AST4-CT-2005-516134

DEEPWELD

Detailed Multi-Physics Modelling of Friction Stir Welding

Specific Targeted Research Project

Priority 4 – Aeronautics and Space

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Abstract:
This report describes the activities which have been performed, and the results which have been obtained during the full duration of the DEEPWELD project. It also contains the publishable results of the Final plan for using and disseminating the knowledge.

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Glossary

FE	Finite Element
FSSW	Friction Stir Spot Welding
FSW	Friction Stir Welding
HAZ	Heat affected zone
TF	Thermo-fluid
TM	Thermo-mechanical
TMAZ	Thermo-mechanically affected zone

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1. Project execution

1.1 Summary description of project objectives

Title:	**Detailed Multi-Physics Modelling of Friction Stir Welding**		
Acronym:	DEEPWELD		
Contract Nr.:	AST4-CT-2005-516134		
Total Cost:	2.654.933 €	**EU Contribution:**	1.552.466 €
Starting Date:	01/04/2005	**Duration:**	45 months
Web-site:	www.deepweld.org		

Background

DEEPWELD contributes to strengthening the competitiveness of the aeronautical industry in Europe. In 2005, when the DEEPWELD project started, Friction Stir Welding was a brand new technique able to revolutionize the way aircrafts are built by replacing riveting by welding. The benefits of FSW include the ability to join materials which are difficult to fusion weld. It is a simple, robust process that involves no consumables. When handled properly, FSW results in a defect free weld with superior properties. However, there was a lack of scientific and technical knowledge on its applicability to aircraft structures. This is the reason why DEEPWELD was submitted as a high strategic project.
Nowadays, the background has evolved. The FSW, usually applied to aluminium structures, is progressively extending its capability to steels and superalloys. Moreover, new processes based on the same principle (FSSW e.g.) are developed more and more. In conclusion, the results of the DEEPWELD project keep a pole position in the state of the art, and will be essential for future strategic applications in the field of advanced manufacturing processes.

Project objectives

The overall goal of DEEPWELD is the development of a new multi-physics and multi-scale numerical tool for the accurate modelling of the Friction Stir Welding process. This tool will help to shorten the design cycle and decrease cost by reducing the number of experimental prototypes, replacing them by virtual prototypes. The new tool will be a large step forward compared to current solutions. The DEEPWELD software will be equipped with a thermo-fluid module in order to simulate the important material flow around the tool and an advanced metallurgy model in order to predict the evolution of microstructures. Specifically instrumented experiments will be conducted in order to define accurate thermally varying friction laws, material constitutive laws and data in order to validate the new numerical tool.

Description of the work

The work is organised in four technical work packages.

WP1. Detailed specifications of industrial target applications:
The development of a numerical tool to simulate the FSW process, within the DEEPWELD consortium, will be carried out following specifications of the industrial end-users. This workpackage defines these specifications in terms of materials, applications, performance, software and experiments.

WP2. Physics and Metallurgy:
The *first* objective is to provide quantitative information to be introduced as input in the numerical codes to be developed in the DEEPWELD Project. The *second* objective is to provide sufficient information for better understanding of the physical phenomena occurring during FSW. This is required to select appropriate modelling assumptions for the different models or modules (thermo-fluid, thermo-mechanical, and metallurgical).

WP3. Multi-physics simulation tool development:
Development of a general numerical tool incorporating the coupling of the following fields: mechanical, thermal, metallurgy and flow calculation. The development of this general and multi-physics model will allow for predictive FSW simulations by: 1) eliminating the equivalent heat flux determined from experiments and replacing it by a thermo-fluid calculation to predict the amount of heat generated through plastic work and friction; 2) taking into account the changes in mechanical properties due to transformations in the micro-structure of the material.

WP4. Validation and Applications:
The objectives of this workpackage are: 1) an experimental validation campaign with a wide range of operating conditions; 2) a welding parameters optimisation in order to maximize the quality of the welds; 3) An application to coupons representative of industrial applications; 4) A structural response and certification to provide a quality criterion for the optimization analysis.

A specific workpackage (WP0) is dedicated to project management, risk management as well as dissemination and exploitation activities.

Expected results

The expected result of DEEPWELD is a multi-physics and multi-scale simulation tool for the modelling of the Friction Stir Welding, able to achieve, among other things, accurate predictions of residual stresses, distortions, weld properties and tool loads.
Among other things, the DEEPWELD simulation platform (Morfeo+Samcef, Stir-Kit on Abaqus, routines, metallugical and global power balance models and optimization scheme) will provide both an accurate, fast and validated image of the weld properties (in terms of hardness, residual stresses and metallurgical properties). The distortions of the structure will also be predicted with accuracy. The application of the simulation platform to 3 types of materials and 2 types of FSW processes (conventional and bobbing tool) will be also part of the results. The FSW technology has been highlighted with an application concerning structural panels with FE analysis in compression+shear.

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1.3 Contractors involved

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Institut de Soudure (IdS)	FR
The Queen's University of Belfast (QUB)	UK
EADS	FR
SONACA S.A.	BE
ARMINES-Ecole Nationale Supérieure des Mines de Saint Etienne (ENSMSE)	FR

1.4 Work performed and main achievements

In what follows, the work performed over the full duration of the project as well as the main achievements of DEEPWELD are summarized at the workpackage level.

1.4.1 WP1 - Detailed specifications of industrial target applications

Workpackage 1 defines the specifications of the industrial end-users in terms of materials, applications, performance, software and experiments.

1.4.1.1 Definition of industrial applications making use of FSW

Some applications of interest for aerospace industrial partners associated to the DEEPWELD programme have been defined.
The range of metallic structures that may potentially be assembled by FSW has been divided into two families: thin applications and thick applications. In both cases, butt weld configurations were mainly considered, as they yield the safest and simplest application of FSW process, avoiding some major drawbacks or uncertainties related to other weld configurations such as lap joints, T-joints or some of their derivative configurations.
Figure 1.1 presents some of the applications foreseen for thin applications. 2024 unclad aluminium alloy is mainly considered for the purpose of this programme. The welding shall be done on naturally aged tempers (T3/T4). Additional trials may also be performed on new generation Al-Cu-Li alloys, such as 2198. In this case, the welding operation could be performed on naturally aged tempers (T3/T4), the part being subsequently artificially aged to T6/T8 tempers. Welding in final use temper (T6/T8) may also be envisaged.

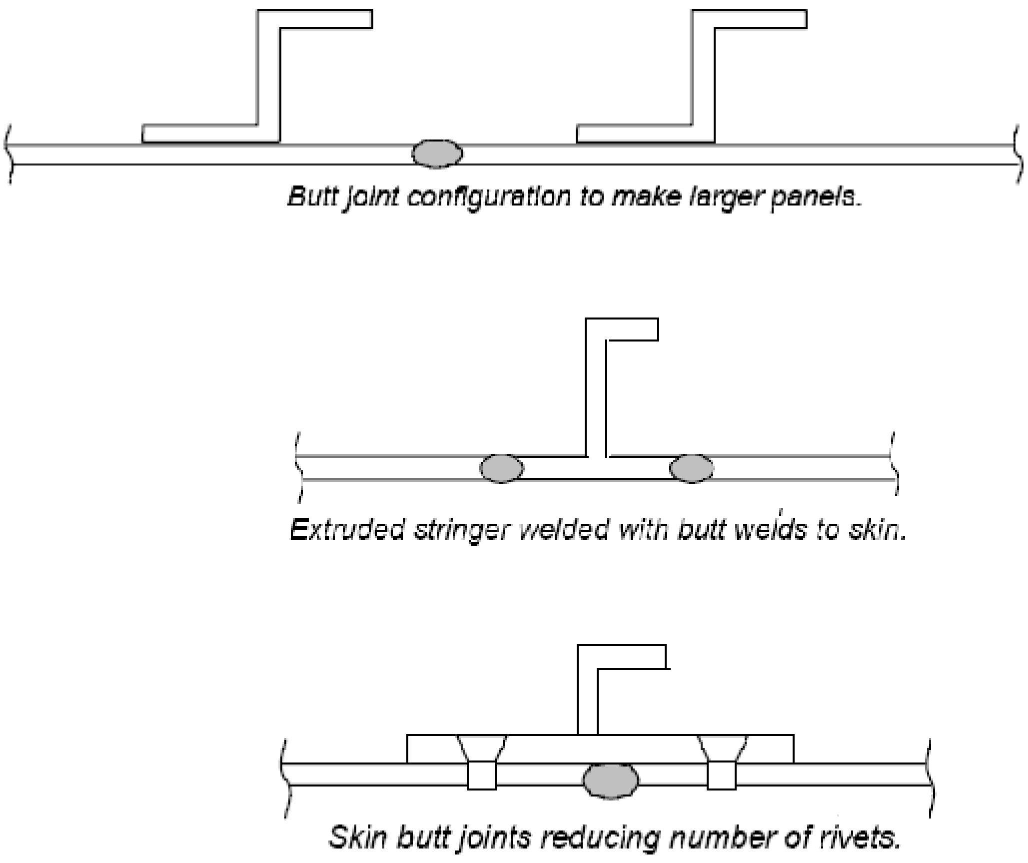


Figure 1.1 : Butt joint configurations for thin products applications

Figure 1.2 presents some of the applications foreseen for thick applications. 7449 alloy is mainly considered in this case. The welding can be performed either on final temper (T79) or on an intermediate temper prior to ageing to T79.

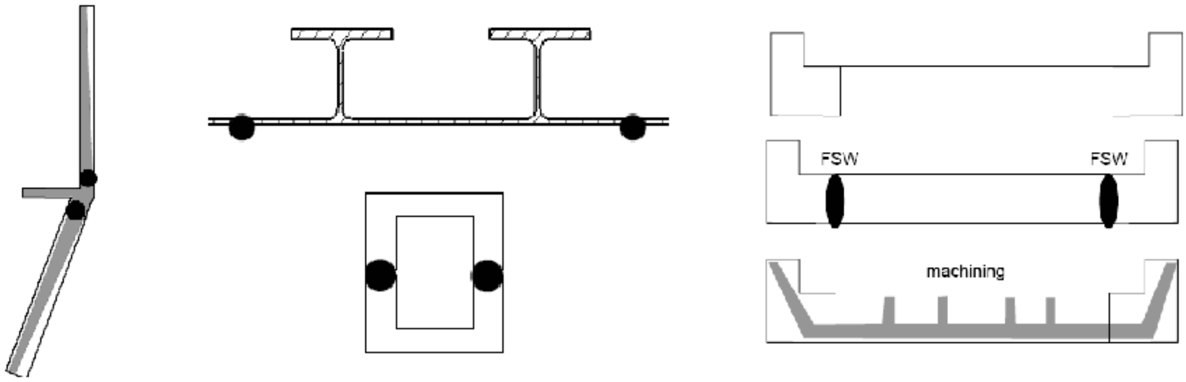


Figure 1.2 : Butt joint configurations for thick products applications

1.4.1.2 Set-up of the basis for numerical modeling

In parallel to the definition of industrial applications, a survey was performed to review the partners' modelling capabilities of the FSW process. Based on this survey, standards were set for the development of the DEEPWELD simulation tool, and its integration in the manufacturing and design phases.
First, a clear description of the FSW process has been made in order to outline the basic aspects to be dealt with : tool, set-up, temperature, metallurgy, mechanics, solid-fluid dynamics, scale of component, materials behaviour, coupling aspects, weld flaws, weld properties, TMAZ, HAZ, nugget zone. A review of each partner's modelling capabilities for the FSW process with respect to these aspects has then been made.
Some performance targets of the DEEPWELD simulation platform have then been defined, based on three categories:
1. At the *local scale* of modelling, its use can provide the image of the fluid flow around the welding tool (shoulder + probe) according to its geometry. A sensitivity study should lead to optimize the shape of the tool based on the flow pattern.
2. At the *global scale* of modelling (simulation of the FSW process), its use can provide the distortion, the distribution of residual stresses and the material behaviour in the welded joint. These results will be useful for the structural calculation.
3. At the *global scale*, a structural calculation can provide the resistance in service of the welded component (bending, tension, compression, shear, fatigue). This study is essential in order to predict the validity of the process. An optimization of the operating parameters is ensured at this stage based on the results from the structural behaviour of the welded component.

This survey of the partners' state of know-how in the numerical modelling of the FSW demonstrates that DEEPWELD is very innovative and can answer to the demands of the industry. By a multi-physics modelling, a determination of the boundary conditions by inverse analysis will be replaced by an accurate calculation of the heat input during the process. Moreover, the coupling between the thermo-fluid and the thermo-mechanical analysis will be of a great importance to determine the distortions and residual stresses more accurately than what was done so far. Finally, a coupling with the metallurgy of aluminium with the FE thermo-fluid model is a major advantage to predict more accurately the behaviour of a weld.

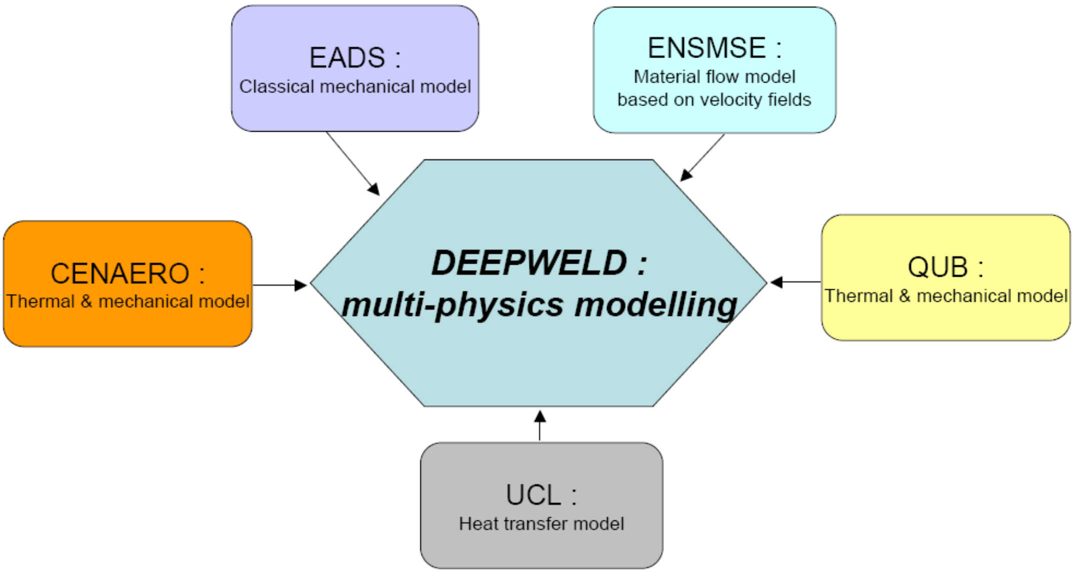


Figure 1.3 : Development of a multi-physics model expanding the know-how of existing models

1.4.1.3 Definition of the validation of the metallurgical and numerical models

Three different validation levels have been defined in order to assess the accuracy of the predictions of the simulation tool:

→ **Level 1** : Validation through experimental determination of measurable features, such as :

- ***Temperature*** during the welding process: this temperature can be monitored by means of thermocouples embedded in the welding tool or captors dispersed in various locations in the welded material. For age-hardening alloys such as those used for aerospace applications, the knowledge of the maximum temperature obtained by welding a given material in a given configuration with given welding parameters is of utmost importance. Indeed, this temperature will condition metallurgical phenomenons such as solution heat treatment, precipitate growth, dynamic recrystallisation, secondary recrystallisation (grain growth), … which will determine all mechanical and corrosion properties of the welded assembly, but also the extent of possible distortions of the welded part.
- ***metallurgical structure*** of the welded region: it has been largely described in the literature that FSW generates a characteristic microstructure, varying in three regions called nugget zone, thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ). The microstructure of these zones can easily be highlighted by means of transverse cuts and metallurgical investigations. It will thus be possible to compare the predictions of the simulation tool and the experimental data, which will allow evaluating to which extent these predictions can reproduce the reality.
- ***material flow***: as well as the metallurgical structure of the joint, the material flow during welding can experimentally be highlighted using tracing particles and doing some metallurgical surveys. The determination of this material flow is also of major importance, as it may account for the presence of harmful defects, such as pores, so-called “tunnelling effect” or “kissing bond” in the welded zone. It will be assessed how solid-fluid dynamics analysis can allow predicting this material flow.
- ***weld properties***: those are especially needed by the aerospace manufacturer, who has to ensure the soundness of the connections manufactured by FSW. Through simple mechanical tests, it shall be evaluated how far the simulation tool can predict mechanical properties and residual stresses and show the influence of welding parameters (tool geometry, welding advancing speed, rotational speed, plunge depth, …) on these properties.

→ **Level 2** : Validation through modelling of the structural response of welded structures

This part of the validation programme draws some link between the validation of the “basic” outputs of the numerical modelling and the validation of the transferability of the prediction of mechanical properties from small scale specimens to sub-components representative of aircraft structures.

It aims at modelling the structural response of a butt-welded panel, making use of local material laws derived from the metallurgical analysis and similar local material laws predicted by the simulation tool.
These local material laws can be used as an input into a general FE code dedicated to stress calculation of structures. Using this FE code, some static structural tests can be numerically reproduced. The results of these simulations shall further be compared to the effective tests results obtained when testing the real panels.
This approach ensures some link between the metallurgical analysis, the numerical modelling predictions and the structural testing of specimens representative of aircraft structures
→ **Level 3** : Validation through structural testing of specimens representative of aircraft structures

This part of the validation programme goes a step further. Indeed, whereas it is worth assessing the numerical predictions of "basic" tensile properties on small-scale coupons, there is a major interest to demonstrate the transferability of these predictions on large-scale sub-components representative of foreseen aerospace applications.
In this way, both static and fatigue tests have been defined on representative panels manufactured using thin sheets and extrusions.

The proposed experimental test program was divided into three stages:

- Stage 1 – *Laboratory specimens*
The first phase mainly includes baseline tensile specimen tests (lateral and longitudinal to the weld lines).
- Stage 2 – *Static tests on sub-component specimens*
This phase addresses multi stiffener sub-component specimens. Combinations of compression and shear loading have been specified on these specimens. These tests have been complemented with numerical calculations of the structural response of the specimens, taking into account the predicted weld properties
All welded skin elements were previously 2024-T3 then the testing specification was expanded to advanced Al-Cu-Li 2198 T8alloy.
- Stage 3 – *Fatigue and crack propagation tests on large panels representative of aircraft sub-components*
Fatigue and crack propagation tests have been specified on 2024-T3 and 2198 T8 butt welded panels.

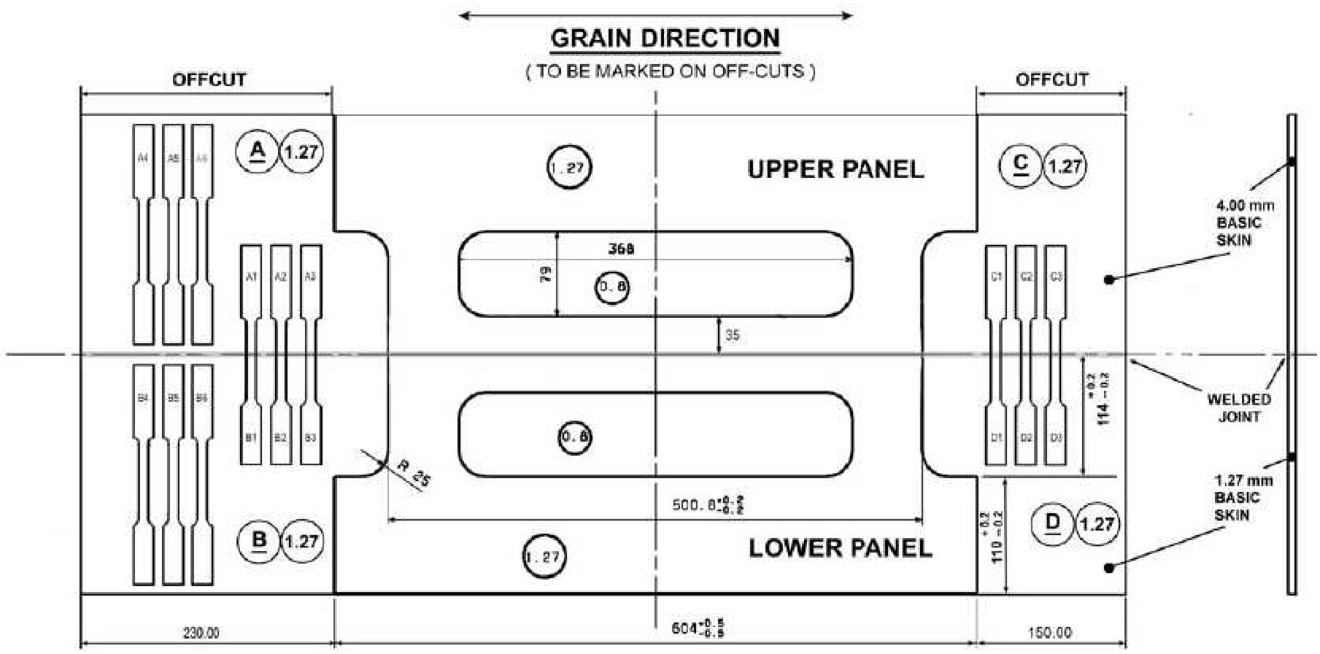


Figure 1.4 : Phase 1 – cutting of tensile test specimens in representative areas of the welded panels

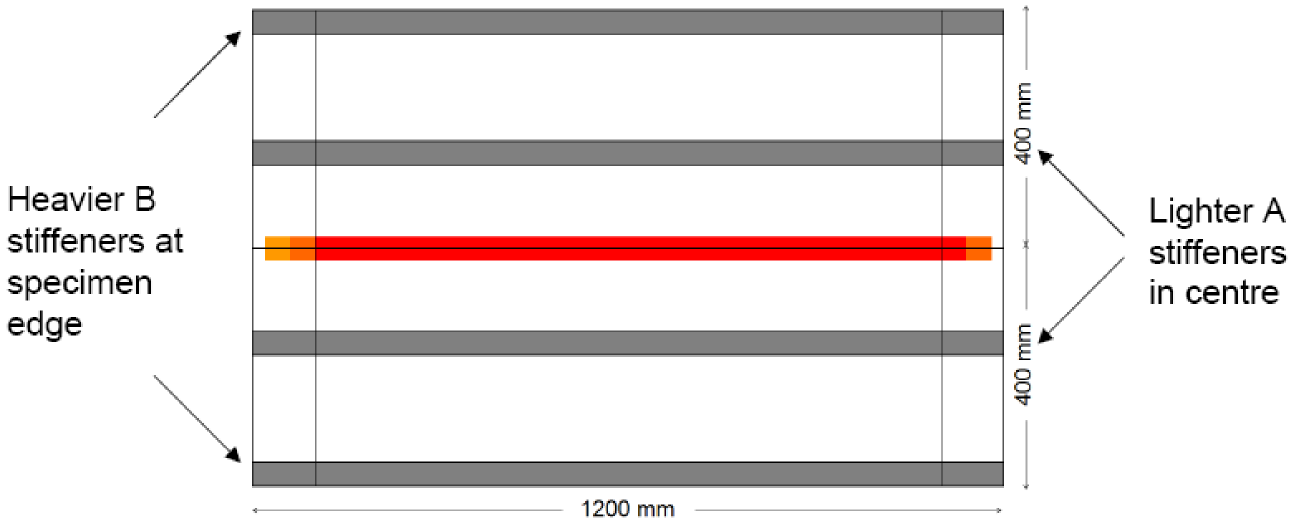


Figure 1.5 : Phase 2 - Specified stiffened and welded test panel for static testing

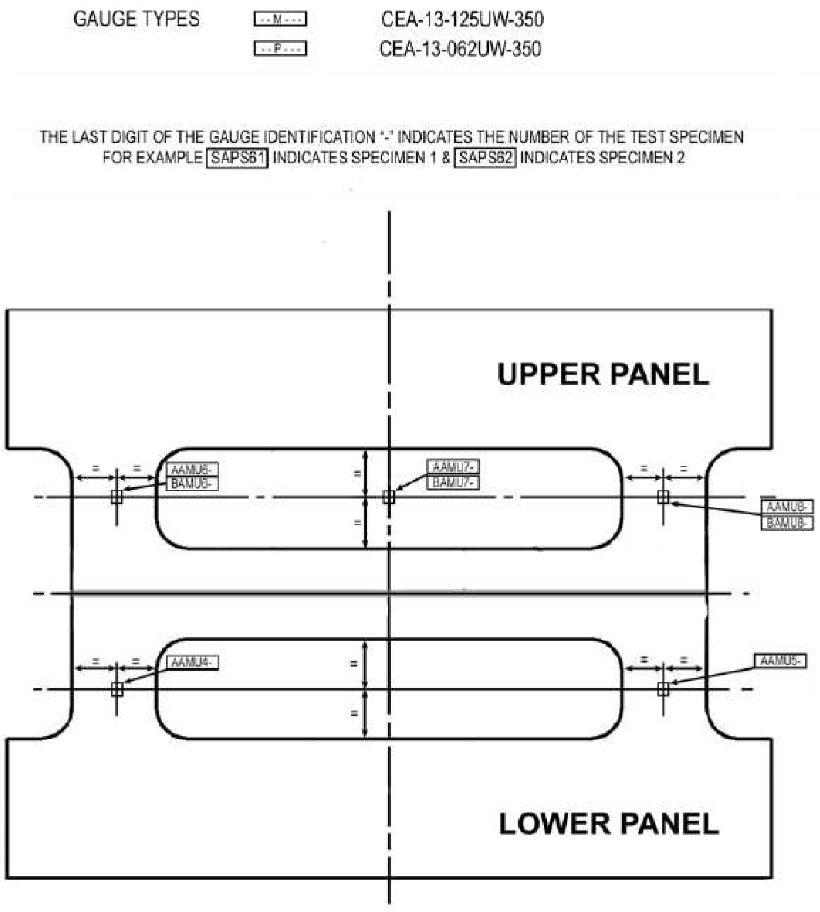


Figure 1.6 : Phase 3 - Specified fatigue test panel with its instrumentation

1.4.2 WP2 – Physics and metallurgy

Workpackage 2 had two main general objectives:

1. The first objective is to provide quantitative information to be introduced as input in the numerical codes. Those are mainly:
    - The thermal and rheological properties of the materials;
    - The friction stress at the interface between the tool's shoulder and pin and the material during welding;
    - The energy dissipated during FSW and its distribution;
    - The effects of temperature and deformation on the microstructures.
2. The second objective is to provide sufficient information for a better understanding of the physical phenomena occurring during FSW. This is required to select appropriate modelling assumptions for the different models or modules. Experimental observations and measurements are concerned with:
    - The torque and forces on the tool;
    - The material flow around the tool;
    - The temperature distribution during welding;
    - The evolutions of the microstructures and properties during thermo-mechanical cycles (torsion test) and isothermal heat treatments representative of those observed in different zones of the joint during welding.

