been working since twenty years on the integration of power electronics systems in embedded systems. In power converters used on the railway traction drives or planes, integration results in compacted modules in which all the elements required to energy transformation are gathered nearest to the power chips. So COTEM project covering the different steps of innovative composite manufacturing makes ENIT improving its expertise on interfacial chemistry and mechanics to better forecast wetting, adhesion and transport properties in order to pursue research activities on multifunctional materials suitable to perform structure more integrated. Results on resin parameters optimization will be implemented through scientific papers.
This innovative technology would able to Labinal Power Systems to open new markets in harder environmental conditions by deferring the thermal limits of use and by decreasing the weight.

A scientific article about resin process parameters optimization and influence of ageing medium on resin properties will be submitted in a peer-reviewed international journal.