It was divided into five main parts:

1. Task 2.1.a: "Friction laws identification";
2. Task 2.1.b: "Constitutive laws identification";
3. Task 2.2.a: "Energy balance";
4. Task 2.2.b: "Material flow";
5. Task 2.3: "Metallurgy".

1.4.2.1 Task 2.1.a: "Friction laws identification"

Experiments on instrumented FSW equipments available at IdS and UCL with measurements of the normal forging force at the same time as the torque with identical tools with and without pin have been performed at UCL and IdS. It is interesting to note that those experiments were carried out under force control by IdS and under displacement control by UCL. Figure 2.1 below is an example of results from this type of experiments. Through very simple modelling assuming that the friction coefficient is constant at the tool-workpiece interface, an average in process stationary value of 0.3 to 0.5 was derived.

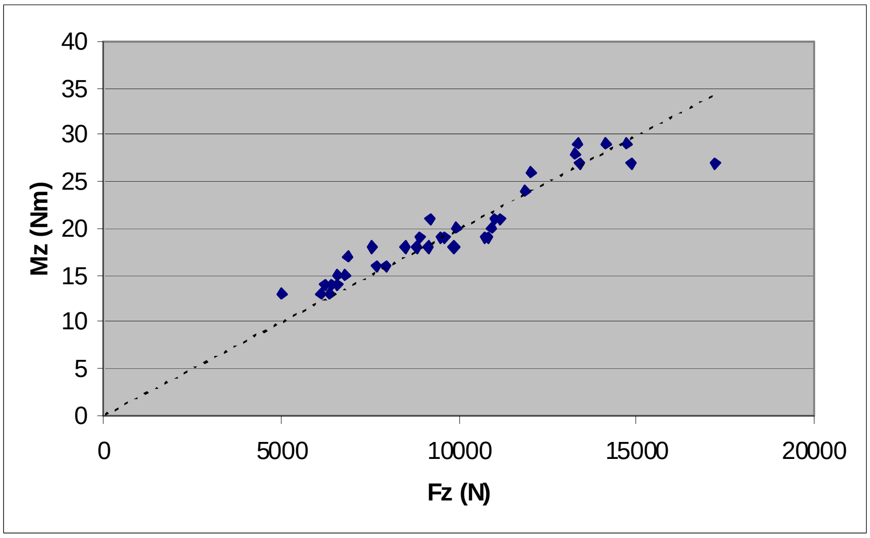


Figure 2.1: Welding Torque M_z as a function of the vertical Forging Force F_z for different welding conditions (tool shoulder of 10 to 15 mm) - *from UCL*

In order to obtain additional and more accurate data on the friction laws prevailing at the welding tool-workpiece interface not only during the stationary stage of the process but also under the transient conditions, very unique measurements of the interface shear stress as a function of the normal stress as a function of the sliding speed and at different temperatures have been subcontracted to the University of Limoges (FR) where a very specific measuring equipment especially designed for that purpose was available. Figure 2.2 shows a typical record during this type of test.

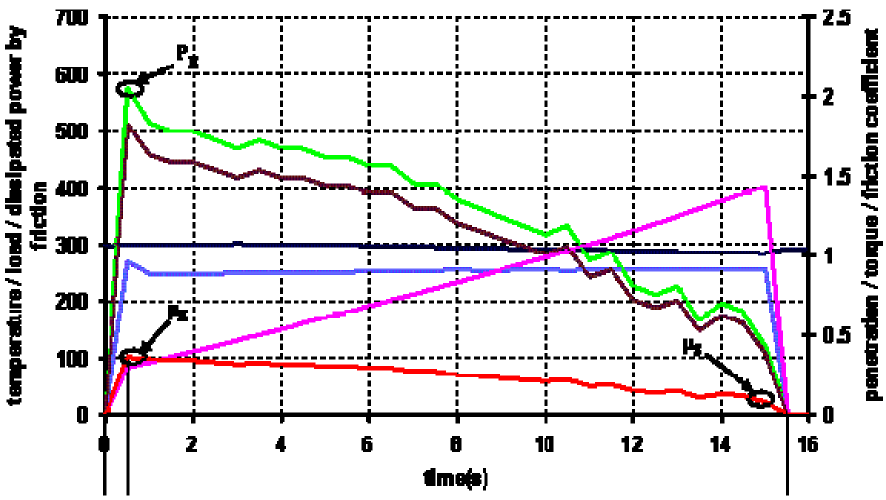


Figure 2.2: Typical record of temperature, displacement, torque and friction coefficient _ *from Université de Limoges*

QUANTECH performed a complete analysis of those results in order to identify the parameters of more realistic friction laws expressing the coefficient of friction as a complex function of the operating parameters, e.g. forging force during welding, temperature at the interface, sliding velocity… to be implemented in the numerical models under development during the DEEPWELD Project.

What is the best simplifying assumption to be used: "completely sticking conditions" or "perfectly sliding conditions", has been since the development of the first model of FSW and remains still now a controversial issue. To the knowledge of the participants, there existed practically no reliable numerical data on the shear interfacial stress prevailing between the welding tool and the workpiece during friction stir welding prior to the DEEEPWELD Project.

1.4.2.2 *Task 2.1.b: "Constitutive laws identification"*

Hot torsion test have been performed at ENSMSE on the following materials:

- AA 7449 extruded profiles in the T7 and/or W51 (solution treated and quenched) tempers,
- AA 2024 5 mm thick sheets in the T351 temper and
- AA 2198 4.8 mm thick sheets in the T8 temper.

It must be noted that due to the low thickness of the last two materials, special sub-size torsion test specimens have been designed and developed especially for those experiments. The torsion tests have performed on each material at three or four different temperatures between 200℃ and 500℃ and at three strain rate s between 0.01 s^{-1} and 5 s^{-1}. The records of the torque as a function of the angular displacement have been treated according to the well known Fields and Backhoffen formulae in order to convert the data into the equivalent stress as a function of the true strain. Figure 2.3 illustrates the typical stress-strain curves obtained by this method.

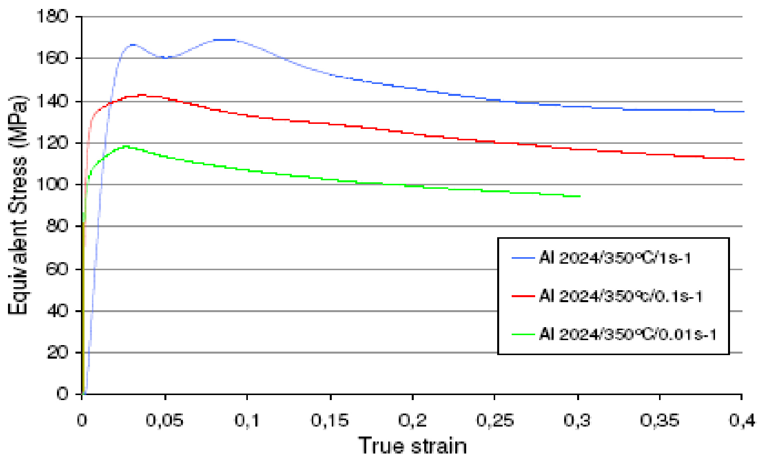
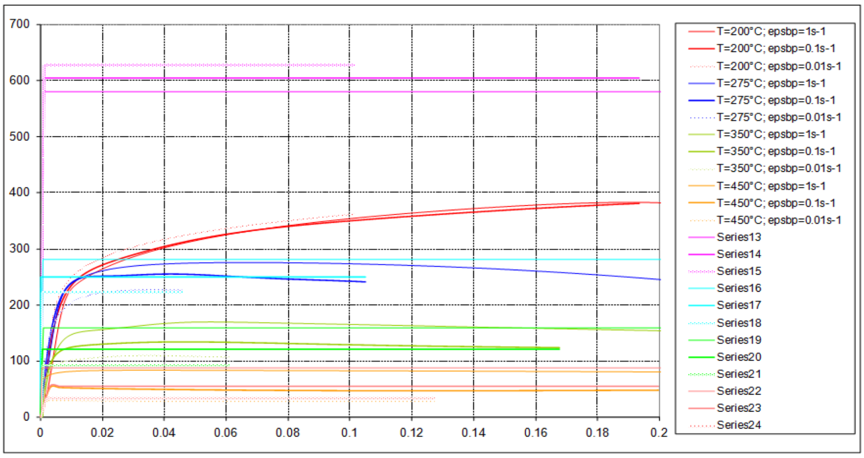


Figure 2.3: Example of stress-strain curves obtained with AA2024 - *from ENSMSE*

Additional uniaxial and in channel die compression tests have also been carried out.

Here again, that experimental part has been followed by a careful identification analysis carried out by QUANTECH in order to provide reliable and realistic constitutive equations to be used as input data in the numerical models under development during the DEEPWELD Project. Possible models have been reviewed and the most appropriate have been selected for the identification analysis. Figure 2.4 gives a typical example of identification results obtained for the aluminium alloy 2024 in the T3 temper.



$$\sigma = K_{sat} \cdot \left(\sqrt{3}\dot{\bar{\varepsilon}}\right)^{m-1} \cdot \dot{\varepsilon}$$

$$K_{sat} = K_{st} \cdot e^{\left(\frac{\beta_{st}}{T}\right)}$$

$$m = m_0 + m_1 \cdot T$$

K_{st} [MPa]	β_{st} [°K]	m_0	m_1 [°K-1]	R^2
8.29	2261	-0.443	9.0E-4	0.98

Figure 2.4: Identification results for the AA 2024 T351 alloy
obtained by calibration to the saturation model - f*rom QUANTECH*

1.4.2.3 <u>Task 2.2.a: "Energy balance"</u>

Fully instrumented welding tests during which the welding torque M_z, all the forces on the welding tool as well as the temperatures in various places of the workpiece, the clamping device and the backing plate as well as in the welding tool were performed by UCL and EADS. UCL concentrated on welding components (AA 2024 T351 3.2 mm thick sheets) with traditional tools while EADS concentrated on welding thick components (AA 7449 W 15 mm extruded profiles) with the bobbin tool technology. Figure 2.5 shows the FSW equipments and weld configurations used at UCL and EADS while figure 2.6 is a typical record of the measurements made during those welding experiments.

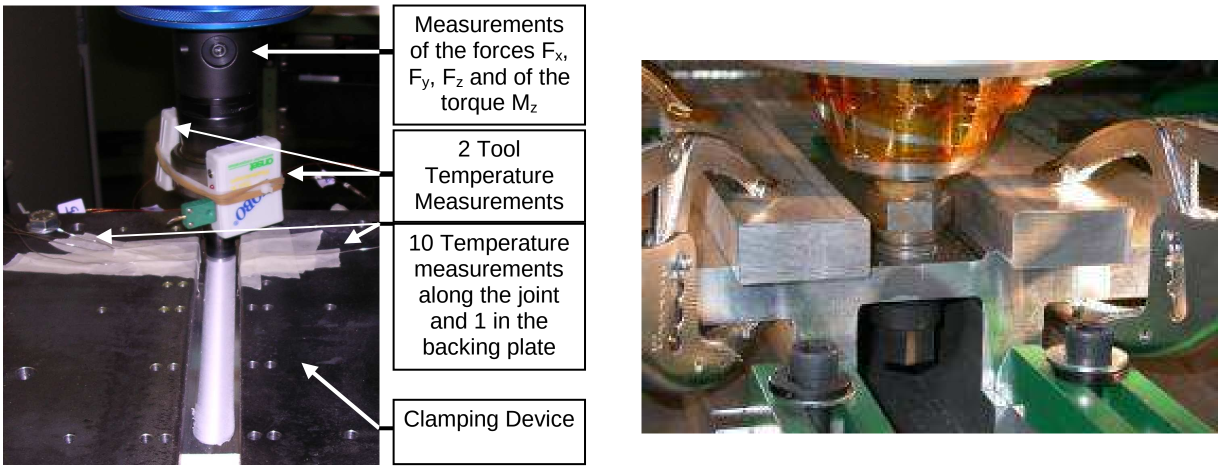


Figure 2.5 : Welding equipment and weld configuration experimented at UCL (left) and EADS (rigth)

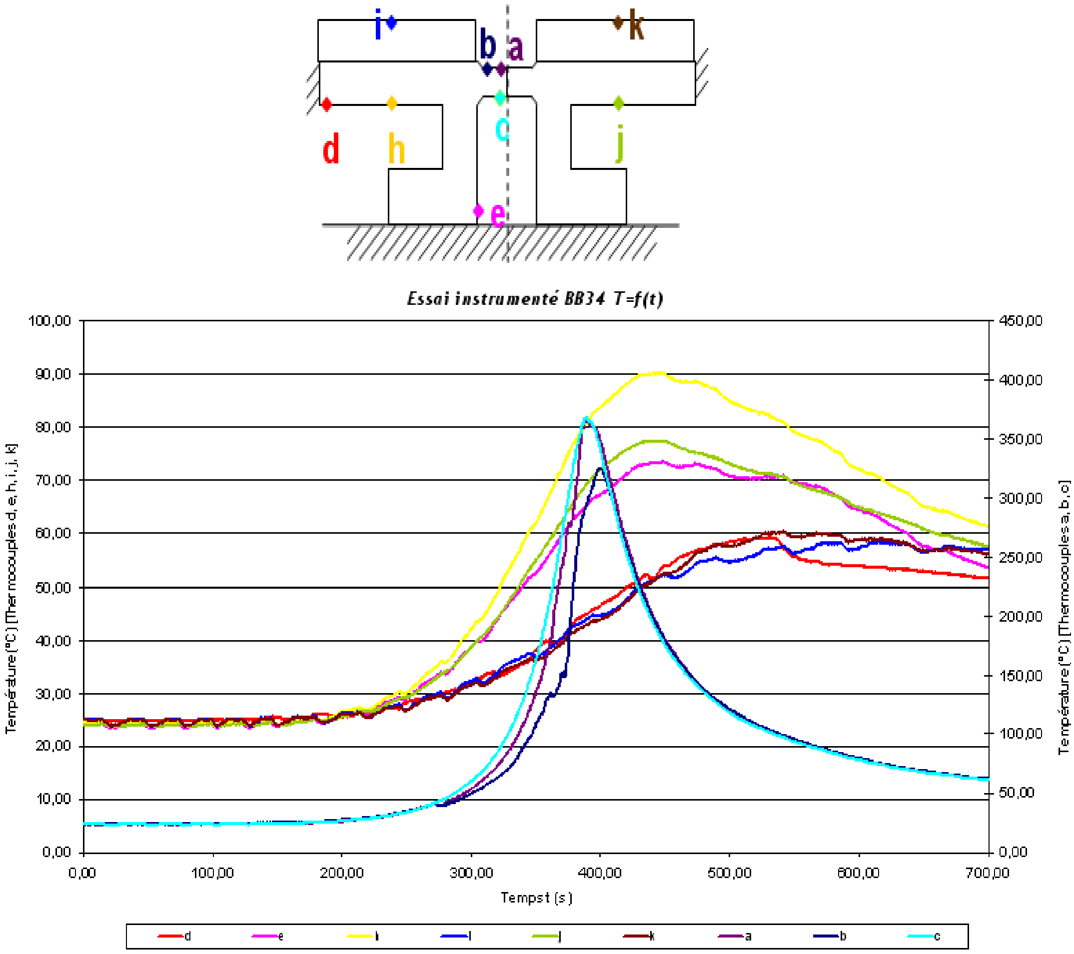


Figure 2.6: Typical record of the temperatures at different places, welding torque and welding forces during one of the instrumented bobbin tool welding experiment made by EADS

Those welding experiments proved to be extremely useful to provide quantitative information on the welding process efficiency, losses of heat into the welding tool and clamping device, contact thermal conductance to be used at the interfaces between the workpieces and the welding tool on the one hand and the clamping device and backing bar on the other hand. To the knowledge of the participants, there existed practically no reliable numerical data on those parameters prior to the DEEEPWELD Project. Even though those experiments allowed to calibrate the value to be given to the coefficients of thermal exchange along the solid interfaces during friction stir welding, the exact laws governing those parameters remains a critical issue that has not been completely solved as yet.

Similar welding experiments – with the same methodology but with different materials, thicknesses and welding parameters - have also been performed by UCL for the Task 4.1 in view of providing experimental data for validating the numerical models developed during the DEEPWELD Project.

1.4.2.4 Task 2.2.b: "Material flow"

UCL and IdS have performed a great number of material flow experiments by introducing copper elements in the shape of thin foils and wires into experimental welds. Those experiments were performed on thin (3.2 mm thick) AA2024 T3 sheets welded with conventional tools. Many configurations have been studied:

- Copper foil initially in the weld axis and parallel to the welding direction
- Copper foil initially at a fixed distance from the weld axis and parallel to the welding direction
- Copper foil initially inclined to the welding direction
- Copper wires initially parallel to the welding direction at different depths in the thickness and distances from the weld axis

- Copper wires initially perpendicular to the welded plane at different depths in the thickness and both on the advancing or retreating sides of the weld.

After welding, the samples have been cut and polished along all possible planes of observation before to be chemically etched in view of observing the material flow under the microscope at low magnifying factors. Some other welded samples were also examined through radiography. Figure 2.7 below is just one example of the observations of the material flow through cutting, polishing and etching followed by metallographic examination.

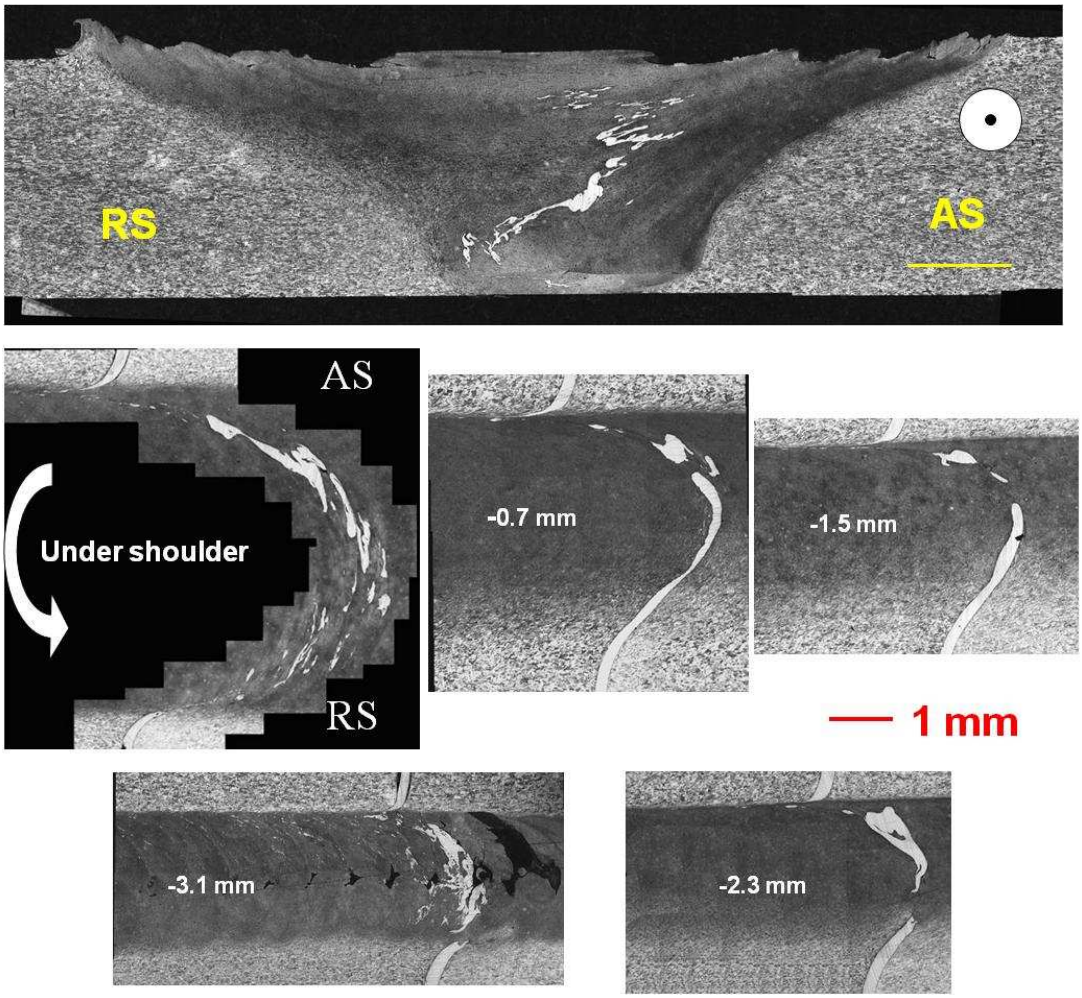


Figure 2.7: Observations of the material flow with a Copper foil used as tracer –
3.2 mm thick AA2024 T3 sheets FSwelded with a conventional tool – *from IdS*

a) Above: Copper foil in the weld axis – plane of observation perpendicular to the welding direction
b) Below: Copper foil perpendicular to the welding direction – planes of observation at constant depths below the upper surface in contact with the welding tool shoulder.

EADS also performed material flow experiments on thick (15 mm thick) extruded profiles in AA 7449 W butt friction stir welded with the bobbin tool technology. They used as tracers thin Copper wire located initially parallel to the welding direction. Figure 2.8 illustrates one of those experiments.

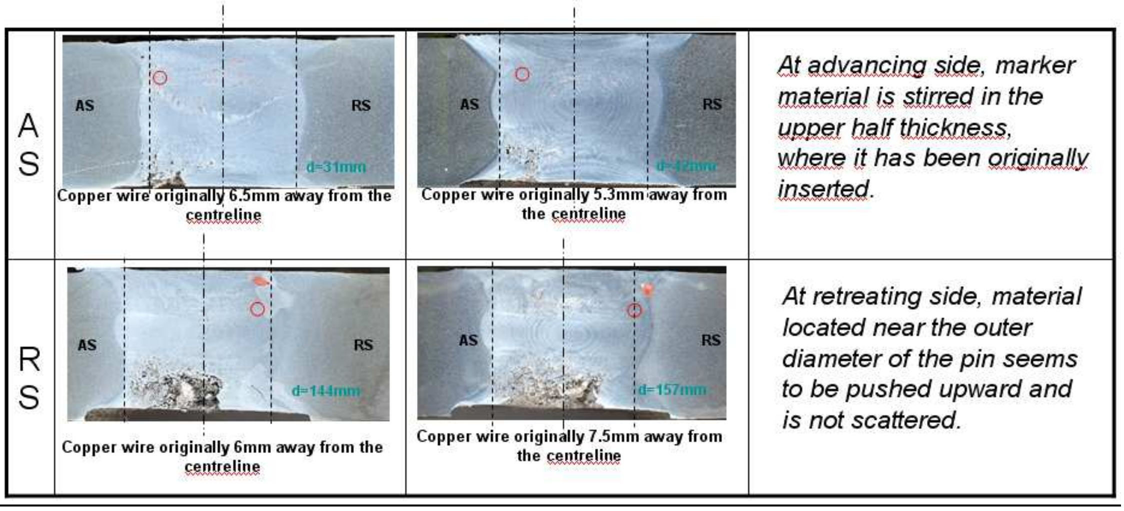


Figure 2.8: Observations of the material flow with a Copper foil used as tracer –
15 mm thick AA7449 W extruded profiles FSwelded with a bobbin tool *– from EADS*

Those material flow experiments proved to be extremely useful to get a better insight and understanding of the stirring action of the welding tool. They provided data to calibrate and validate the thermo-fluid modules of the numerical models under development during the DEEPWELD Project. In fact, a very good agreement between experimental observations and numerical simulation could be obtained in a latter stage of the Project, both for the semi-analytical model developed at ENSMSE and the Morfeo code developed by CENAERO.

Let us finally mention that other material flow experiments with low melting material used as tracers have also been performed in order to obtain information on the maximum temperatures that occurred during welding at different locations in the weld nugget. This would have been a world premiere since obviously no thermocouple can be placed there since they would be destroyed due to the stirring action of the tool. Unfortunately, it was not possible to get sufficiently accurate information to use them directly.

1.4.2.5 Task 2.3: "Metallurgy"

A **first part** of that task has been devoted to the systematic standard characterisation of the properties of joints welded with different materials, thicknesses and welding parameters. This was done by UCL for the joints welded with conventional tools and by EADS for the joints made with bobbin tools. This included the detection of any surface or volume defects, if any, and then standard mechanical tests such as bending tests, transverse tensile tests, hardness profiles determination at different depths in a transverse section and metallographic examinations.

The hardness profiles measurements proved to be extremely useful in a latter stage of the project to test and validate some of the metallurgical modelling module introduced into the numerical codes under development during the DEEPWELD Project.

A **second part** of that task has been devoted to providing relevant experimental data for the selection, development and calibration of models for describing the metallurgical phenomena occurring during friction stir welding. This was divided in two parts that will be developed below.

- *Modelling the precipitate coarsening and dissolution* that occurs in the HAZ, TMAZ and nugget of the friction welded joints

  CIMNE made a review of the models existing in the literature for describing the hardening precipitate evolution during thermal cycles imposed to heat treatable aluminium alloys. The simplest model developed by Grong in 1991 was reselected since it has the very important advantage to rely on data that can be measured easily (while most of the other models require the knowledge of the precipitate size distribution that can only be obtained through costly and difficult TEM examinations).
  UCL performed the hardness measurements after isothermal treatments that are required to identify the Grong's model parameters to be introduced in the predictive computations for the following three alloys:

- o AA 2024 T3
- o AA 7449 T7 (not W since the model predicts only softening and works best only on fully hardened microstructures – what is already mostly the case for the T3 temper)
- o AA 2198 T8.

CIMNE developed then a new original procedure for a better identification of the physical parameters included in the model - e. g. the energy of activation - that have to be implemented later in the most advanced versions of the codes under development. An example of the results of such identification analysis is shown in figure 2.9. UCL also suggested a way to predict hardness taking into account the natural ageing after welding.

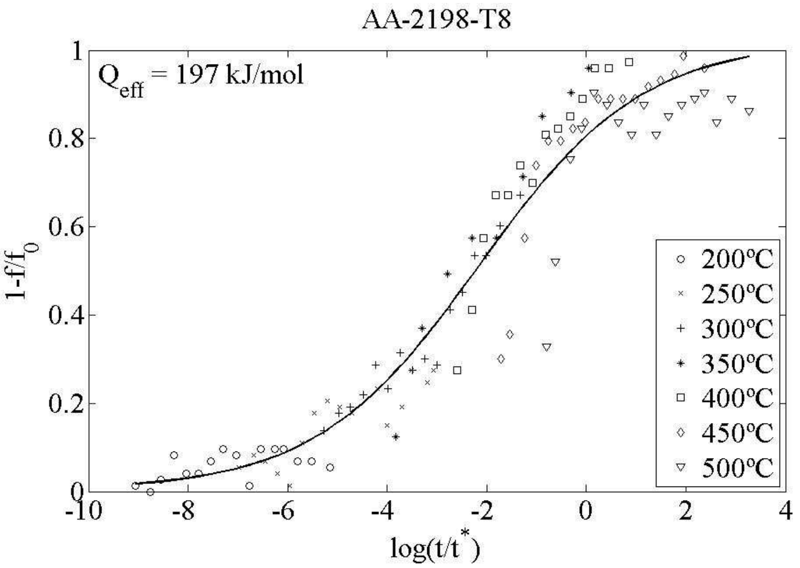


Figure 2.9: Example of the calibration of the of the Grong's softening model due to precipitate dissolution for the alloy 2198 T8 – *from UCL and CIMNE*

- *Modelling the dynamic recrystallisation* occurring in the nugget of the friction stir welded joints that results in a spectacular grain size refinement characteristic of FSW.

  ENSME made all the experiments and needed developments to adapt the "Continuous Dynamic Recrystallisation (CDRX)" model developed by Gourdet and Montheillet in 2003 for the three alloys: AA 2024, AA7449 and AA 2198. This model requires the identification of a hardening *h* and a softening *r* parameters whose identified values were significantly respectively higher and lower than those reported initially by Gourdet for pure aluminium. The high amounts of alloying elements in the alloys studied in the DEEPWELD Project explain this difference.
  CIMNE performed also a more sophisticated identification analysis to identify the parameters of this CDRX model leading to similar conclusions.
  The model proved to be able to predict grain sizes of the correct order of magnitude in the nugget zone.

1.4.2.6 Conclusions on WP2

All the objectives of the Workpackage 2 have thus been attained. It allowed generating new and original experimental data absolutely needed to introduce realistic input data into the numerical models and software developed during the DEEPWELD Project. One may refer here especially to:

- the thermal and rheological properties of the three investigated aluminium alloys,
- the interfacial stress prevailing at the interface between the welding tool and the workpiece,
- information on the process efficiency,
- indication on the contact conductance at the interface between the workpiece and the clamping device and backing bar,
- …

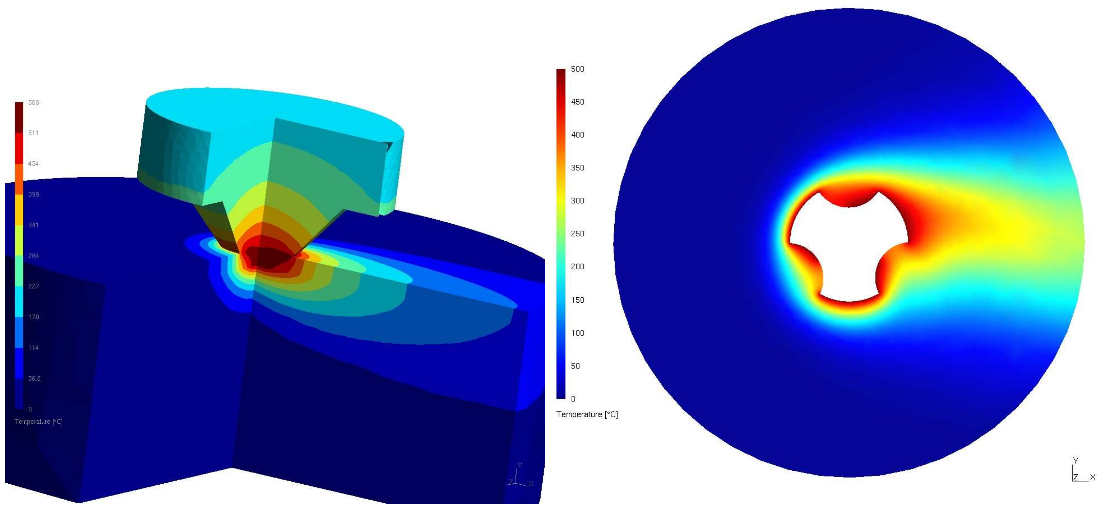
It also allowed a better understanding of the interaction between the thermal cycles, the forces on the welding tool and the material flow on the one hand and, on the other hand, between the thermal cycles, the evolution of microstructure and the resulting mechanical properties of the welded joints by providing:

- the physical basis for a scientific development of models based on physical laws,
- relevant experiments to calibrate those models and
- appropriate experimental data to validate in a later stage the numerical software developed during the DEEPWELD Project.

1.4.3 WP3 – Multi-physics simulation tool development

1.4.3.1 Task 3.1 Thermo-fluid calculation module

Task 3.1 focussed on the development of a steady state and transient thermo-fluid model. Both models were implemented in the Morfeo FE code developed by CENAERO. Figure 3.1 shows the temperature fields obtained with the steady state and transient models respectively. A rotating frame of reference was used for the transient model therefore allowing any tool to be easily modelled, irrespective of its geometrical complexity. The accuracy of the predicted flow field was verified by comparing the results with the flow visualisation experiments using copper marker material performed by IdS and EADS in WP2. Particular attention was given to modelling the back plate and tool explicitly.



a) b)

Figure 3.1: Temperature fields obtained with steady state (a) and transient (b) thermo fluid models

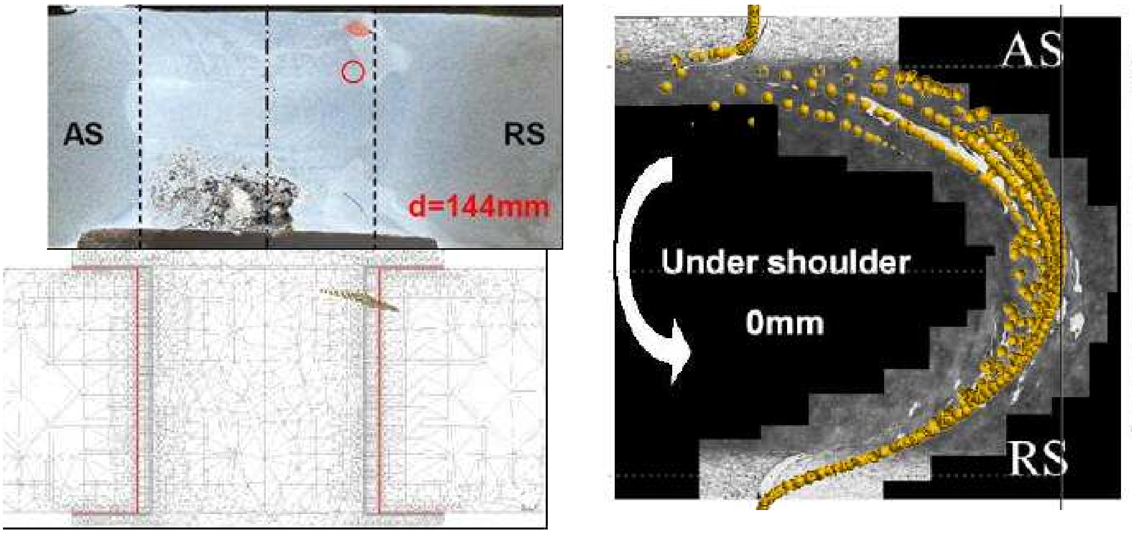


Figure 3.2: Comparison of simulated and experimentally observed flow patterns.

ENSMSE developed an analytical model of the flow around a FSW tool. The velocity field was defined on the basis of an additive combination of analytical flow fields and FE simulation results. Based on this flow field a finite difference solver was used to calculate the resulting temperature field.

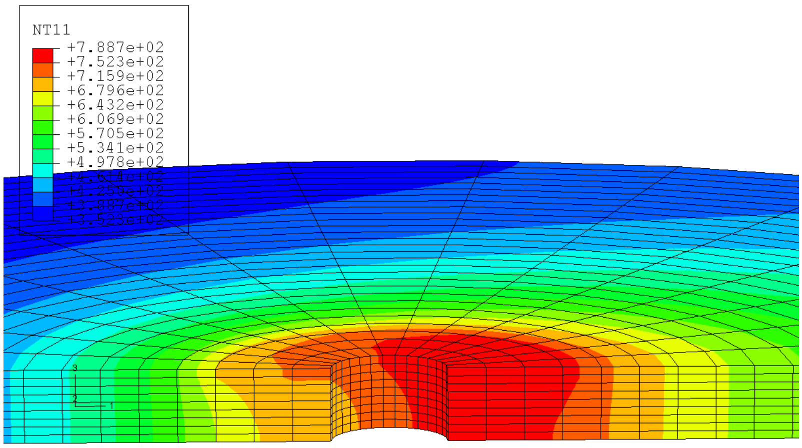
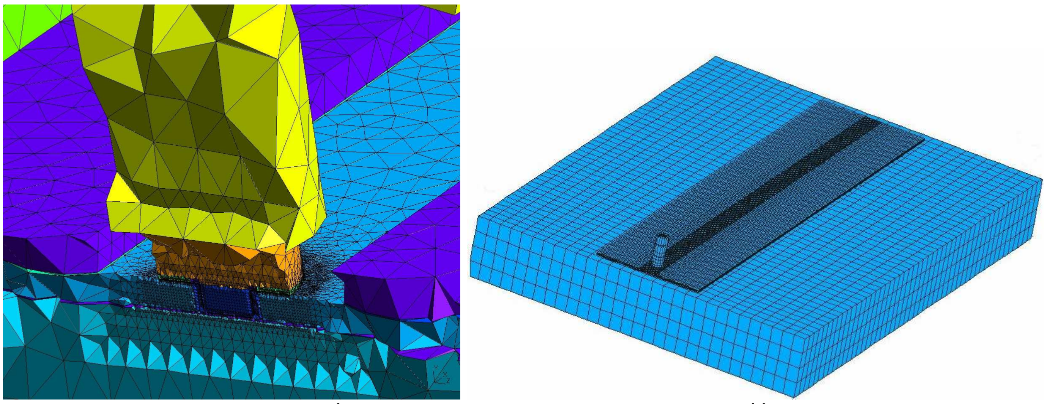


Figure 3.3: Temperature obtained with the semi-analytical flow model.

1.4.3.2 <u>Task 3.2 Coupled thermo-mechanical-flow module</u>

The first objective of SAMTECH in this task was to implement a staggered thermo-mechanical solver in SAMCEF by coupling the SAMCEF/THERMAL and SAMCEF/MECANO modules. Using a staggered coupling allows information (temperatures, displacements, heating generated by plasticity and friction as well as contact data) to be exchanged at every time step between the thermal and the mechanical models. In order to achieve this, a new supervisor module of SAMCEF is used. A second objective was the coupling of this supervisor to the Morfeo thermo-fluid solver. This objective was achieved by CENAERO and SAMTECH by using the Mesh-based parallel Code Coupling Interface (MpCCI) from Fraunhofer SCAI, and allows the heat source predicted by the Morfeo thermo-fluid model to be used in the SAMCEF thermo-mechanical model. The local thermo-fluid model (see Figure 3.4a) predicts the amount of heat generated by the FSW tool. This information is then transferred using MpCCI to the global thermo-mechanical model (see Figure 3.4b) to predict residual stresses. Figure 3.5 shows the evolution of temperature at two points in the workpiece. The points are both located at mid thickness and identical distance from the weld centreline on the advancing side and retreating side respectively. It can be seen that both models predict the measured cycles reasonably well. The differences observed between the thermo-fluid and thermo-mechanical results can be explained by the differences in the modelling of the thermal contact. These differences are due to the Eulerian versus Lagrangian description, as well as the velocity-pressure versus displacement formulation employed in the thermo-fluid and thermo-mechanical models respectively. Using this approach, it is no longer necessary to first perform an instrumented FSW experiment to determine the heat input in a thermo-mechanical model. Hence, this allows for a predictive modelling approach for residual stresses and metallurgy.



a) b)

Figure 3.4: Meshes used in thermo fluid (a) and thermo mechanical (b) model.

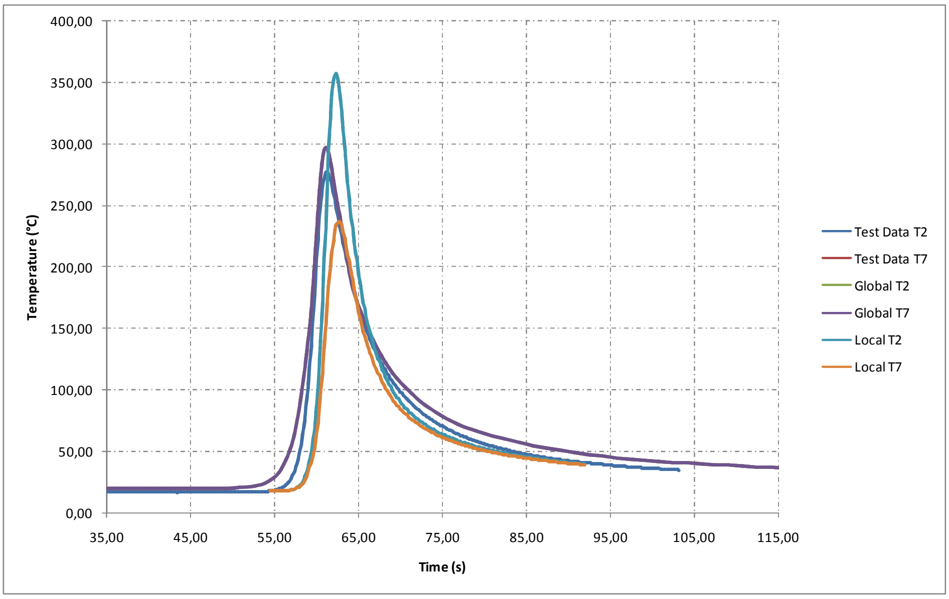


Figure 3.5: Temperature evolution during FSW predicted by TF, TM model and measurements.

EADS has implemented a simplified axisymmetric thermo-fluid model to predict the heat source and coupled this to the ABAQUS FE code. The resulting temperature fields are shown in Figure 3.6.

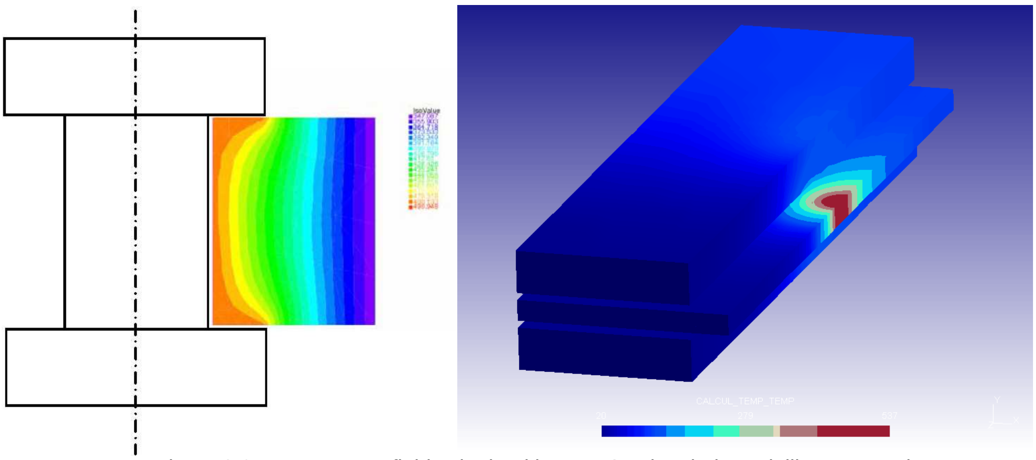


Figure 3.6: Temperature fields obtained by EADS using their modelling approach.

1.4.3.3 Task 3.3 Implementation of complex friction laws

In this task the friction law, proposed by QUANTECH in WP2, was implemented and validated by CENAERO. In this law the friction coefficient is function of temperature and pressure. Figure 3.7 shows the influence of the friction on the temperature calculation. This feature can now be used to predict the thermal cycles due to both friction and deformation (see Figure 3.7). CIMNE provided support to CENAERO for the implementation of complex friction laws and aspects related to the influence of frictional dissipation on the heat source.

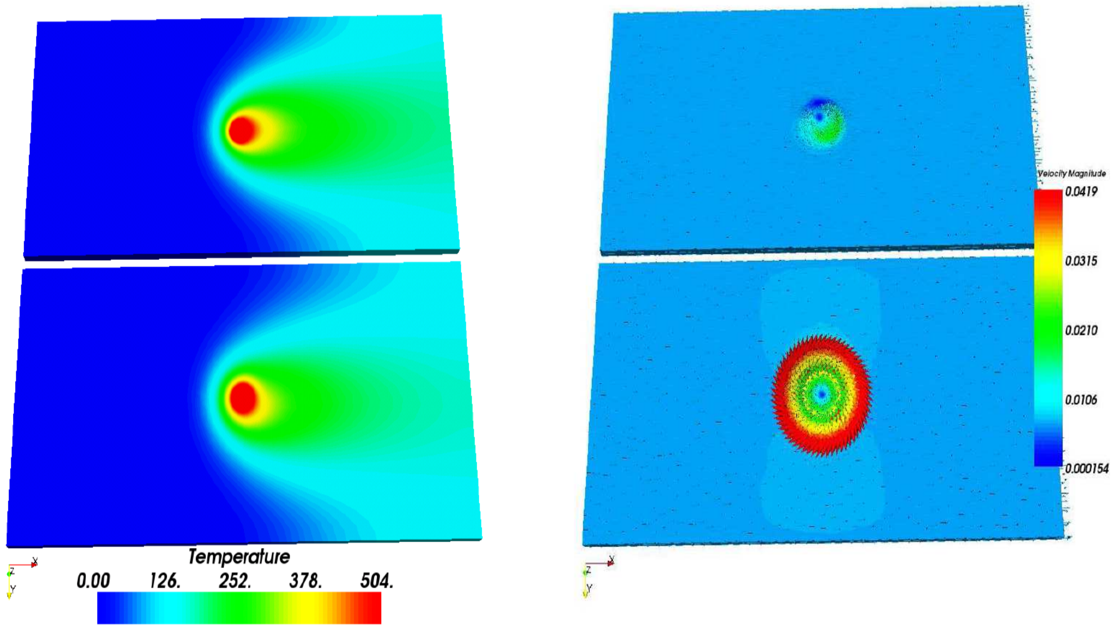


Figure 3.7: Influence of the friction law on the temperature calculation

1.4.3.4 Task 3.4 Implementation of complex constitutive and metallurgy laws

In **task 3.4** ("Implementation of complex constitutive and metallurgy laws"), as a result of the review performed by CIMNE on different microstructural models, the relevant microstructural models and the micro-macro coupling have been implemented in a number of subroutines written in Fortran code. Figures 3.8 and 3.9 show some of the results obtained for the dissolution of precipitates model and the continuous dynamic recrystallisation model.

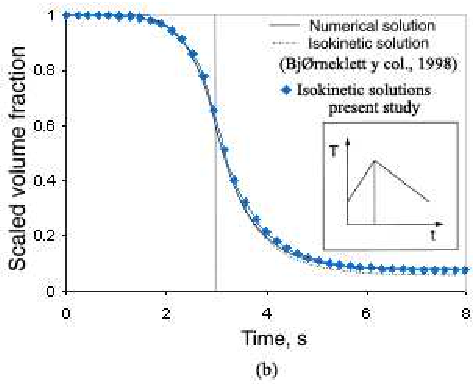


Figure 3.8: Evolution of relative volume fractions and
Hardness distribution for a given thermal cycle

Finally, a dissolution of hardening precipitates in fully hardened aluminium alloys model based on Myhr&Grong (1991) has been developed and implemented. The effective activation energy, master curve and hardness evolution under isothermal conditions for different aluminium alloys, such as AA-2014-T6, AA-6005A-T6, AA-7449-T79 and AA-2198-T8 (see figure 3.10), have been identified. In particular, an explicit mathematical expression of the master curve, well suited for numerical implementation, has been obtained using neural networks algorithms.

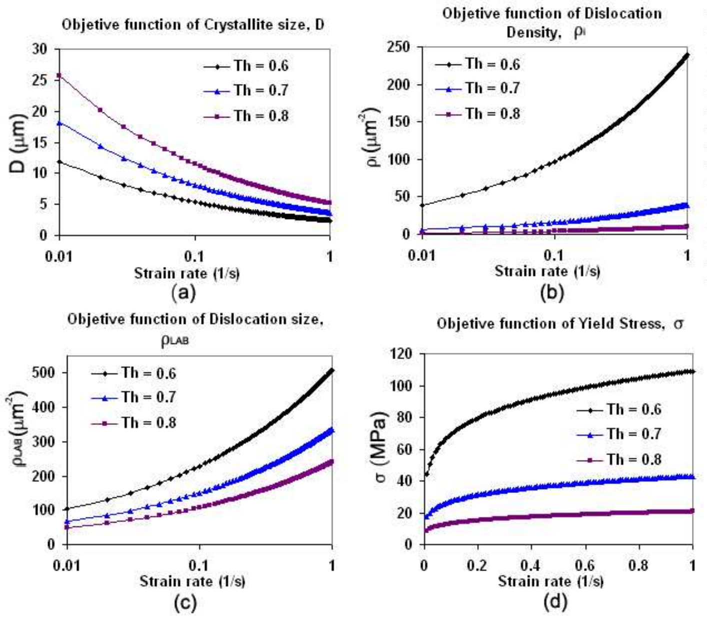


Figure 3.9: Evolution of microstructural parameters and yield stress with the strain rate at different temperatures (CDRX model)

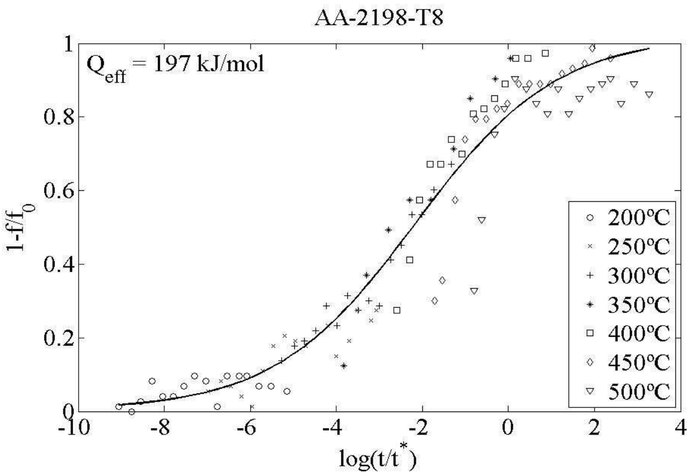


Figure 3.10. Master curve and effective activation energy for the AA-2198-T8

CENAERO has fully integrated these models as well as the streamline calculation and Continuous Dynamic Recrystallisation (CDRX) model into the DEEPWELD multi-physics simulation tool. This allows for the metallurgy to be calculated in a section across the weld joint based on the streamline data obtained from the thermo fluid model (see Figure 3.11 and 3.12). SAMTECH and CENAERO have implemented and validated the micro-macro constitutive law and its integration in the DEEPWELD multi-physics software. Finally, work on the implementation of the advanced metallurgy model by Kamp and Robson for AA7449 has started.

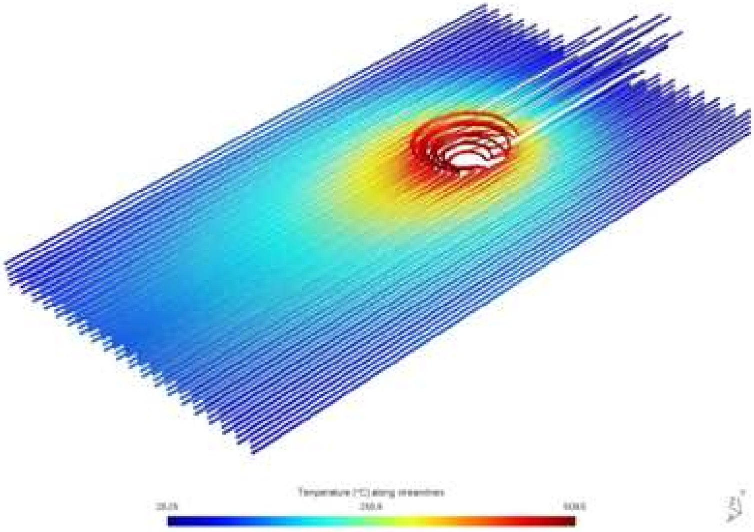


Figure 3.11: Streamlines obtained from the thermo-fluid model.

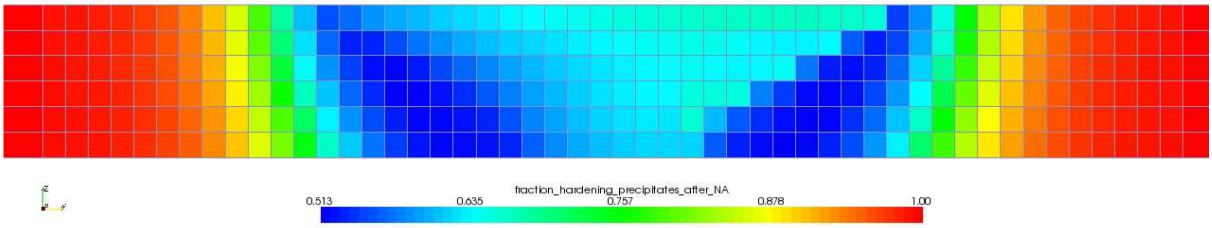


Figure 3.12: Modelled fraction of hardening precipitates after natural ageing.

1.4.3.5 Task 3.5 Pre- and post-processing

Finally, in **task 3.5** ("Pre- and post-processing"), the implementation of a thermal analysis in SAMCEF Field was finalised. A complete thermo-mechanical model (mechanical and thermal part) can now be defined within the same interface "SAMCEF Field" (see Figure 3.13).

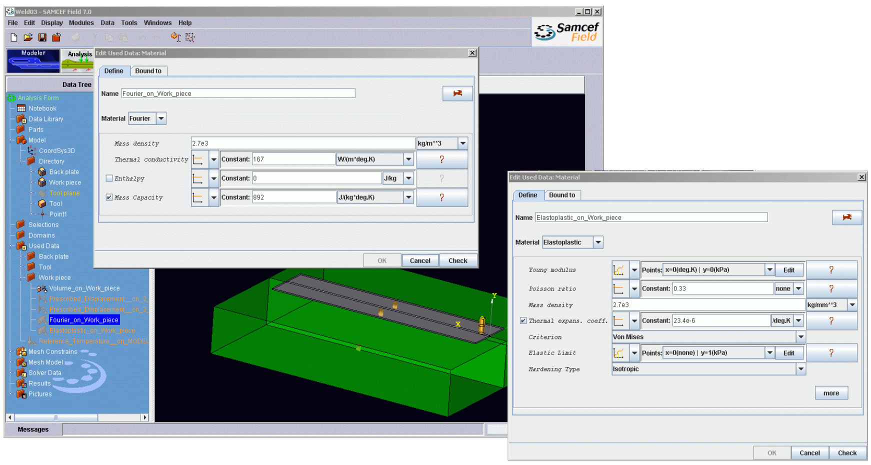


Figure 3.13: Definition of thermal analysis in SAMCEF Field.

1.4.3.6 Conclusions on WP3

The objectives of the Workpackage 3 have been met:

- the thermo-fluid and semi-analytical models were developed and validated in terms of prediction of flow and temperature field,
- a staggered thermo-mechanical solver was implemented in SAMCEF,
- the thermo-fluid model was successfully coupled to the staggered thermo-mechanical solver,
- complex friction laws were implemented,
- metallurgy models and micro-macro coupling were implemented and validated,
- pre- and post processing tools were implemented.

The numerical models and software developed in WP3 during the DEEPWELD Project has allowed for:

- the detailed validation of the 3D flow field predicted by the thermo-fluid model by comparing results to flow visualisation experiments performed in WP2;
- the prediction of residual stresses without requiring the use of experimentally calibrated heat sources thanks to the coupling of the thermo-fluid and thermo-mechanical models;
- the prediction of metallurgical properties and hardness thanks to the coupling of the thermo-fluid and metallurgy models;
- the metallurgical changes in the weld region to be taken into account in the predictions of residual stresses and ultimately welded part performance thanks to the coupling of the thermo-fluid-metallurgy model to the thermo-mechanical model.

1.4.4 WP4 – Validation and applications

The materials of concern are AA2024-T351, AA2198-T8, AA7449-T79. The first two were procured by SONACA. The last one was procured by EADS in the W511 condition, it was then T79 treated before welding by UCL, after welding by EADS.

All the welds are butt welds.

1.4.4.1 Conventional FS welds on thin parts

At the laboratory coupon level, instrumented conventional FS welds were run by UCL (2mm thick AA2024-T351 sheets and 4mm thick AA7449-T79 sheets) and IdS (1.6mm thick AA2024-T351 and AA2198-T8). The operating conditions are defined by the following process parameters: travelling speed, rotating speed, tool load and torque. UCL and IdS have determined the operating window in order to get welds that meet the expected quality as checked by metallography, to look for the presence of defects, by microhardness measurements and by mechanical tests.

The monitoring of temperature in the tool, near the weld and in the backing bar allowed for a better understanding in the process in terms of heat loss into the welding tool and clamping device, in terms of contact thermal conductance to be used at the interfaces between the workpieces and the welding tool on the one hand and the clamping device and backing bar on the other hand.

Figure 4.1 shows a typical set of experimental data (temperatures, welding forge, welding torque).

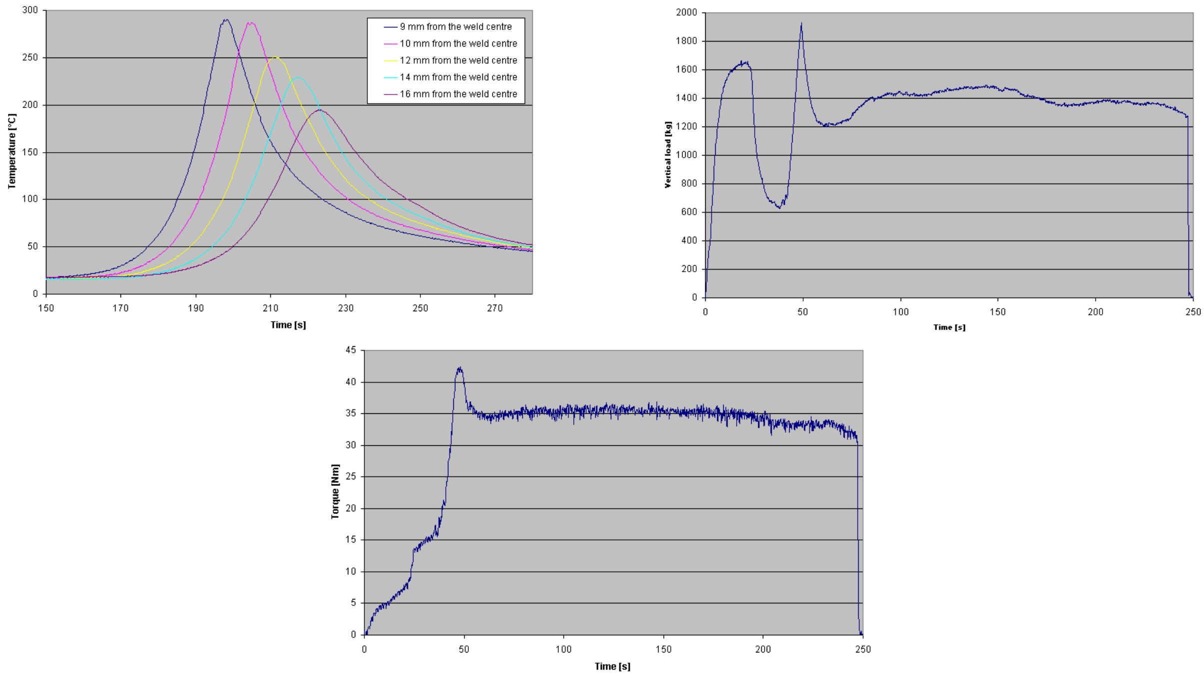


Figure 4.1: Typical record of the temperatures at different places in the welded joint, forging force and welding torque during one instrumented welding experiment made by UCL (AA 7449 T79 4mm thick – tool rotational speed: 400 rpm , welding speed: 100 mm/min).

Using input data required for the models from the results obtained in WP2, CENAERO has validated its thermo-fluid (TF) model and thermo-mechanical (TM) model by comparing its simulation results to the instrumented tests performed by UCL in Task 4.1. A total of nine welds were simulated. This allowed the accuracy of the model to be assessed for two different alloys, and several sheet thicknesses and sets of operating parameters. The experimental data available for model validation were: temperature, tool torque and forces measurements during welding, hardness measurements after natural ageing, residual stress measurements using the crack compliance method. Figure 4.2 shows the evolution of the peak temperature as a function of the distance to the weld.

The simulation results were obtained by predicting the amount of heat generated by the tool in the TF model and transferring this to the TM model. The comparison of predicted power versus measured power (via tool torque) is shown in figure 4.3. Then knowing, from WP2, which metallurgy will be produced, the residual stress can be predicted with the TM model. The results are shown in Figures 4.3 and 4.4 and yield a fair correlation with the measured data.

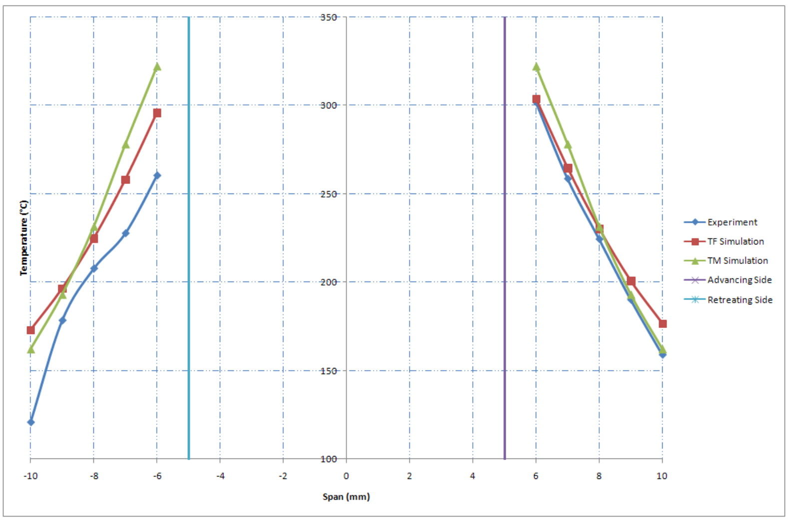


Figure 4.2: Evolution of peak temperature in a section across the weld (Experiment, TF and TM model).

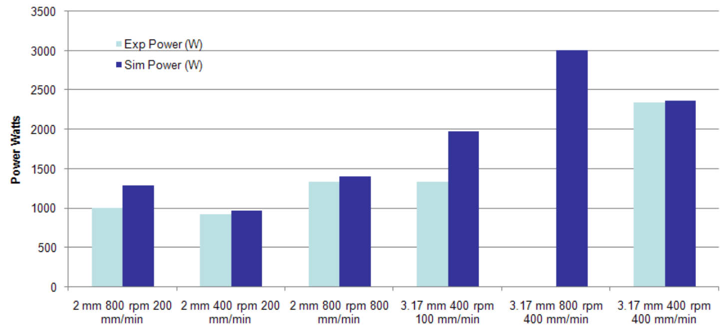


Figure 4.3: Comparison of measured and predicted (TF model) heat input for a range of welds.

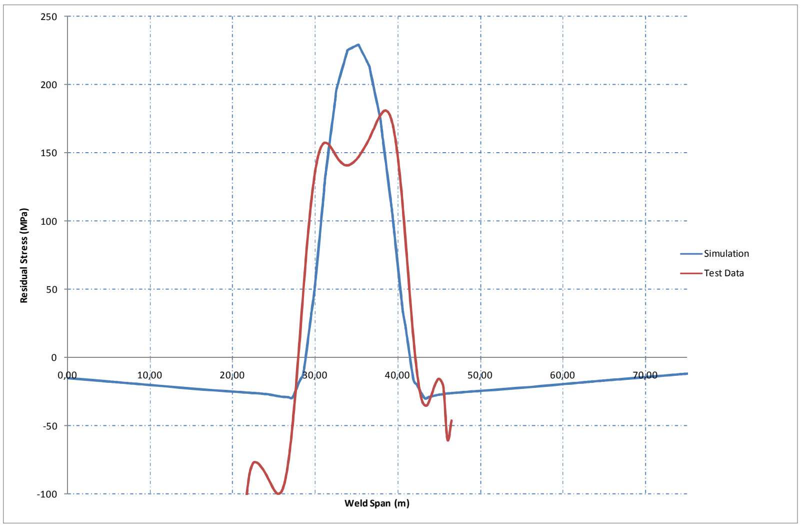


Figure 4.4: Comparison of residual stress prediction and measurement for AA2024-T351 weld.

In order to help find the best set of parameters (travelling speed, rotating speed) by simulation to produce the FS welds that meet the required mechanical properties, denoted by the hardness, three models were coupled: the ENSMSE global power balance model, the CIMNE optimisation tool, the CENAERO simulation tool. The ENSMSE model defines an objective function for the optimisation tool: the required average temperature of the weld. The optimisation tool of CIMNE is based on a neural networks library software called “FLOOD”. It has been linked to MORFEO FE software of CENAERO. The evaluation of the objective function is performed in two steps: FLOOD defines a suitable set of operational parameters, the advancing and rotating tool speeds, then MORFEO solves the FSW simulation for the given set of operational parameters. The Optimisation of the FSW operational process parameters has been done using an evolutionary algorithm, which is a zero-order stochastic method based on the mechanics of natural genetics and biological evolution. Figure 4.5 depicts the diagramme flow of the evolutionary algorithm.

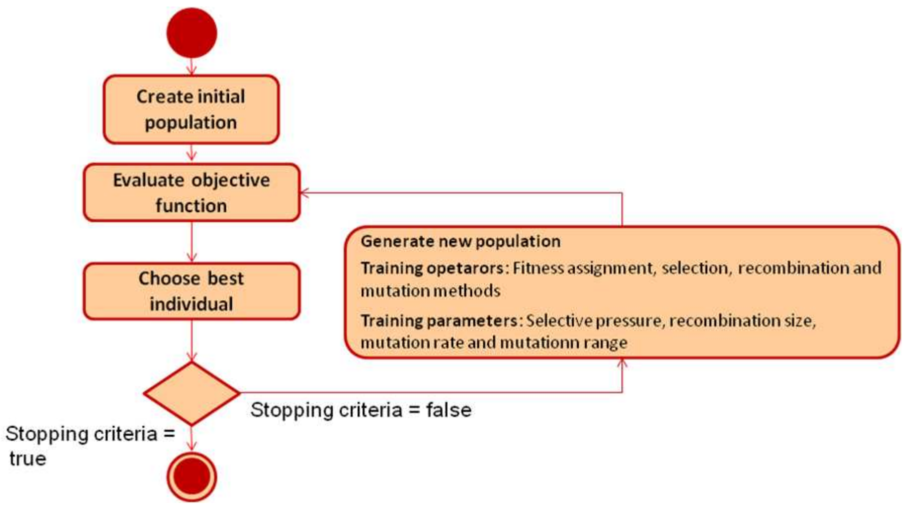


Figure 4.5: Diagramme flow of the evolutionary algorithm used in FLOOD.

Based on the actual parameter sets used by UCL in their experiments for the AA7449-T79 aluminium alloy, which resulted in good quality welds, a domain of weldability, defining a suitable range of values for the process parameters, has been defined as:

- travelling speed weldability domain: [1.6E-03 m/s, 3.3E-03 m/s],
- Rotating speed weldability domain: [41.89 rad/s, 62.83 rad/s].

A numerical simulation of the optimization of a FSW process for the AA-7449-T79 aluminium alloy has been carried out. The **optimal process parameters**, advancing and rotating speed, which give an optimal weld quality, minimizing the maximum hardness drop at the cross section under the tool, are given by,

- **Optimal advancing tool speed**: 2.080E-03 m/s, 124.8 mm/m
- **Optimal rotating tool speed**: 54.216 rad/s, 517.725 rpm

Note that the optimal values obtained for the process operational parameters, lie in the middle of the range given by the **weldability domain**.
The **maximum hardness drop** at the cross section under the tool, for the optimal process parameters, is given by:

- **Optimal maximum hardness drop**: 79.754.

At the industrial coupon level, instrumented conventional FS welds were run by IdS (1.6mm thick AA2024-T351 and AA2198-T8) to produce best welds in the operating window. IdS has selected best welding conditions based on metallography, X rays and mechanical evaluation (on 2024T321: traveling speed = 600 mm/min; rotating speed = 800 RPM; Force = 590 kg). IdS has then welded “optimized” industrial coupons for SONACA and QUB who will assess their mechanical response.

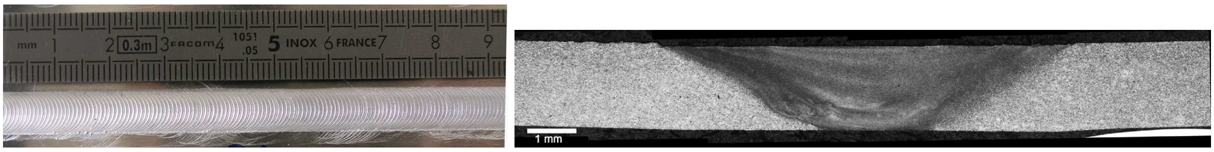


Figure 4.6: optical and metallographic examination of FS welds by IdS.

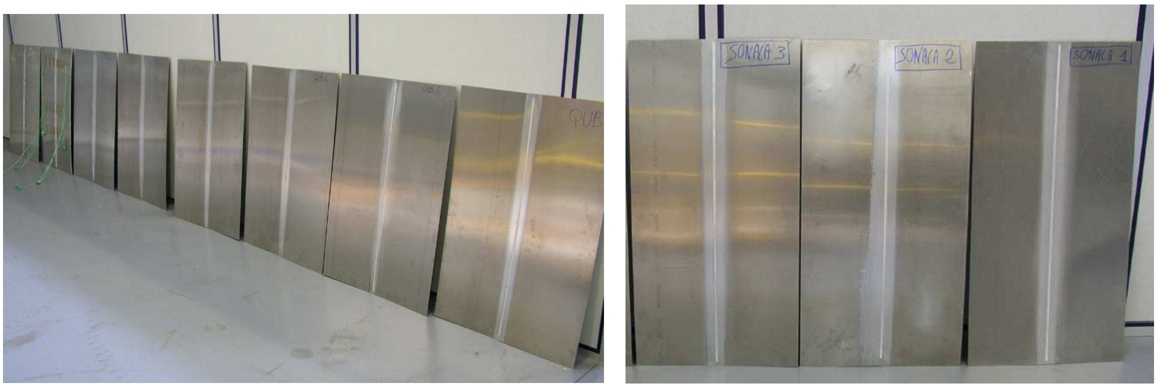


Figure 4.7: industrial FS welded parts by IdS.

Thermal cycles have been recorded as well.

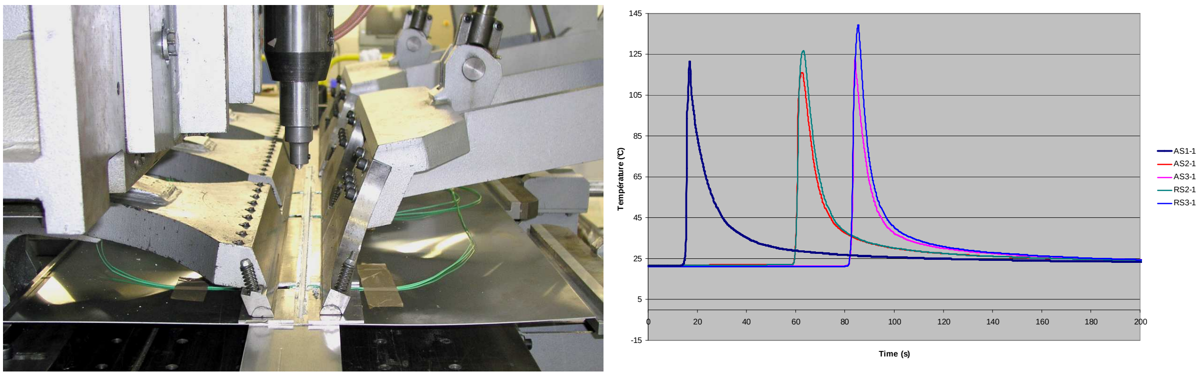


Figure 4.8:FSW set-up for industrial parts and temperature monitoring by IdS.

CENAERO has applied its simulation software to the welds representative of aeronautical components performed by IdS. Figure 4.9 shows the comparison of the residual stresses predicted by the thermo-mechanical model and the measured residual stresses. The results are in relatively close agreement with the measured values, therefore demonstrating that the software developed within the DEEPWELD project can be successfully used to predictively simulate the FSW process.

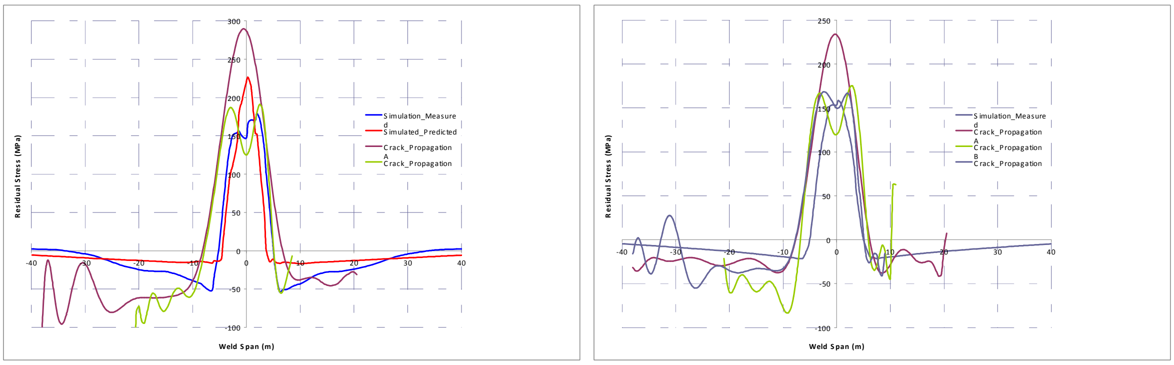


Figure 4.9: Comparison of residual stress prediction and measurement for IdS welds.

The structural response of industrial coupons made out of 2024 and 2198 was assessed by SONACA, QUB and QUANTECH: fatigue and damage tolerance of FS welded joints, deformability of FS welded sheets, buckling resistance of stiffened panels as used in industry.

SONACA undertook a preliminary investigation into the fatigue and damage tolerance behaviour of riveted joints and FS welded joints, both out of Al-2024 T3 and Al-2198-T8, under an R ratio of 0.1. AL-2198 results in better fatigue performance over AL-2024 on riveted joints. The fatigue performance of FSW joints shows longer fatigue over the riveted joints. The data on fatigue crack growth showed that the growth of the crack was slower in the welded specimens than initially predicted for long crack lengths.

QUB has evaluated the static properties of the industrial welds: the tensile specimens showed at least 90% of the parent material properties were being retained in the weld. This is a minimal reduction in strength compared to many manufacturing methods, and indicates good joint efficiency.

QUB has tested stiffened panels under compression + shear. The panels are as used in industry (with 4 stringers and 2 frames, all riveted) but showing a skin with an FS weld in the middle, parallel to the stringers and located in between the two inner stringers. The front side of panels were speckled in order to monitor full field displacement (Figure 4.10).

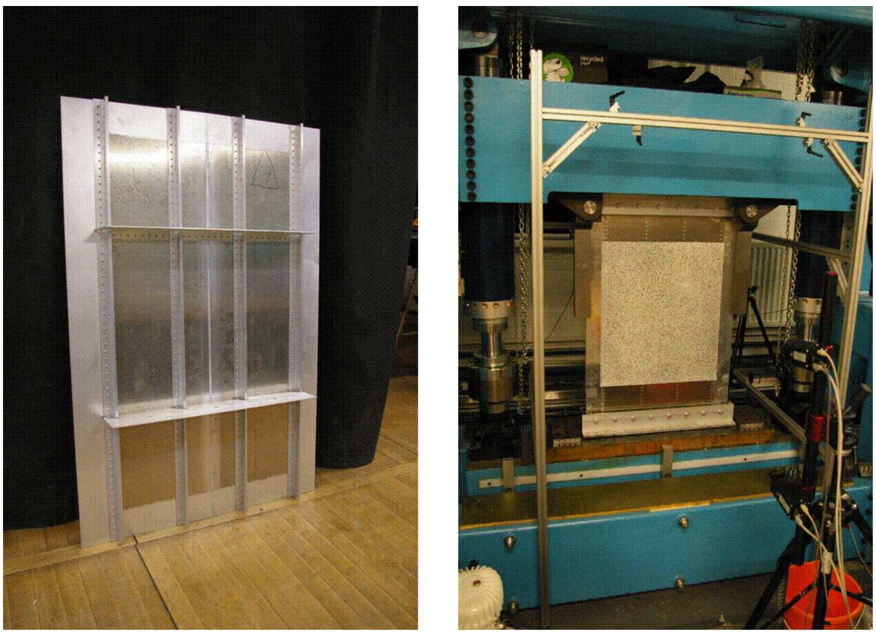


Figure 4.10: Stiffened panels and test set-up.

The resulting tests were successful from the perspective of proving the value of FSW. None of the panels failed at the weld, and moreoever significant effort was made to put the weld under high stress by varying the ratio of shear to compression in the test.

Figure 4.11 shows the failure load plotted against the loading ratio and it can be seen that the classical ellipse is obtained. The behaviour of the welded panels is at least as good as that of non welded ones. The FE simulations which were carried out by QUANTECH on non welded panels agree fairly well with the corresponding experimental data.

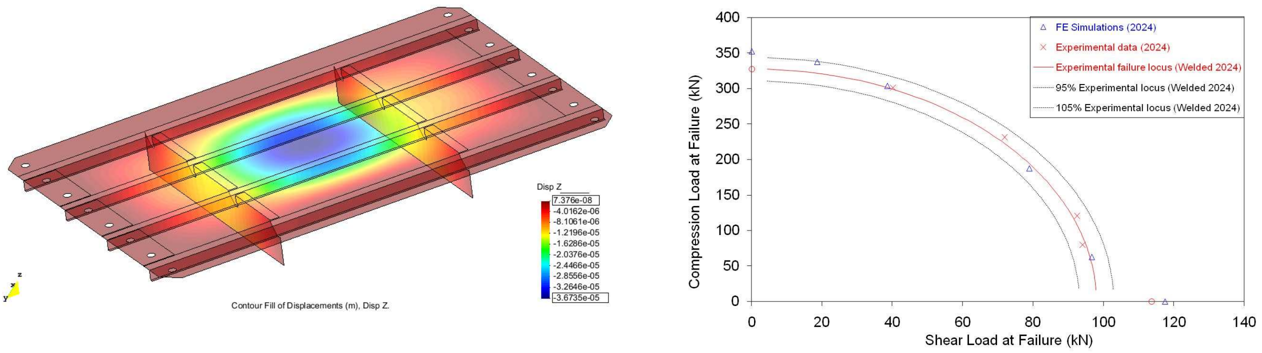


Figure 4.11: Shear/Compression Load failure curve on 2024 stiffened panels: experiments by QUB and FE simulation by QUANTECH.

QUANTECH also performed prospective dynamic simulations of the Hydraulic Bulging test of welded sheets employing AA2198-T8 material properties. Failure takes place in the vicinity of the weld line.

1.4.4.2 Bobbin Tool FS welds on thick parts

At the laboratory coupon level, intrumented Bobbin Tool FS welds were run by EADS (15mm thick AA7449-W511). The operating conditions are defined by the following process parameters: travelling speed, rotating speed, tool load and torque. For the bobbin tool, an additional parameter such as pin length or pin force is investigated. A post welding heat treatment to T79 was done on the welded parts, similarly to what would be done in an industrial manufacturing sequence. Characterisation samples were cut out in the welded and aged coupons. Microhardness measurements, transverse tensile tests and observation of defects were carried out to help determine the “optimised coupon” that will serve the purpose of industrial coupons. The range of “optimal parameters” is actually narrow.

EADS has developed in WP3 a coupled CFD/FE approach to simulate FSW. It is called STIRKIT®. The numerical strategy is as follows: coupling of a local modelling dealing with fluid/thermal (external CFD code) to a global modelling dealing with thermal analysis. After convergence, thermal field and total dissipated power are available. The latter result can be used to perform a sequentially coupled thermo-mechanical analysis with ABAQUS, giving thus a prediction of distortions and residual stresses. It is able to bring a better understanding of the process in terms of material behaviour, tool/matrix interface and heat generation and conduction.

EADS has implemented its improved simulation tool STIR-KIT® to identify the material thermal conductance, the sticking and friction coefficients at the tool/matrix interface on a bobbing tool FSW case of 7449W511 alloy. Recorded temperature data during the FSW test were used. The simulation results have allowed for a better understanding of the relationship between the generated power and input variables such as material behavior and sticking and friction coefficients.

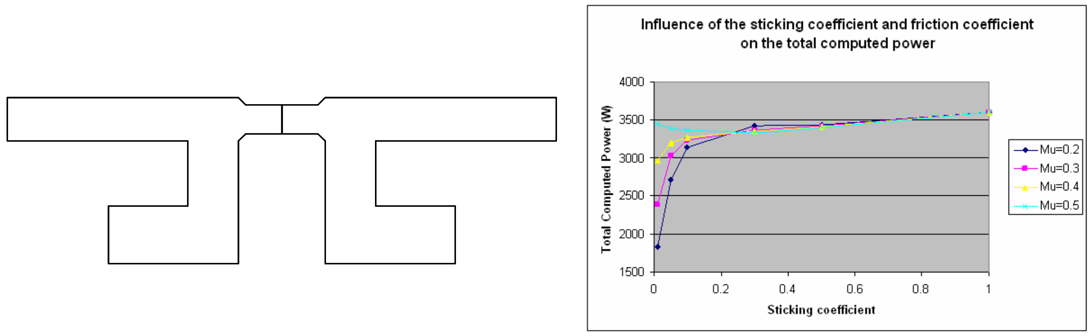
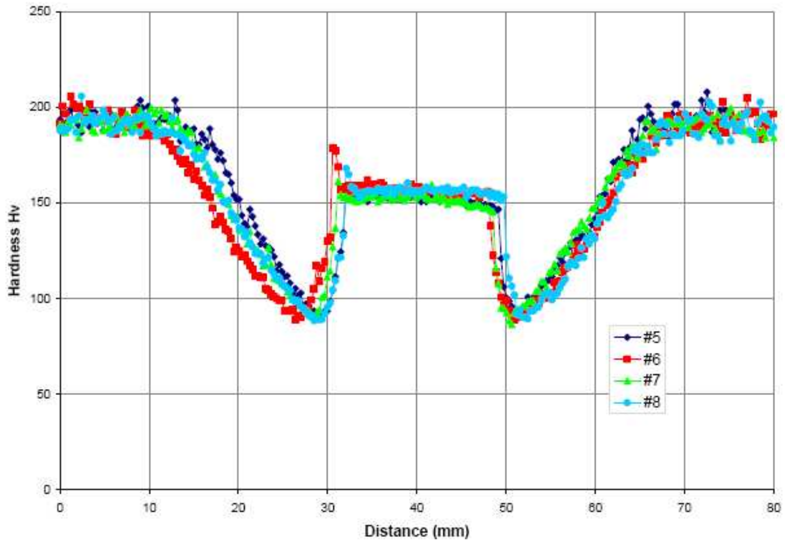


Figure 4.12: Influence of the sticking and friction coeffciients on the computer total power by EADS.

<u>At the industrial coupon level</u>, the welded coupons were representative of an Airbus keel beam case, with thickness to be welded of 15mm. EADS proceeded with the examination of the industrial coupons and use of the simulation tool to support the analysis. This has allowed to validate the simulation tool on industrial coupons at the same time. The coupons were welded in the W511 temper and a post welding T79 has been applied. The loss in hardness and strength is about 50-60% for the heat affected zone and only 20-30% in the nugget (Figure 4.13).

The nuggets are mainly free of defects. Compared to as welded coupons, the post welding ageing enables to increase the hardness of the base metal and the nugget, but a small decrease in the HAZ is observed. The observed mechanical property evolutions across the weld were interpreted in terms of GP zones and η' precipitates evolution according to the probable local thermal history. These assumptions were then confirmed by the examination of experimental temperature measurements and the peak temperature and cooling rate profiles across the weld generated from a thermal model (Figure 4.14).



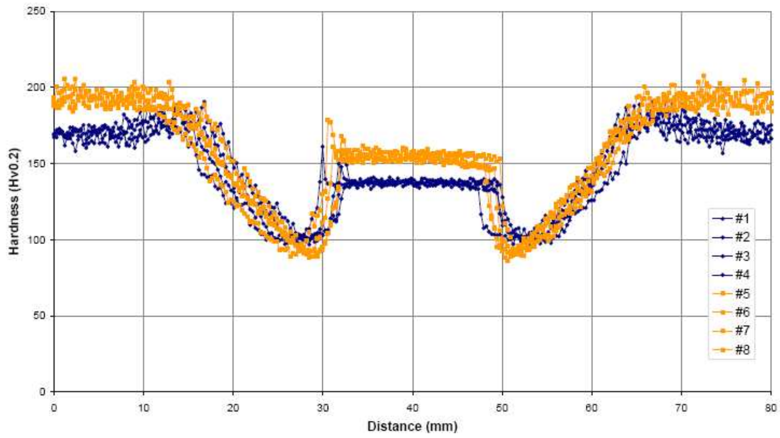
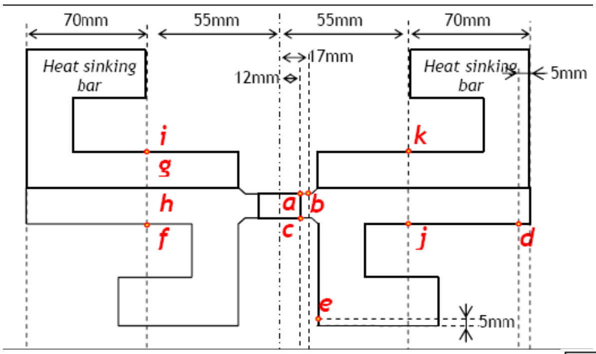
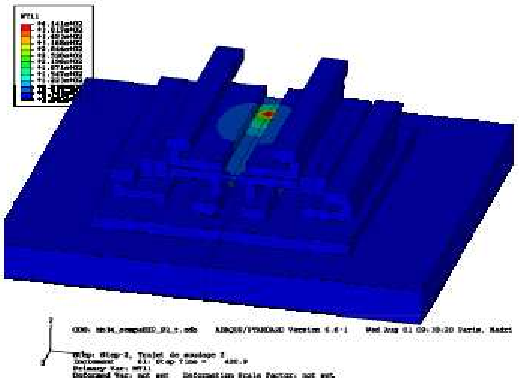
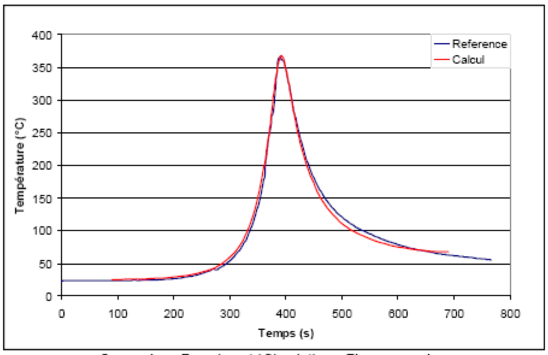


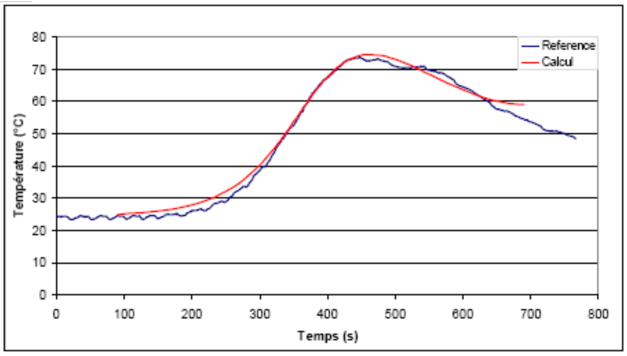
Figure 4.13: Hardness profiles on 4 coupons (average of 3 line measurements on each coupon). Beneficial effect of a T79 post welding heat treatment Picture of the measurement lines on the coupons.



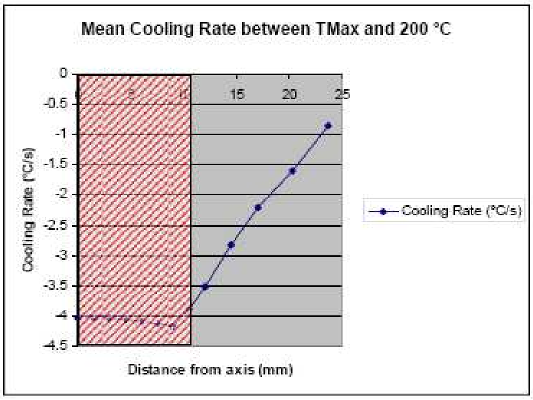




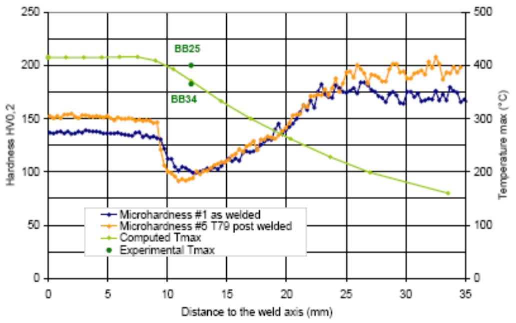
Comparison Experiment / Simulation – Thermocouple a.



Comparison Experiment / Simulation – Thermocouple e.



Thermal field during welding by simulation.



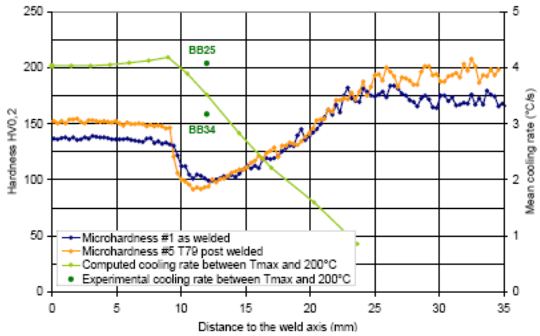


Figure 4.14: Experimental hardness profiles, peak temperature, computed peak temperature profile, cooling rate and computed cooling rate across the weld.

1.4.4.3 Conclusions on WP4

The following methodologies and approaches were implemented to produce acceptable welds and to validate the simulation calculations:

- intrumented experimental FSW tests to obtain data useful to better understanding FSW, to validate the simulation and to define the process parameters window.
- mechanical characterisation, optical and metallographic examinations to help optimise the welding.
- validation of the simulation tool based on a coupled local thermo-fluid model and a global thermo-mechanical model: validate first the heat generation simulation with experimental data from instrumented laboratory coupons.
- Rationalise the determination of the process operating window with the help of an optimisation algorithm coupled to the welding simulation tool and an analytical model of global power balance as an objective function.
- use the simulation tool as a guidance for welding industrial coupons and validate the tool on residual stress data.
- assess the mechanical response of stiffened panel with FS welded skin through experiments and FE calculations.

They highlight the specific competencies shown by the partners in the fields of test instrumentation, FSW testing, mechanical testing, modelling and numerical simulation.

The achieved step is the validation of a more predictive approach by modelling the material flow or the generation of heat due to friction or plastic deformation.

The impact of DEEPWELD achievements on the aeronautical industry is promising in terms of finding more applications to the FSW technology and saving time and cost in the development cycle. The DEEPWELD simulation platform may be used to guide manufacturing people to find the process parameters operating window with less trials. The platform may also help design people for assessing the feasibility of some FSW concepts on the structures.

In conclusion, the developed simulation platform within DEEPWELD has been validated on laboratory and industrial coupons. It is then considered that the objective of DEEPWELD is met.

1.5 Conclusions

DEEPWELD targeted the development of a general numerical tool capable of simulating the complete physics of the Friction Stir Welding process by coupling the following fields: mechanical, thermal, metallurgy and material flow. In this process, friction is the most important effect on temperature excursions until the material along the friction zone is plasticized. Then the material is subjected to large shear deformation around the tool, and heating is due to visco-plastic power instead of friction power. Hence the coupling between the mechanical and flow effects is of prime importance to predict the correct heat input. Furthermore the various combinations of high temperatures, high strains and high strain rates induce micro-structural changes in the material. These micro-structural changes directly alter and affect the macro-structural properties of the material and therefore its behavior during the manufacturing process. It is vital that the micro- and the subsequent macro-structural behaviors are accurately modeled in order to properly simulate the welding process.

The new simulation tool (developed in the framework of DEEPWELD) is based on a multi-scale approach where a new advanced finite element solver based on a velocity-pressure formulation solves the material flow and thermal effects around the tool taking into account complex thermally varying friction laws. The material flow solver at the lowest scale is coupled with a state-of-the-art industrial software either SAMCEF or ABAQUS to compute the complete process from the starting transitory phase, through a steady phase and eventually up to the ending phase of the process. New metallurgy models were implemented in the industrial code in order to take into account the changes in micro-structure due to the stirring and cooling of the metal. Much care was devoted to the applicability of the new technique on an industrial basis, this is the reason why existing industrial software for thermo-mechanical analysis were used but complemented by advanced multi-scale features.

The main originality of DEEPWELD system which was lying in accounting for all physical phenomena was reached with success. In what follows, a series of innovations gathered by the DEEPWELD project is listed.

Innovation 1
Multi-scale multi-physics solution based on industrial software

DEEPWELD does not aim at re-inventing existing, proven, industrial finite element solvers, but to complement them with sufficiently advanced features in order to simulate specifically a process such as Friction Stir Welding. The objective is then to perform analysis at different scales. First, a thermo-fluid simulation is performed at the scale of the flow material around the tool, advanced friction models and metallurgy are implemented in this new solver. The information such as thermal fields, strain, strain rates of the material flow region are then passed onto the industrial thermo-mechanical solver in order to compute a **global scale analysis for the whole process**. The thermo-mechanical solver is equipped with metallurgy modules capable of accurately predicting the evolution of microstructures during the process. Coupling between local scale thermo-fluid analysis and global process thermo-mechanical modelling is achieved.

Innovation 2
Material flow visualisation

To support the development described in the previous paragraph, experiments were conducted to visualize material flow. Those data were used to validate the thermo-fluid finite element tool and also to calibrate the analytical flow model. Techniques used to visualize the material flow rely on the introduction of elements such as very small balls, very thin wires or sheets that are used as tracers of the material flow. Also, an innovative method was proposed consisting of using a number of tracers with known low melting temperatures, e.g. solder alloys to be selected also on the basis of their melting temperature. By using such tracers, it was unfortunately not possible to obtain information neither on the tracer particles displacements during FSW and nor on the maximum temperatures attained during their displacement, in particular in the nugget where thermocouples and thermographic measurements are impossible. This method was demonstrated not efficient during the project.

Innovation 3
No experimentally calibrated heat flux

DEEPWELD focused on **eliminating equivalent heat flux** used in current state-of-the-art thermo-mechanical simulation of Friction Stir Welding process. Indeed, in the latter, an equivalent heat flux must be determined on a case by case basis from experiments measuring heat input and tool loads and tuned to obtain good correlations between simulation and measurements. Hence, this methodology is a major burden for any optimisation of welding parameters or application to different alloys and tools. The objective is to replace it by **a thermo-fluid calculation** to predict the amount of heat generated through plastic work and friction as described before. Therefore, the thermo-fluid module was enhanced by the implementation of a complex friction law.
This objective was very challenging, indeed, few attempts of material flow modelling around the tool could be found in the literature but apart from a few of them, no link was made to the thermal aspect of the process. DEEPWELD project passed this challenging objective with success.

Innovation 4
Understanding friction effects

In the Friction Stir Welding process, friction between the tool and the workpiece is a strategic phenomenon to model in order to obtain an accurate simulation. A Coulomb friction law is of course no longer valid for a flowing material. Therefore, **new friction laws** depending on temperature and the mechanical status of the material were developed. Those served as input to the new thermo-fluid simulation tool. Instrumented experiments were conducted to determine the parameters of the laws by inverse analysis, experiments were focused on:

- the direct measurement of the local friction (shear) interface stress as a function of the temperature, pressure, etc ;

- measurement of forces and torques on FSW equipment in order to obtain global information as a function of operating welding parameters (rotational speed, tilt angles, advancement speed, etc).

Innovation 5
Further develop micro-structure thermal evolution

The accurate characterization of the evolution of the microstructures of the different zones of the weld during the process is very important to predict the mechanical properties of the resulting welded parts. In particular in the nugget zone when a high strain rate is directly related to the flow. The thermo-fluid module provided the temperature/strain rate data to the metallurgical module and so, to predict accurately the material behavior. Therefore, **new constitutive laws** were developed and implemented considering:

- the micro model describing the metallurgical evolution, including prediction of grain growth, phase composition and final material properties, induced by the temperature and strain rate;
- the constitutive model at macro-level;
- the coupling between the micro and the macro constitutive models using continuum theory within the finite element simulation software.

A **global simulation of the microstructural evolutions** during the process was performed: grain/ subgrain size, textures, hardening precipitation. Validations were carried out by experimental data and microstructures were investigated by means of the Field Emission Gun Scanning Electron.

Innovation 6
Validation based on experiments on force and displacement controlled machines

The consortium conducted experiments on two types of machines: force controlled machine at IdS and on displacement controlled machine at UCL. These two controlling techniques are widely used for FSW and it is expected that using both in the same research programme provided a good opportunity to give a better understanding of the phenomena occurring at the tool-workpiece interface as well as of the respective advantages and disadvantages of both control techniques.

Innovation 7
Optimisation of welding parameters

The new multi-physics multi-scale solver was developed to minimize the number of experiments required to calibrate the different parameters of the numerical solution. The objective was of course to be able to apply the solver “as is” to different geometries, plate thickness, etc, provided the material metallurgy module remains within the validity limits. Hence, it is now possible to optimize process parameters in order to obtain required microstructures of the welds.

Innovation 8
Application to welding of real-life coupons representative of aeronautical applications

The final objective of DEEPWELD was to validate the predicted solutions of the new solver on coupons representative of aeronautical applications. The solver is now able to accurately compute macroscopic properties such as residual stresses, distortions, mechanical properties of the joints, etc. These results were validated by experiments conducted on welded panels. In addition, the mechanical properties of the latter were compared to classical riveted panels, which should in the future allow for the definition of guidelines on the usage of Friction Stir Welding for the design of aeronautical parts.

2. Dissemination and Use – Publishable results

2.1 Project and results overview

2.1.1 Project summary

EC PROGRAMME (see annex 1)	FP6-AEROSPACE
PROJECT TITLE	Detailed Multi-Physics Modelling of Friction Stir Welding
PROJECT ACRONYM:	DEEPWELD
CONTRACT NUMBER :	AST4-CT-2005-516134
PROJECT WEB SITE (if any) :	http://www.deepweld.org
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Coordinator telephone	+32 71 91 93 30
Coordinator organisation name	CENAERO
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PARTNERS NAMES :	▪ QUANTECH ATZ (ES) ▪ SAMTECH S.A. (BE) ▪ Centro Internacional de Mètodes Numèrics en Enginyeria (CIMNE, ES) ▪ Université Catholique de Louvain (UCL, BE) ▪ Institut de Soudure (IdS, FR) ▪ The Queen's University of Belfast (QUB, UK) ▪ EADS (FR) ▪ SONACA S.A (BE) ▪ ARMINES-Ecole Nationale Supérieure des Mines de Saint Etienne (ENSMSE, FR)
EC PROJECT OFFICER:	
EC PO name	Gerhard Pauly
EC PO e-mail	gerhard.pauly@ec.europa.eu
EC Directorate General	Directorate General Research

2.1.2 Overview of main project results

No.	Self-descriptive title of the result	Category (A, B, C)*	Partner(s) owning the result(s) (referring in particular to specific patents, copyrights, etc.) & involved in their further use
1	Modelling of precipitates dissolutions in hardened aluminium alloys using neural networks	A	CIMNE in collaboration with UCL
2	Validity and relevancy of the CDRX model to describe the microstructural evolution in the nugget zone of Friction Stir Welded zones.	A	ENSMSE
3	Better understanding of friction laws, material flow, energy balance and modelling of FSW	A	UCL in collaboration with various other partners
4	Finite Element modelling of Friction Stir Welding for prediction of residual stresses, distortions and post-weld metallurgy	A	CENAERO
5	New generation welding software specialized in FSW numerical modelling (Morfeo Software)	A	CENAERO
6	Software to simulate FSW and support development of the technology	A	EADS IW
7	Methodology for the Inverse Analysis to calibrate the parameters of strain-rate and temperature dependant material models.	A	Quantech
8	Procedure For Estimating Process Effects On Cost And Performance Of Stiffened Panels	A	QUB (owner), CENAERO (future use & collaboration)
9	Modelling and Idealisation Guidelines for FSW Panels in Aerospace	B	QUB
10	A better understanding of Friction Stir Weld formation: optimising welding parameters in order to obtain optimum mechanical properties	A	IdS

* Category A: results usable outside the consortium
B: results usable within the consortium
C: non usable results

2.2 Description of each result

No. & TITLE OF RESULT

No*.	**Self-descriptive title of the result***
1	Modelling of precipitates dissolutions in hardened aluminium alloys using neural networks

CONTACT PERSON(S) FOR THIS RESULT

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URL	
Specific Result URL	

SUMMARY*

A new approach using neural networks (NN) is proposed for the identification of microstructural parameters for precipitates dissolution in precipitation hardenable aluminium alloys. The model is based on the kinetics of dissolution of precipitates model for hardenable aluminium alloys given by Myhr and Grong (1991). Shercliff et al. (2005) showed that the Myhr and Grong (1991) model overestimated the amount of the relative volume fraction of precipitates at later stages. In this work we are showing that the Shercliff et al. (2005) model underestimates the amount of relative volume fraction of precipitates at early states and a new parametrization of the master curve is proposed. The novel methodology has been applied to different aluminium alloys, including the AA7449 T79, AA 2198 T8 and AA 6005 A. Experimental tests have been performed in order to get the isothermal time evolution of Vickers hardness at different temperatures.

Within the NN framework, the modeling of precipitates dissolution in precipitation hardenable aluminium alloys consists of three main steps. First, a suitable function space defining the neural network is selected. Here a multilayer perceptron with one input, one sigmoid hidden neuron and one linear output neuron is used to span the function space. The NN also includes an independent parameter describing the effective activation energy of the model. Second, a variational formulation is considered selecting a suitable objective functional. Finally, the reduced function optimization problem is solved using a training algorithm. Here a quasi-Newton method is chosen to train the neural network. BFGS and Brent training operators are used for the train direction and train rate, respectively. The proposed approach has been applied to the selected aluminium alloys. Numerical results for the effective activation energy and the new parameterized master curves are given.

The results obtained for the different aluminium alloys, effective activation energy and master curve, have been implemented in the FE software for the simulation of FSW processes MORFEO, developed by CENAERO, and can be applied in the computational simulation of FSW processes with applications in the aeronautical and aerospace industries.

The main innovative features of the results obtained are the following:

- New characterization of the master curve for different aluminium alloys
- Explicit expression for the master curve allowing in an easy way the characterization of the dissolution of hardening precipitates model and its implementation into a FE software for the simulation of FSW processes
- Master curve for the AA-2198-T8 aluminium alloy, of great interest for industrial aeronautical industries
- Methodology of identification of master curve and effective activation energy using neural networks

SUBJECT DESCRIPTORS*

Subject descriptors codes	389	47	129	373	614

CURRENT STAGE OF DEVELOPMENT

Current stage of development	
Scientific and/or Technical knowledge (Basic research)	X
Guidelines, methodologies, technical drawings	
Software code	
Experimental development stage (laboratory prototype)	
Prototype/demonstrator available for testing	
Results of demonstration trials available	
Other (please specify.):	

INTELLECTUAL PROPERTY RIGHTS

Type of IPR	
Patent applied for	
Patent granted	
Patent search carried out	
Licence agreement(s) reached	
Partnership / other contractual agreement(s)	X
Exclusive rights	
Registered design	
Trademark applications	
Copyrights registered	
Secret know-how	
Other - please specify :	

MARKET APPLICATION SECTORS

Market application sectors	73l	35.3	72		

COLLABORATIONS SOUGHT*

Kind of collaboration					
R&D	Further research or development	X	**FIN**	Financial support	X
LIC	Licence agreement		**VC**	Venture capital/spin-off funding	
MAN	Manufacturing agreement		**PPP**	Private-public partnership	
MKT	Marketing agreement/Franchising		**INFO**	Information exchange	
JV	Joint venture		**CONS**	Available for consultancy	X
			Other	(please specify)	

POTENTIAL OFFERED FOR FURTHER DISSEMINATION AND USE

CIMNE has developed and implemented an inverse analysis methodology using neural networks which allows the identification of the effective activation energy and master curve characterizing the dissolution of precipitates for fully hardened aluminium alloys.

This methodology has been successfully implemented in the FE software MORFEO, developed by CENAERO for the simulation of FSW processes, and it has been applied for different aluminium alloys of interest in FSW processes with applications to the aeronautical and aerospace industries.

The inverse methodology developed and the results obtained in the metallurgical characterization of precipitates dissolution in fully hardened aluminium alloys have been presented in 2 international conferences, as an invited keynote lecture in one of them, and 1 international seminar on FSW modelling.

PROFILE OF ADDITIONAL PARTNER(S) FOR FURTHER DISSEMINATION AND USE

Additional partners for further dissemination and use of the results obtained by CIMNE could be companies in the aeronautical sector and research centres and universities with expertise in materials characterization and computational simulation of FSW processes.

No. & TITLE OF RESULT

No*.	Self-descriptive title of the result*
2	Validity and relevancy of the CDRX model to describe the microstructural evolution in the nugget of Friction Stir Welded zones.

CONTACT PERSON(S) FOR THIS RESULT

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URL	
Specific Result URL	

SUMMARY*

In the DEEPWELD project the model for continuous dynamic recrystallization developed by Montheillet and Gourdet was applied and calibrated for the three aluminium alloys studied. A specific procedure for calibration was founded to prevent problems due to the low accuracy of the early stage hot torsion curves, required to calibrate the hardening and recovery parameters of the CDRX model. The results founded for these parameters are in good agreement with those founded on the AA1200 (nearly pure aluminium). Actually the hardening parameter is founded higher and recover parameter lower than for the AA1200. This justifies the relevancy of the model traducing the effect of alloying element on the microstructural behaviour of the Aeronautic alloys chosen in the context of DEEPWELD.

SUBJECT DESCRIPTORS*

Please categorise the result using codes from Annex 2 (maximum: 5)

Subject descriptors codes	389	378			

CURRENT STAGE OF DEVELOPMENT

Current stage of development	
Scientific and/or Technical knowledge (Basic research)	*X*
Guidelines, methodologies, technical drawings	
Software code	
Experimental development stage (laboratory prototype)	
Prototype/demonstrator available for testing	
Results of demonstration trials available	
Other (please specify.):	

INTELLECTUAL PROPERTY RIGHTS

Type of IPR	
Patent applied for	
Patent granted	
Patent search carried out	
Licence agreement(s) reached	
Partnership / other contractual agreement(s)	
Exclusive rights	
Registered design	
Trademark applications	
Copyrights registered	
Secret know-how	
Other - please specify : No IPR, this results is to published in a scientific review	X

MARKET APPLICATION SECTORS

Market application sectors	27	35.3			

COLLABORATIONS SOUGHT*

Kind of collaboration					
R&D	Further research or development	***X***	**FIN**	Financial support	***X***
LIC	Licence agreement		**VC**	Venture capital/spin-off funding	
MAN	Manufacturing agreement		**PPP**	Private-public partnership	***X***
MKT	Marketing agreement/Franchising		**INFO**	Information exchange	***X***
JV	Joint venture		**CONS**	Available for consultancy	***X***
			Other	(please specify)	

POTENTIAL OFFERED FOR FURTHER DISSEMINATION AND USE

Knowledge on the characterisation of the metallic material evolution at high temperature. Optimisation of the mechanical service properties of the products obtained through high temperature forming.

PROFILE OF ADDITIONAL PARTNER(S) FOR FURTHER DISSEMINATION AND USE

Partners involved in the manufacturing of metallic alloys especially high temperature transformation.

No. & TITLE OF RESULT

No*.	Self-descriptive title of the result*
3	Better understanding of friction laws, material flow, energy balance and modelling of FSW

CONTACT PERSON(S) FOR THIS RESULT

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URL	
Specific Result URL	

SUMMARY*

During the DEEPWELD project, several experiments allowed UCL and the participants to have a better knowledge of the various phenomena occurring during FSW.

- Among them, welding experiments with records of the forces and torque have been conducted in order to have a better understanding of the frictions laws.
- Other fully instrumented welding experiments (with records of the temperatures, forces and torque) allowed UCL to have a better knowledge of the energy balance in the weld.
- Also, some welds using copper inserts allowed UCL to analyse the material flow.
- Finally, isothermal heat treatment has been realized on AA2024 T3, AA7449 and AA2198 T8 in order to calibrate the parameters of a softening model.

The results obtained have already been and will be further reported in a number of publications written in collaboration with the other participants, e. g. CENAERO, ENSMSE, IdS, CIMNE.

SUBJECT DESCRIPTORS*

Subject descriptors codes	388	389	602	605	

CURRENT STAGE OF DEVELOPMENT

Current stage of development	
Scientific and/or Technical knowledge (Basic research)	X
Guidelines, methodologies, technical drawings	
Software code	
Experimental development stage (laboratory prototype)	
Prototype/demonstrator available for testing	
Results of demonstration trials available	
Other (please specify.):	

INTELLECTUAL PROPERTY RIGHTS

Type of IPR	
Patent applied for	
Patent granted	
Patent search carried out	
Licence agreement(s) reached	
Partnership / other contractual agreement(s)	
Exclusive rights	
Registered design	
Trademark applications	
Copyrights registered	
Secret know-how	
Other - please specify : Not applicable	X

MARKET APPLICATION SECTORS

Market application sectors	35.3.B				

COLLABORATIONS SOUGHT*

Kind of collaboration					
R&D	Further research or development	X	**FIN**	Financial support	
LIC	Licence agreement		**VC**	Venture capital/spin-off funding	
MAN	Manufacturing agreement		**PPP**	Private-public partnership	
MKT	Marketing agreement/Franchising		**INFO**	Information exchange	
JV	Joint venture		**CONS**	Available for consultancy	
			Other	(please specify)	

POTENTIAL OFFERED FOR FURTHER DISSEMINATION AND USE

Experience in modelling and experiments relative to FSW.
Expertise in aluminium alloys

PROFILE OF ADDITIONAL PARTNER(S) FOR FURTHER DISSEMINATION AND USE

Universities, research centres and companies in the aeronautic sector

No. & TITLE OF RESULT

No*.	Self-descriptive title of the result*
4	Finite Element modelling of Friction Stir Welding for prediction of residual stresses, distortions and post-weld metallurgy

CONTACT PERSON(S) FOR THIS RESULT

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URL	http://www.cenaero.be
Specific Result URL	-

SUMMARY*

In the frame of the DEEPWELD project, a multi-physics and multi-scale model was developed in CENAERO's in-house Finite Element code Morfeo (Manufacturing Oriented Finite Element tOol). The finite element model uses a staggered thermal-fluid solution scheme. The model uses an Eulerian formulation with a mixed velocity-pressure discretization for the fluid flow. The material behaviour is assumed to be viscoplastic (Norton-Hoff power law). The thermal calculation takes into account the heating due to the viscoplastic deformation. The size of the meshes is such that the parallel version of Morfeo was used in order to limit the simulation times. The results of these simulations are velocity, strain-rate, deformation power and temperature fields. These data may then be used in subsequent analyses. The deformation power may be used as a heat source in a global thermo-mechanical simulation to determine residual stresses. Using the velocity field the flow lines may be calculated and strain-rate and temperature fields can be interpolated along each streamline. This data can then be used as an input to a model which calculates the evolution of the metallurgy evolution (precipitation, grain-size, etc.). All these developments provided CENAERO with a better understanding of the FSW process.

Moreover, a large series of experiments were gathered by the consortium for a better understanding of the physical phenomena occurring during the FSW. Industrial welds were performed and instrumented in order to better understand the behavior of the components during assembly operations.

High level scientific and technological expertise based on the results from the project described here above, are used for supporting the manufacturing industry. The know-how acquired during the DEEPWELD project will be used for helping the manufacturing industry to optimize their welding process by decreasing costs and improving products' quality.

The expertise acquired by CENAERO during the DEEPWELD project has started to be exploited during the project. Some industrial contacts, partners and customers asked CENAERO to solve technical problems related to FS welding designs (Renault e.g.).

SUBJECT DESCRIPTORS*

Subject descriptors codes	565	400	373	155	579

CURRENT STAGE OF DEVELOPMENT

Current stage of development	
Scientific and/or Technical knowledge (Basic research)	
Guidelines, methodologies, technical drawings	
Software code	X
Experimental development stage (laboratory prototype)	
Prototype/demonstrator available for testing	
Results of demonstration trials available	
Other (please specify.):	

INTELLECTUAL PROPERTY RIGHTS

Type of IPR	
Patent applied for	
Patent granted	
Patent search carried out	
Licence agreement(s) reached	X
Partnership / other contractual agreement(s)	X
Exclusive rights	
Registered design	
Trademark applications	
Copyrights registered	
Secret know-how	
Other - please specify :	

MARKET APPLICATION SECTORS

Market application sectors	D35				

COLLABORATIONS SOUGHT*

Kind of collaboration					
R&D	Further research or development	X	**FIN**	Financial support	X
LIC	Licence agreement	X	**VC**	Venture capital/spin-off funding	X
MAN	Manufacturing agreement		**PPP**	Private-public partnership	X
MKT	Marketing agreement/Franchising	X	**INFO**	Information exchange	
JV	Joint venture		**CONS**	Available for consultancy	X
			Other	(please specify)	

POTENTIAL OFFERED FOR FURTHER DISSEMINATION AND USE

CENAERO is a research center specialized in simulation techniques with a high added value on applied researches. Niche and high-tech applications are the core business of CENAERO. DEEPWELD is a successful example of how CENAERO develops a new concept in collaboration with a European consortium.
The developments gathered within the DEEPWELD project may be exploited in the future. All developed features of Morfeo may be extended and used for new applications and processes, like hot forging, regular friction welding processes, FSSW, hot forming, etc. It can be clearly seen that taking advantage of one project and its high scientific/technological level, it will be possible to extend the market and collaboration with potential partners.

PROFILE OF ADDITIONAL PARTNER(S) FOR FURTHER DISSEMINATION AND USE

In the field of welding, and more particularly, the FSW applications, several companies (large and medium size) have already asked support to CENAERO in simulation and more details about capabilities and the price list of the software developed. We may list a few contacts: Edison Welding Institute (USA), Brazilian Synchrotron Light Laboratory (Brazil), Airbus France, Renault (France), Techspace Aero (Belgium), etc.
CENAERO is also very close to Research centers and universities for laboratory tests, physics understanding and support in the field of experiments.
A good balance between academics, research centers and industry (end-users) is an essential point for ensuring a successful project. CENAERO is aimed to pursue on this way, at the image of DEEPWELD.

No. & TITLE OF RESULT

No*.	Self-descriptive title of the result*
5	New generation welding software specialized in FSW numerical modelling (Morfeo software)

CONTACT PERSON(S) FOR THIS RESULT

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Specific Result URL	http://www.cenaero.be/Page_Generale.asp?DocID=15324&la=1&langue=EN

SUMMARY*

Time reduction and improvement of quality in the field of industrial manufacturing and material forming require more and more the use of a virtual approach coupled with the classical trial and error method. Numerical tools can minimize the number of expensive trials performed for the optimization of a given process. Nowadays, many companies develop this activity, convinced of the strategic interest lying in Computed Aided Manufacturing.

Therefore, the Virtual Manufacturing (VM) group of CENAERO, with the aim of perfectly fitting to the industry specific needs, develops an in-house Finite Element code, Morfeo (Manufacturing Oriented Finite Element tOol). The aim is to develop a numerical tool able to simulate the welding and machining processes for large size components and within a reasonable computation time. All the efforts are focused on these two categories of processes and particular attention is given to the industrial functionalities of Morfeo.

The DEEPWELD project gave CENAERO the great opportunity to extend the capabilities and features of Morfeo to a major and new welding process: Friction Stir Welding. Therefore, numerous developments were required besides the investigation of new algorithms and numerical methodologies. The high level of expertise of both CENAERO and the rest of the consortium provided the successful experimental validation of the developed numerical tool. The application of Morfeo to industrial parts demonstrated its capability to assess a production level.

The next step for CENAERO is to commercialize the software product developed in the framework of DEEPWELD. Therefore, licenses of the software will be commercially distributed to manufactures and industrial customers. The software will be distributed to universities and research centers for setting-up new fruitful collaborative research projects. Finally, the software will be developed further on with new processes and new capabilities for ensuring the commercial exploitation and constant improvement of CENAERO consultancy services.

SUBJECT DESCRIPTORS*

Subject descriptors codes	565	400	373	155	579

CURRENT STAGE OF DEVELOPMENT

Current stage of development	
Scientific and/or Technical knowledge (Basic research)	
Guidelines, methodologies, technical drawings	
Software code	X
Experimental development stage (laboratory prototype)	
Prototype/demonstrator available for testing	
Results of demonstration trials available	
Other (please specify.):	

INTELLECTUAL PROPERTY RIGHTS

Type of IPR	
Patent applied for	
Patent granted	
Patent search carried out	
Licence agreement(s) reached	X
Partnership / other contractual agreement(s)	X
Exclusive rights	
Registered design	
Trademark applications	
Copyrights registered	
Secret know-how	
Other - please specify :	

MARKET APPLICATION SECTORS

Market application sectors	D35				

COLLABORATIONS SOUGHT*

Kind of collaboration					
R&D	Further research or development	X	**FIN**	Financial support	X
LIC	Licence agreement	X	**VC**	Venture capital/spin-off funding	X
MAN	Manufacturing agreement		**PPP**	Private-public partnership	X
MKT	Marketing agreement/Franchising	X	**INFO**	Information exchange	
JV	Joint venture		**CONS**	Available for consultancy	X
			Other	(please specify)	

POTENTIAL OFFERED FOR FURTHER DISSEMINATION AND USE

The Morfeo software is currently on the market and usually sold to external customers. An industrial version is available and an academic license is distributed at a discounted fee to the universities. The development and improvement of Morfeo is a continuous and non-ending process. The goal is to ensure that Morfeo stays at the top of the State of the Art.

The developments gathered within the DEEPWELD project may be exploited in the future. All developed features of Morfeo may be extended and used for new applications and processes, like hot forging, regular friction welding processes, FSSW, hot forming, etc. It can be clearly seen that taking advantage of one project and its high scientific/technological level, it will be possible to extend the market and collaboration with potential partners.

PROFILE OF ADDITIONAL PARTNER(S) FOR FURTHER DISSEMINATION AND USE

In the field of welding, and more particularly, concerning the FSW applications, several companies (large and medium size) have already asked support to CENAERO in simulation and more details about capabilities and the price list of the software developed. We may list a few contacts: Edison Welding Institute (USA), Brazilian Synchrotron Light Laboratory (Brazil), Airbus France, Renault (France), Techspace Aero (Belgium), etc.

CENAERO is also very close to Research centers and universities for laboratory tests, physics understanding and support in the field of experiments.

A good balance between academics, research centers and industry (end-users) is an essential point for ensuring a successful project. CENAERO is aimed to pursue on this way, at the image of DEEPWELD.

No. & TITLE OF RESULT

No*.	Self-descriptive title of the result*
6	Software to simulate FSW and support development of the technology

CONTACT PERSON(S) FOR THIS RESULT

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Specific Result URL	

SUMMARY*

EADS IW has developed a simplified thermo-fluid model of Bobbin-Tool Friction Stir Welding. The model is implemented within a user-friendly software. The software allows to perform fast thermo-fluid simulations in order to study the process response to parameter changes. Parametric studies can be performed as well.
The model can be coupled to thermo-mechanical simulations in order to form a complete simulation chain, able to compute residual stresses and distortions as a function of process parameters and welding configuration.

The software is a key element of a global methodology to apply FSW to new applications and structures.
Results are exploited for bobbin tool FSW processes and products (parts of EADS aircraft, helicopter and spacecrafts), directly using EADS IW approach, on an individual basis or as a group of EADS partners if common concepts. End users are thus EADS IW researchers and EADS business units employees.

Further additional research will be the adaptation of EADS IW simulation approach to other materials.
Potential impact is linked to the expected benefits for EADS products: innovative concepts will foster sales and grow employment, will foster lighter structures thus less fuel consumption and cleaner products with respect to the environment.

SUBJECT DESCRIPTORS*

Subject descriptors codes	378	388	565		

CURRENT STAGE OF DEVELOPMENT

Current stage of development	
Scientific and/or Technical knowledge (Basic research)	X
Guidelines, methodologies, technical drawings	
Software code	X
Experimental development stage (laboratory prototype)	
Prototype/demonstrator available for testing	
Results of demonstration trials available	
Other (please specify.):	

INTELLECTUAL PROPERTY RIGHTS

Type of IPR	
Patent applied for	
Patent granted	
Patent search carried out	
Licence agreement(s) reached	
Partnership / other contractual agreement(s)	
Exclusive rights	
Registered design	
Trademark applications	
Copyrights registered	
Secret know-how	X
Other - please specify : Property recognized by a Court Bailiff	X

MARKET APPLICATION SECTORS

Market application sectors	35.3				

COLLABORATIONS SOUGHT*

Kind of collaboration					
R&D	Further research or development	X	**FIN**	Financial support	
LIC	Licence agreement		**VC**	Venture capital/spin-off funding	
MAN	Manufacturing agreement		**PPP**	Private-public partnership	
MKT	Marketing agreement/Franchising		**INFO**	Information exchange	
JV	Joint venture		**CONS**	Available for consultancy	
			Other	(please specify)	

POTENTIAL OFFERED FOR FURTHER DISSEMINATION AND USE

Collaborations would be welcomed within national or European projects to further FSW know-how in general and simulation capabilities in general.

PROFILE OF ADDITIONAL PARTNER(S) FOR FURTHER DISSEMINATION AND USE

Industrial or Academic partner: FSW modelling and/or experimental capabilities

No. & TITLE OF RESULT

No*.	Self-descriptive title of the result*
7	Methodology for the Inverse Analysis to calibrate the parameters of strain-rate and temperature dependant material models.

CONTACT PERSON(S) FOR THIS RESULT

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Specific Result URL	

SUMMARY*

Quantech is able to propose advanced friction and constitutive models for special materials, like aluminium alloys, including thermal and rheological properties.

Quantech has also the experience to perform the inverse analysis for these advanced models based on a family of experimental curves provided by experimentalist partners.

Quantech will benefit from the know-how acquired in developing friction and constitutive laws as well as the inverse analysis and calibration procedures performed during the DEEPWELD project.
Thus new material models will be furthermore implemented in the simulation software being developed and commercialized by the company.

The end-users of the results could be the metal manufacturers, manufacturers of machinery, equipments and manufactures of aircraft and spacecraft.

The potential of the identified laws parameters is much higher considering a wider application range.

This knowledge can be exploited not only commercially but also for academic purposes on demand.

Quantech will keep collaborating with CENAERO and SAMTECH in order to assist for the license protection and software optimization procedures, new features and improved friendly user interface if requested.

SUBJECT DESCRIPTORS*

Subject descriptors codes	565	313	388	373	

CURRENT STAGE OF DEVELOPMENT

Current stage of development	
Scientific and/or Technical knowledge (Basic research)	X
Guidelines, methodologies, technical drawings	
Software code	
Experimental development stage (laboratory prototype)	
Prototype/demonstrator available for testing	
Results of demonstration trials available	
Other (please specify.):	

INTELLECTUAL PROPERTY RIGHTS

Type of IPR	
Patent applied for	
Patent granted	
Patent search carried out	
Licence agreement(s) reached	
Partnership / other contractual agreement(s)	
Exclusive rights	
Registered design	
Trademark applications	
Copyrights registered	
Secret know-how	
Other - please specify :	

MARKET APPLICATION SECTORS

Market application sectors	28	29	35.3	73	

COLLABORATIONS SOUGHT*

Kind of collaboration					
R&D	Further research or development	X	**FIN**	Financial support	X
LIC	Licence agreement		**VC**	Venture capital/spin-off funding	
MAN	Manufacturing agreement		**PPP**	Private-public partnership	
MKT	Marketing agreement/Franchising		**INFO**	Information exchange	
JV	Joint venture		**CONS**	Available for consultancy	
			Other	(please specify)	

POTENTIAL OFFERED FOR FURTHER DISSEMINATION AND USE

Actual activities that will be offered to the potential partners:

Quantech® ATZ develops software for specialised sectors and takes responsibility for the quality, maintenance, marketing and sales of the software as well as the customisation, specialised development, training and support needs of the user community. Important agreements are held with research institutes in order to provide a controlled research and development environment guided by industrial needs.

Quantech® ATZ manages and participates in European, national and world-wide industrial research and development projects within its numerical analysis, information technology and engineering fields of expertise.

Quantech® ATZ provides a warm and friendly consultancy and customised training service for the industrial sector carrying out numerical analyses, providing help, advice and encouragement in a variety of engineering fields. In all these aspects the company policy is to provide a high quality service based on knowledgeable engineering expertise coupled with state-of-the-art research solutions and software tools.

PROFILE OF ADDITIONAL PARTNER(S) FOR FURTHER DISSEMINATION AND USE

Additional partners are welcome. They should have experience in the experimental testing of advanced materials. They will have to provide the experimental work required for the calibration of strain-rate and temperature-dependent materials alloys. The mutual collaboration will help to increase the actual database of advanced material alloys for commercial profits.

No. & TITLE OF RESULT

No*.	Self-descriptive title of the result*
8	Procedure For Estimating Process Effects On Cost And Performance Of Stiffened Panels

CONTACT PERSON(S) FOR THIS RESULT

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URL		
Specific Result URL		

SUMMARY*

The FSW process affects material properties causing stress and distortion in the structure after it has been welded. A procedure has been developed and validated with the tests which can include these effects in the performance analysis.

Airframe designers will be able to use this method in trade offs and studies on new manufacturing processes. But its application is wider than aerospace and applied to any stiffened panel structures.

The method will be encapsulated in a software tool which will automate the analysis process and provide quick results to the user to aid decision making.

SUBJECT DESCRIPTORS*

Subject descriptors codes	20	155	373		

CURRENT STAGE OF DEVELOPMENT

Current stage of development	
Scientific and/or Technical knowledge (Basic research)	
Guidelines, methodologies, technical drawings	X
Software code	
Experimental development stage (laboratory prototype)	
Prototype/demonstrator available for testing	
Results of demonstration trials available	
Other (please specify.):	

INTELLECTUAL PROPERTY RIGHTS

Type of IPR	
Patent applied for	
Patent granted	
Patent search carried out	
Licence agreement(s) reached	
Partnership / other contractual agreement(s)	X
Exclusive rights	
Registered design	
Trademark applications	
Copyrights registered	
Secret know-how	
Other - please specify :	

MARKET APPLICATION SECTORS

Market application sectors	28	35.3			

COLLABORATIONS SOUGHT*

Kind of collaboration					
R&D	Further research or development	X	**FIN**	Financial support	X
LIC	Licence agreement		**VC**	Venture capital/spin-off funding	
MAN	Manufacturing agreement		**PPP**	Private-public partnership	
MKT	Marketing agreement/Franchising		**INFO**	Information exchange	X
JV	Joint venture		**CONS**	Available for consultancy	X
			Other	(please specify)	

POTENTIAL OFFERED FOR FURTHER DISSEMINATION AND USE

We have extensive analysis, design and testing capability and would be delighted to partner with advanced engineering companies particularly in the area of stiffened panels, metallic or composite.

We have state of the art software and modelling capability and an exceptional combined shear and compression test rig with advanced digital image correlation systems for full field strain measurement in addition to more traditional strain and displacement measurement systems.

PROFILE OF ADDITIONAL PARTNER(S) FOR FURTHER DISSEMINATION AND USE

Any advanced engineering company, especially airframe manufacturers but also smaller entities who have advanced manufacturing and design capability. Both financial support and in-kind materials are needed in general, but a willingness to share problems and new ideas is also welcome.

No. & TITLE OF RESULT

No*.	Self-descriptive title of the result*
10	A better understanding of Friction Stir Weld formation: optimising welding parameters in order to obtain optimum mechanical properties

CONTACT PERSON(S) FOR THIS RESULT

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Specific Result URL	

SUMMARY*

Through the DEEPWELD project, IdS performed analyses in order to feed the DEEPWELD model (material flow visualisation, thermal cycles measurements, natural aging characterisation, grain size assessments and residual stresses measurements) and to weld aeronautical panels with optimized welding conditions. The material flow visualization enables the understanding of the effect of the welding conditions on the weld formations. The different flows have been characterized in the 3 plans of the weld joint and have been compared with success with the simulations carried out by CENAERO.

Moreover, thanks to the natural aging characterization results, the kinetic of the Guiner Preston zones precipitation in Thermo-Mechanically Affected Zone and in Stir Zone have been plotted for two aluminium alloy (20246T3 and 2198-T8). This enables the understanding of the influence of the dislocation density on the precipitation and to improve the comprehension of the friction stir weld metallurgy.

Residual stresses has been assessed on validation coupons and compared to the simulation. This gives an idea of the level of residual stresses on representative panels.

SUBJECT DESCRIPTORS*

Subject descriptors codes	7	388	389		

CURRENT STAGE OF DEVELOPMENT

Current stage of development	
Scientific and/or Technical knowledge (Basic research)	
Guidelines, methodologies, technical drawings	
Software code	
Experimental development stage (laboratory prototype)	X
Prototype/demonstrator available for testing	
Results of demonstration trials available	
Other (please specify.):	

INTELLECTUAL PROPERTY RIGHTS

Type of IPR	
Patent applied for	
Patent granted	
Patent search carried out	
Licence agreement(s) reached	
Partnership / other contractual agreement(s)	
Exclusive rights	
Registered design	
Trademark applications	
Copyrights registered	
Secret know-how	
Other - please specify :	

MARKET APPLICATION SECTORS

Market application sectors	3.5.3	6.1.1.e			

COLLABORATIONS SOUGHT*

Kind of collaboration					
R&D	Further research or development	X	**FIN**	Financial support	
LIC	Licence agreement		**VC**	Venture capital/spin-off funding	
MAN	Manufacturing agreement		**PPP**	Private-public partnership	
MKT	Marketing agreement/Franchising		**INFO**	Information exchange	X
JV	Joint venture		**CONS**	Available for consultancy	
			Other	(please specify)	

POTENTIAL OFFERED FOR FURTHER DISSEMINATION AND USE

Collaborations would be welcomed within national or European projects concerning the welding in general. Indeed, INSTITUT DE SOUDURE carried out a lot of feasibility studies on different kind of materials (steel, titanium alloys, nickel base alloys, aluminium alloys, …..) using all types of welding and brazing process (Arc welding, Laser Bean Welding, Electron Bean Welding, Friction Stir Welding, Resistance Spot Welding,….).

INSTITUT DE SOUDURE has an extended experience in all domains using welding.

PROFILE OF ADDITIONAL PARTNER(S) FOR FURTHER DISSEMINATION AND USE

Industrial or Academic partners

ANNEX 1 : FP6 EC programmes

FP6-AEROSPACE

FP6-CITIZENS

FP6-COORDINATION

FP6-EURATOM-FISSION

FP6-EURATOM-FUSION

FP6-EURATOM-JRC

FP6-EURATOM-NUCHORIZ

FP6-EURATOM-NUCTECH

FP6-EURATOM-NUWASTE

FP6-EURATOM-RADPROT

FP6-FOOD

FP6-INCO

FP6-INFRASTRUCTURES

FP6-INNOVATION

FP6-IST

FP6-JRC

FP6-LIFESCIHEALTH

FP6-MOBILITY

FP6-NEST

FP6-NMP

FP6-POLICIES

FP6-SME

FP6-SOCIETY

FP6-SUPPORT

FP6-SUSTDEV

ANNEX 2: SUBJECT DESCRIPTOR CODES

1 ACARIANS
2 ACCIDENTOLOGY
3 ACCOUNTING
4 ACOUSTICS
5 ADMINISTRATIVE SCIENCES, ADMINISTRATION
6 ADULT EDUCATION, PERMANENT EDUCATION
7 AERONAUTICS
8 AGEING
9 AGRICULTURAL CHEMISTRY
10 AGRICULTURAL ECONOMICS
11 AGRICULTURAL ENGINEERING/TECHNOLOGY
12 AGRICULTURAL MARKETING/TRADE
13 AGRICULTURAL PRODUCTION SYSTEMS
14 AGRICULTURAL SCIENCES, AGRICULTURE
15 AGRI-FOOD, AGRI-ENVIRONMENT
16 AGRONOMY
17 AIR TRAFFIC CONTROL OPERATIONS/PROCEDURES/SLOT ALLOCATION
18 AIR TRAFFIC MANAGEMENT/FLOW MANAGEMENT
19 AIR TRANSPORT TECHNOLOGY
20 AIRCRAFT
21 AIRPORT OPERATIONS/PROCEDURES
22 ALGAE
23 ALGEBRA
24 ALGEBRAIC TOPOLOGY
25 ALGORITHMS AND COMPLEXITY
26 ALLERGOLOGY
27 ALTERNATIVE PROPULSION SYSTEMS
28 ANALYTICAL CHEMISTRY
29 ANIMAL BANKS AND REPOSITORIES
30 ANIMAL BIOTECHNOLOGY
31 ANIMAL BREEDING/REPRODUCTION/NUTRITION
32 ANIMAL FEED, ANIMAL PRODUCTION
33 ANIMAL HEALTH, ANIMAL WELFARE
34 ANIMAL PARASITIC DISEASES
35 ANIMAL PHYSIOLOGY
36 ANIMAL PRODUCTS
37 ANTHROPOGENIC IMPACT ON ECOSYSTEMS
38 ANTHROPOLOGY
39 ANTIBIOTICS
40 ANTICANCER THERAPIES
41 ANTI-FRAUD
42 APPLIED MATHEMATICS
43 APPLIED PHYSICS
44 AQUACULTURE, AQUACULTURE TECHNOLOGY
45 ARCHIVISTICS/DOCUMENTATION/TECHNICAL DOCUMENTATION
46 ARCTIC ENVIRONMENT
47 ARTIFICIAL INTELLIGENCE
48 ARTS
49 ASSESSMENT AND MANAGEMENT OF LIVING RESOURCES
50 ASTRONOMY
51 ASTROPHYSICS/PLANETARY GEOLOGY
52 ATOMIC AND MOLECULAR PHYSICS
53 AUDIOVISUAL COMMUNICATION
54 AUTOMATION, ROBOTIC CONTROL SYSTEMS
55 BACTERIOLOGY
56 BANKING
57 BENCHMARKING TECHNIQUES
58 BIOASSAYS
59 BIOCATALYSTS
60 BIOCHEMICAL TECHNOLOGY
61 BIOCHEMISTRY, METABOLISM
62 BIOCOMPUTING, MEDICAL INFORMATICS, BIOMATHEMATICS, BIOMETRICS
63 BIODEGRADATION
64 BIODIVERSITY
65 BIOFERTILIZERS
66 BIOGAS PRODUCTION
67 BIOLOGICAL COLLECTIONS: MUSEA AND RELATED INFORMATION RESOURCES
68 BIOLOGICAL ENGINEERING

69 BIOLOGICAL MONITORING/RISK FACTORS AND ASSESSMENT

70 BIOLOGICAL SCIENCES, BIOLOGY

71 BIOMASS PROCESS INTEGRATION AND ENVIRONMENTAL IMPACTS

72 BIOMECHANICS, BIOMEDICAL ENGINEERING

73 BIOMEDICAL ETHICS

74 BIOMEDICAL SCIENCES

75 BIOMOLECULES, BIOPLASTICS, BIOPOLYMERS

76 BIOPHYSICS, MEDICAL PHYSICS

77 BIOREACTORS

78 BIOREMEDIATION

79 BIOSAFETY

80 BIOSENSORS

81 BIOTECHNOLOGY, BIOENGINEERING

82 BIOTRANSFORMATION

83 BOREAL FOREST

84 BRAIN DEVELOPMENT

85 BRAIN THEORY, BRAIN MAPPING

86 BROADBAND TECHNOLOGIES

87 BROADCASTING

88 BROKERAGE SERVICES

89 BUILDING CONSTRUCTION, SHELL SUSTAINABILITY

90 BUSINESS COMMUNICATION

91 BUSINESS ECONOMICS/STUDIES, ORGANISATION AND PROCESSES

92 CARBOCHEMISTRY, PETROCHEMISTRY, FUELS AND EXPLOSIVES TECHNOLOGY

93 CARBOHYDRATES AND OTHER MACROMOLECULES METABOLISM

94 CARBON DIOXIDE CAPTURE/STORAGE/DISPOSAL

95 CARDIOVASCULAR SYSTEM

96 CARE AND HEALTH SERVICES, HELP TO THE HANDICAPPED

97 CELL COMMUNICATION

98 CENTRAL AND EASTERN EUROPEAN COUNTRIES

99 CERAMIC MATERIALS AND POWDERS

100 CERTIFICATION

101 CHEMICAL METROLOGY

102 CHEMICAL TECHNOLOGY AND ENGINEERING

103 CHEMISTRY/HOMOGENEOUS AND HETEROGENEOUS CATALYSIS/THEORETICAL/NANOCHEMISTRY

104 CHRONOLOGY, DATATION TECHNOLOGY

105 CIVIL ENGINEERING (INCL PAVEMENTS AND STRUCTURES)

106 CLINICAL GENETICS, BIOLOGY

107 CLINICAL PHYSICS, RADIOLOGY, TOMOGRAPHY, MEDICAL INSTRUMENTATION, MEDICAL IMAGING

108 CLINICAL RESEARCH, CLINICAL TRIALS, COMPUTERISED CLINICAL SYSTEMS

109 COAL MINING TECHNOLOGIES

110 COASTAL MORPHOLOGICAL CHANGES AND COASTAL DEFENSE MECHANISMS

111 COASTAL ZONE ECOSYSTEMS AND MANAGEMENT

112 COATS AND SURFACE TREATMENT

113 COGNITIVE SCIENCE

114 COLLOIDS

115 COMBINATORIAL CHEMISTRY

116 COMBINED HEAT AND POWER SYSTEMS

117 COMBUSTION BASICS AND EFFICIENCY

118 COMMERCIAL AND INDUSTRIAL ECONOMICS

119 COMMON AGRICULTURAL POLICY

120 COMMUNICATION ENGINEERING/TECHNOLOGY

121 COMMUNICATION SCIENCES/HUMAN COMPUTER INTERACTIONS

122 COMMUNITY DEVELOPMENT, COMMUNITY STUDIES

123 COMPANY RE-ENGINEERING/ORGANISATIONAL DEVELOPMENT

124 COMPOSITE MATERIALS

125 COMPUTATIONAL BIOLOGY

126 COMPUTATIONAL CHEMISTRY AND MODELING

127 COMPUTATIONAL MATHEMATICS/DISCRETE MATHEMATICS

128 COMPUTATIONAL PHYSICS

129 COMPUTER SCIENCE/ENGINEERING, NUMERICAL ANALYSIS, SYSTEMS, CONTROL

130 COMPUTER TECHNOLOGY/GRAPHICS, META COMPUTING

131 COMPUTER-BASED TRAINING

132 CONDENSED MATTER: ELECTRONIC, MAGNETIC AND SUPERCONDUCTIVE PROPERTIES

133 CONDENSED MATTER: MECHANICAL AND THERMAL PROPERTIES

134 CONDENSED MATTER: OPTICAL AND DIELECTRIC PROPERTIES

135 CONDENSED MATTER: SOFT MATTER AND POLYMER PHYSICS

136 CONSUMER SCIENCES, CONSUMERS' RIGHTS

137 CONTROL ENGINEERING

138 COOPERATIVE WORKING

139 CORROSION

140 COSMOLOGY

141 CRIMINOLOGY

142 CROP, CROP INPUTS/MANAGEMENT/YIELD ESTIMATION

143 CULTURAL HERITAGE: PRESERVATION AND RESTORATION/CULTURAL STUDIES

144 CULTURE COLLECTIONS: MICROBIAL, CELL, TISSUE, GERMPLASM

145 CURRICULUM STUDIES

146 CYBERNETICS

147 CYTOGENETICS

148 CYTOLOGY, CANCEROLOGY, ONCOLOGY

149 DATA PROTECTION, STORAGE TECHNOLOGY, CRYPTOGRAPHY

150 DATABASES, DATABASE MANAGEMENT, DATA MINING

151 DECENTRALISED GENERATION OF ELECTRICITY/HEAT

152 DECISION SUPPORT TOOLS

153 DEEP WATER EXPLOITATION

154 DEMOGRAPHY

155 DESIGN, DESIGN ENGINEERING

156 DEVELOPMENT OF CLEAN FUELS FOR TRANSPORT

157 DEVELOPMENT POLICIES AND STUDIES

158 DEVELOPMENT TECHNOLOGY, ANIMAL GROWTH, ONTOLOGY, EMBRYOLOGY

159 DIAGNOSTICS, DIAGNOSIS

160 DIGITAL SYSTEMS, DIGITAL REPRESENTATION

161 DISABILITIES, HANDICAPS AND HANDICAPPED

162 DISEASES: RARE/CHRONIC/DEGENERATIVE, ETIOLOGIC FACTORS

163 DIVERSIFICATION IN AGRICULTURE/FORESTRY

164 DNA CHIP

165 DNA THERAPIES

166 DOWNSTREAM PROCESSING

167 "DRILLING TECHNOLOGY; DEEP DRILLING"

168 DRUG ABUSE, ADDICTION

169 DRUG DISCOVERY, PROFILING, TARGETING

170 DRYLAND AND ARID ZONE ECOSYSTEMS

171 EARTH OBSERVATION APPLICATIONS AND POLICY

172 EARTH OBSERVATION TECHNOLOGY AND INFORMATION EXTRACTION

173 EARTH SCIENCE, EARTH OBSERVATION/STRATIGRAPHY/SEDIMENTARY PROCESSES

174 EARTH SCIENCES FOR CLIMATE RESEARCH

175 ECOLOGY, ECOSYSTEMS, ECOLOGICAL EVOLUTION/DYNAMICS

176 ECONOMIC AND ENVIRONMENT IMPACTS

177 ECONOMIC AND SOCIAL SCIENCES

178 ECONOMICS IN AGRICULTURE/FORESTRY/RURAL DEVELOPMENT

179 ECONOMICS OF DEVELOPMENT/GROWTH/INNOVATION

180 ECONOMICS, ECONOMIC PLANNING

181 ECOSYSTEM RESEARCH AND CONSERVATION

182 ECOTOXICOLOGY

183 EDUCATION AND TRAINING, LIFELONG LEARNING, REMOTE LEARNING

184 EDUCATIONAL MULTIMEDIA

185 EDUCATIONAL SCIENCES

186 ELECTRICAL ENGINEERING/TECHNOLOGY

187 ELECTROMAGNETISM

188 ELECTRONIC COMMERCE, ELECTRONIC PAYMENT, ELECTRONIC SIGNATURE

189 ELECTRONIC DATA INTERCHANGE

190 ELECTRONIC HEALTH RECORDS

191 ELECTRONIC PUBLISHING, AUTHORING TOOLS

192 ELECTRONICS, ELECTRONIC ENGINEERING

193 EMERGENCY MANAGEMENT

194 EMISSION

195 EMPLOYMENT STUDIES

196 ENDOCRINOLOGY, SECRETING SYSTEMS, DIABETOLOGY

197 ENERGY AND CLIMATE CHANGE

198 ENERGY CONVERSION PROCESSES OR CYCLES/CONVERSION FROM COAL

199 ENERGY MANAGEMENT SYSTEM

200 ENERGY MARKET ANALYSIS

201 ENERGY PRODUCTION FROM BIOMASS / WASTE

202 ENERGY RESEARCH/RTD POLICY

203 ENERGY, RENEWABLE ENERGIES, ELECTRICITY STORAGE

204 ENGINEERING, CONCURRENT ENGINEERING

205 ENTOMOLOGY, PLANT PARASITOLOGY

206 ENTREPRENEURSHIP, SPIN OFFS, NEW TECHNOLOGY BASED BUSINESS

207 ENVIRONMENT, ENVIRONMENTAL SCIENCE

208 ENVIRONMENTAL ECONOMICS/NATURAL RESOURCES ECONOMICS

209 ENVIRONMENTAL HEALTH

210 ENVIRONMENTAL IMPACTS/INTERACTIONS

211 ENVIRONMENTAL INDICATORS/MONITORING/RISK ASSESSMENT

212 ENVIRONMENTAL LAW/TREATIES/POLICY

213 ENVIRONMENTAL TECHNOLOGY/ENGINEERING, POLLUTION CONTROL

214 EPIDEMIOLOGY

215 ERGONOMICS

216 EROSION

217 EUROPEAN INTEGRATION

218 EUROPEAN LAW

219 EUROPEAN STUDIES

220 EVALUATION

221 EXPLOITATION OF RESEARCH RESULTS

222 EXTENSIFICATION

223 EXTERNALITIES

224 FARMHOUSE CONSTRUCTION

225 FARMING SYSTEMS

226 FERMENTATION

227 FINANCIAL SCIENCE, FINANCE

228 FINE CHEMICALS, DYES AND INKS

229 FISH/FISHERIES

230 FISHING METHODOLOGIES/SELECTIVITY

231 FOOD AND DRINK TECHNOLOGY

232 FOOD CHEMISTRY, FOOD INGREDIENTS

233 FOOD MICROBIOLOGY

234 FOOD PROCESSING/PACKAGING

235 FOOD QUALITY MANAGEMENT/POLICY/LABELLING

236 FOOD TOXICOLOGY

237 FOREST ECOSYSTEMS

238 FOREST GENETICS

239 FOREST PHYSIOLOGY AND PATHOLOGY

240 FOREST POLICY, FOREST MANAGEMENT

241 FOREST PROTECTION

242 FOREST SCIENCES

243 FORMAL SAFETY AND ENVIRONMENTAL ASSESSMENT

244 FREIGHT TRANSPORT

245 FUEL CELLS

246 FUELS: ALTERNATIVE FUELS IN TRANSPORTS

247 FUNCTIONAL FOODS

248 FUNGI

249 FUTURE AND EMERGING TECHNOLOGIES

250 GAS CONVERSION

251 GAS TURBINES FOR ENERGY CONVERSION

252 GASES, FLUID DYNAMICS, PLASMAS/ELECTRIC DISCHARGES

253 GASTRO-ENTEROLOGY

254 GENDER ISSUES, GENDER STUDIES

255 GENE THERAPY

256 GENERAL PATHOLOGY, PATHALOGICAL ANATOMY

257 GENETIC COMPARATIVE ANALYSIS

258 GENETIC ENGINEERING

259 GENETIC MAPPING, GENE SEQUENCE

260 GENETIC RESISTANCE

261 GENETIC SELECTION

262 GENETICALLY MODIFIED ORGANISMS

263 GENETICS

264 GENOMES, GENOMICS

265 GEOGRAPHIC INFORMATION SYSTEMS

266 GEOGRAPHY

267 GEOLOGICAL ENGINEERING/GEOTECHNICS

268 GEOMETRY/TOPOLOGY

269 GEOPHYSICS, PHYSICAL OCEANOGRAPHY, METEOROLOGY, GEOCHEMISTRY, TECTONICS

270 GERONTOLOGY AND GERIATRICS

271 GLOBAL CHANGE: BIOGEOCHEMICAL AND HYDROLOGICAL CYCLES

272 GLOBAL CHANGE: CLIMATE CHANGE

273 GLOBAL CHANGE: HUMAN HEALTH

274 GLOBAL CHANGE: LAND COVER AND DEGRADATION

275 GLOBAL CHANGE: OZONE AND ATMOSPHERIC COMPOSITION

276 GLOBAL CYCLES OF ENERGY AND MATTER

277 GREEN TECHNOLOGIES/CHEMICALS

278 GRID CONNECTION

279 HAZARDS: INDUSTRIAL

280 HAZARDS: NATURAL

281 HEALTH AND POPULATION, HEALTH EDUCATION

282 HEALTH FINANCING / ECONOMICS

283 HEALTH RISK EVALUATION

284 HEALTH SCIENCES/POLICIES/LAW

285 HEALTH SERVICE MANAGEMENT

286 HEALTH SYSTEMS RESEARCH

287 HEALTH, HEALTH PHYSICS

288 HETEROGENEOUS CATALYSIS

289 HIGH CONTAINMENT, HIGHT CONTAINMENT FACILITIES

290 HIGH FREQUENCY TECHNOLOGY, MICROWAVES

291 HIGH-THROUGHPUT SCREENING

292 HISTOLOGY, CYTOCHEMISTRY, HISTOCHEMISTRY, TISSUE CULTURE

293 HISTORY

294 HISTORY AND PHILOSOPHY OF SCIENCE AND MEDICINE

295 HOME SYSTEMS

296 HORMONES

297 HORTICULTURE, ORNAMENTAL PLANTS

298 HUMAN FACTORS IN TRANSPORT

299 HUMAN GENETICS

300 HUMAN RIGHTS

301 HUMAN SCIENCES, HUMANITIES

302 HVAC SYSTEMS AND MANAGEMENT

303 HYBRID AND ELECTRIC VEHICLES

304 HYDROBIOLOGY, MARINE BIOLOGY, AQUATIC ECOLOGY, LIMMOLOGY

305 HYDROCARBONS EXPLORATION AND PRODUCTION

306 HYDROELECTRICITY/SMALL HYDRO/HYDROPOWER

307 HYDROGEN

308 HYDROGEOLOGY, GEOGRAPHICAL AND GEOLOGICAL ENGINEERING

309 IDENTIFICATION SYSTEMS

310 IMAGING, IMAGE PROCESSING

311 IMMUNOLOGY, IMMUNOTHERAPY, IMMUNOASSAYS

312 IN VITRO TESTING/TRIAL METHODS

313 INDUSTRIAL ENGINEERING

314 INDUSTRIAL POLICY/RELATIONS

315 INDUSTRIAL PSYCHOLOGY/SOCIOLOGY

316 INDUSTRIAL TECHNOLOGY/ECONOMICS

317 INFECTIONS

318 INFORMATICS

319 INFORMATICS LAW

320 INFORMATION MANAGEMENT

321 INFORMATION TECHNOLOGY/SCIENCE

322 INFRASTRUCTURE MANAGEMENT

323 INLAND NAVIGATION

324 INNOVATION ASSISTANCE

325 INNOVATION FINANCE

326 INNOVATION MONITORING

327 INNOVATION POLICY/STUDIES

328 INNOVATION TRAINING

329 INORGANIC CHEMISTRY

330 INSECTS

331 INSTRUMENTATION TECHNOLOGY

332 INTANGIBLE INVESTMENTS

333 INTEGRATED ENVIRONMENTAL ASSESSMENT

334 INTEGRATED GLOBAL SAFETY

335 INTEGRATION OF RENEWABLE ENERGY SYSTEMS

336 INTELLECTUAL PROPERTY

337 INTELLIGENT AGENTS

338 INTELLIGENT VEHICLES AND WATERBORNE TRANSPORT SYSTEMS

339 INTERMODAL TRANSPORT

340 INTERNATIONAL COMMERCE/ECONOMICS

341 INTERNATIONAL TREATIES / MULTILATERAL AGREEMENTS

342 INTERNET TECHNOLOGIES

343 INVERTEBRATES

344 JOURNALISM

345 KNOWLEDGE ENGINEERING

346 LABOUR MARKET STUDIES/ECONOMICS

347 LAND USE PLANNING/LANDSCAPE/LANDSCAPE ARCHITECTURE

348 LANGUAGE SCIENCES/ENGINEERING/TECHNOLOGY, LINGUISTICS

349 LARGE SCALE GENERATION OF ELECTRICITY/HEAT

350 LASER TECHNOLOGY

351 LAW: INTERNATIONAL / PRIVATE / PUBLIC

352 LEARNING MECHANISMS

353 LIBRARY SCIENCE/SYSTEMS

354 LIFE CYCLE MANAGEMENT

355 LIPIDS, STEROIDS, MEMBRANES

356 LIQUID BIOFUELS

357 LOGISTICS

358 LOW INPUT PRODUCTION

359 MACROECONOMICS (INCL. MONETARY ECONOMICS)

360 MACROMOLECULAR CHEMISTRY/NEW MATERIAL/SUPRAMOLECULAR STRUCTURES

361 MACROSOCIOLOGY

362 MAINTENANCE MANAGEMENT

363 MANAGEMENT OF ENTERPRISES

364 MANAGEMENT OF URBAN AREAS

365 MANAGEMENT STUDIES

366 MARINE ECOSYSTEMS

367 MARINE SCIENCES/MARITIME STUDIES

368 MARINE: INSTRUMENTATION AND UNDERWATER TECHNOLOGY

369 MARINE: OCEANOGRAPHY (PHYSICAL AND OPERATIONAL)

370 MARITIME SAFETY

371 MARKET ANALYSIS/ECONOMICS/QUANTITATIVE METHODS

372 MARKET STUDY, MARKETING

373 MATERIALS TECHNOLOGY/ENGINEERING

374 MATHEMATICAL ANALYSIS/PARTIAL DIFFERENTIAL EQUATIONS

375 MATHEMATICAL LOGIC: SET THEORY, COMBINATORICS/SEMANTICS

376 MATHEMATICAL PHYSICS

377 MATHEMATICS

378 MECHANICAL ENGINEERING, HYDRAULICS, VIBRATION AND ACOUSTIC ENGINEERING

379 MEDIA STUDIES/LAW/MASS COMMUNICATIONS

380 MEDICAL ANTHROPOLOGY

381 MEDICAL SCIENCES/RESEARCH

382 MEDICAL TECHNOLOGY

383 MEDICINAL CHEMISTRY

384 MEDICINE (HUMAN AND VERTEBRATES)

385 MEMBRANE TECHNOLOGY

386 MENTAL STRESS

387 METABOLIC REGULATION AND SIGNAL TRANSDUCTION

388 METAL TECHNOLOGY AND METAL PRODUCTS

389 METALLURGY

390 METROLOGY, PHYSICAL INSTRUMENTATION

391 MICROBIAL BIOTECHNOLOGY, MICROBIAL MODELLING

392 MICROBIAL SYSTEMATICS/DIVERSITY

393 MICROBIOLOGY

394 MICROECONOMICS (THEORETICAL AND APPLIED)

395 MICROELECTRONICS

396 MICROENGINEERING, MICROMACHINING

397 MICROSYSTEMS

398 MINING

399 MOBILE COMMUNICATIONS

400 MODELLING/MODELLING TOOLS, 3-D MODELLING

401 MOLECULAR BIOLOGY

402 MOLECULAR BIOPHYSICS

403 MOLECULAR DESIGN, DE NOVO DESIGN

404 MOLECULAR EVOLUTION

405 MOLECULAR GENETICS

406 MOLECULAR MARKERS AND RECOGNITION

407 MONOCLONAL ANTIBODIES

408 MOTHER AND CHILD HEALTH

409 MOTORS AND PROPULSION SYSTEMS

410 MOUNTAIN AND HIGHLAND ECOSYSTEMS

411 MULTIMEDIA

412 MULTISENSORY TECHNOLOGY, MULTI-SENSING

413 MUSEUM SCIENCE

414 MYCOLOGY

415 NANOBIOTECHNOLOGY

416 NANOFABRICATION, NANOTECHNOLOGY

417 NARROW BAND TECHNOLOGIES

418 NATURAL GAS

419 NATURAL HISTORY OF DISEASES

420 NATURAL OILS, FATS AND WAXES

421 NATURAL RESOURCES EXPLORATION

422 NATURAL SCIENCES

423 NEMATODS

424 NETWORK TECHNOLOGY, NETWORK SECURITY

425 NETWORKED ORGANISATIONS

426 NEUROBIOLOGY, NEUROCHEMISTRY, NEUROLOGY, NEUROPSYCHOLOGY, NEUROPHYSIOLOGY

427 NEUROINFORMATICS

428 NEUTRON PHYSICS

429 NEW MEANS OF TRANSPORT

430 NITROGEN FIXATION

431 NOISE AND VIBRATIONS

432 NON-COMMUNICABLE DISEASES

433 NON-LINEAR DYNAMICS AND CHAOS THEORY

434 NON-METALLIC MINERAL TECHNOLOGY

435 NUCLEAR CHEMISTRY

436 NUCLEAR ENGINEERING AND TECHNOLOGY

437 NUCLEAR MEDICINE, RADIOBIOLOGY

438 NUCLEAR PHYSICS

439 NUCLEIC ACID METABOLISM

440 NUCLEIC ACIDS, POLYNUCLEAOTIDES, PROTEIN SYNTHESIS

441 NUMBER THEORY, FIELD THEORY, ALGEBRAIC GEOMETRY, GROUP THEORY

442 NUTRITION

443 OBSERVATION SYSTEMS / CAPACITY / DATASETS / INDICATORS

444 OCCUPATIONAL HEALTH, INDUSTRIAL MEDICINE

445 OCEAN / ENERGY

446 ODONTOLOGY, STOMATOLOGY

447 OFFSHORE TECHNOLOGY, SOIL MECHANICS, HYDRAULIC ENGINEERING

448 ON-LINE INFORMATION SERVICES, ON-LINE DEMOCRATY, ON-LINE BUSINESS

449 OPERATIONS RESEARCH, ACTUARIAL MATHEMATICS

450 OPTICAL MATERIALS

451 OPTICS

452 OPTRONICS

453 ORGANIC CHEMISTRY

454 ORGANIC FARMING

455 ORGANIC WASTE

456 ORGANOMETALLIC CHEMISTRY

457 ORPHAN DRUGS

458 OTHER RENEWABLE ENERGY OPTIONS

459 OTORHINOLARYNGOLOGY, AUDIOLOGY, AUDITIVE SYSTEM AND SPEECH

460 PALEOCLIMATOLOGY

461 PALEONTOLOGY/PALEOECOLOGY

462 PAPER TECHNOLOGY, RECYCLING

463 PARASITOLOGY (HUMAN AND ANIMAL)

464 PARTICLE PHYSICS/FIELDS THEORY

465 PASSENGER TRANSPORT

466 PATENTS, COPYRIGHTS, TRADEMARKS

467 PATHOLOGY

468 PATHOPHYSIOLOGY

469 PERIPHERALS TECHNOLOGIES (MASS DATA STORAGE, DISPLAY TECHNOLOGIES)

470 PERI-URBAN AGRICULTURE

471 PESTICIDES, BIOPESTICIDES

472 PETROCHEMISTRY, PETROLEUM ENGINEERING

473 PETROLOGY, MINERALOGY, GEOCHEMISTRY

474 PHARMACEUTICALS AND RELATED TECHNOLOGIES

475 PHARMACOLOGICAL SCIENCES, PHARMACOGNOSY, TOXICOLOGY

476 PHOTONIC NETWORKS

477 PHOTOVOLTAIC SYSTEMS, CELLS AND MODULES MANUFACTURING, TECHNOLOGY DEVELOPMENT

478 PHYSICAL CHEMISTRY/SOFT MATTER

479 PHYSICAL GEOGRAPHY, CARTOGRAPHY, CLIMATOLOGY

480 PHYSICAL MEDICINE, KINESITHERAPY, REVALIDATION, REHABILITATION

481 PHYSICAL SCIENCES

482 PHYSICAL STRESS

483 PHYSICS OF FLUIDS

484 PHYSIOLOGICAL DISORDERS

485 PHYSIOLOGY

486 PHYTOREMEDIATION

487 PHYTOTECHNOLOGY, PHYTOPATHOLOGY, CROP PROTECTION

488 PIPELINE TECHNOLOGY

489 PLANT AND ASSOCIATED MICROORGANISM BIOTECHNOLOGY

490 PLANT BIOCHEMISTRY

491 PLANT BIOLOGY

492 PLANT GENETICS/SELECTION/BREEDING

493 PLANT HEALTH/PROTECTION

494 PLANT INPUTS/NUTRITION/PRODUCTION

495 PLANT PHYSIOLOGY

496 PLANT PRODUCTS

497 POLITICAL SCIENCES/THEORY/ECONOMY/COMPARATIVE POLITICS

498 POLYMER TECHNOLOGY, BIOPOLYMERS

499 POPULATION GENETICS

500 PORT MANAGEMENT

501 POSITIONING AND GUIDANCE SYSTEMS

502 POST HARVEST TREATMENT - FOOD

503 POST HARVEST TREATMENT - NON-FOOD

504 PRECISION ENGINEERING

505 PRION DISEASES

506 PROBABILITY THEORY

507 PROCESS EFFICIENCY

508 PROCESS ENGINEERING

509 PRODUCTION TECHNOLOGY

510 PROGRAMMING/INFORMATION SYSTEMS

511 PROJECT ENGINEERING

512 PROTEINS, ENZYMOLOGY, PROTEIN ENGINEERING

513 PROTEOMES, PROTEOMICS

514 PSYCHIATRY, MEDICAL PSYCHOLOGY, PSYCHOSOMATICS

515 PSYCHOLOGICAL SCIENCES, PSYCHOLOGY

516 PUBLIC ADMINISTRATION

517 PUBLIC HEALTH

518 PUBLIC PERCEPTION, PUBLIC RELATIONS

519 PUBLIC POLICY STUDIES

520 PUBLISHING

521 PULP TECHNOLOGY

522 QUALITY, QUALITY CONTROL, TRACEABILITY

523 QUANTUM INFORMATION PHYSICS

524 QUANTUM MECHANICS

525 QUANTUM TECHNOLOGY

526 R&D POLICY AND PROGRAMME EVALUATION AND IMPACT ASSESSMENT

527 RADIODIAGNOSTICS, RADATION BIOLOGY

528 RADIOECOLOGY

529 RAILWAY TRANSPORT TECHNOLOGY

530 REACTION MECHANISMS AND DYNAMICS

531 REACTOR SAFETY

532 REFERENCE MATERIALS/METHODS

533 REFRIGERATION AND COOLING

534 REGIONAL ECONOMICS/STUDIES/DEVELOPMENT

535 REHABILITATION SYSTEMS

536 REMOTE SENSING

537 REPRODUCTIVE HEALTH

538 REPRODUCTIVE MECHANISMS

539 RESEARCH METHODOLOGY IN SCIENCE

540 RESEARCH NETWORKING

541 RESEARCH POLICY

542 RESERVOIR CHARACTERISATION AND MONITORING

543 RESIDUES

544 RESPIRATORY SYSTEM

545 RE-STRUCTURING OF PUBLIC ADMINISTRATIONS

546 ROAD SAFETY

547 ROAD TRANSPORT TECHNOLOGY

548 RTD SYSTEMS AND POLICIES AND THEIR INTERACTION WITH OTHER RELATED POLICIES

549 RURAL DEVELOPMENT, RURAL SOCIOLOGY AND SOCIO-ECONOMICS

550 SAFETY TECHNOLOGY

551 SAMPLE BANKS

552 SATELLITE (TECHNOLOGY, SYSTEMS, POSITIONING, COMMUNICATION)

553 SCIENCE AND TECHNOLOGY INDICATORS

554 SCIENCE POLICY

555 SCIENCE, TECHNOLOGY AND THE MEDIA

556 SEA FOOD

557 SEARCH AND RESCUE

558 SECURITY SYSTEMS

559 SEMICONDUCTOR PHYSICS AND TECHNOLOGIES

560 SENSORY SCIENCE, SENSORS, INSTRUMENTATION

561 SEROLOGY AND TRANSPLANTATION

562 SET ASIDE

563 SIGNAL PROCESSING

564 SILVICULTURE, FORESTRY, FOREST TECHNOLOGY

565 SIMULATION, SIMULATION ENGINEERING

566 SIMULATOR TRAINING

567 SKELETON, MUSCLE SYSTEM, RHEUMATOLOGY, LOCOMOTION

568 SMART CARDS

569 SOCIAL ECONOMICS

570 SOCIAL LAW

571 SOCIAL MEDICINE

572 SOCIAL SHAPING OF TECHNOLOGY

573 SOCIETAL BEHAVIOUR

574 SOCIO-ECONOMIC ASPECTS OF ENVIRONMENTAL CHANGE

575 SOCIO-ECONOMIC RESEARCH

576 SOCIO-ECONOMICAL IMPACTS IN AGRICULTURE/FORESTRY/RURAL DEVELOPMENT

577 SOCIO-ECONOMICS

578 SOCIOLOGY

579 SOFTWARE ENGINEERING, MIDDLEWARE, GROUPWARE

580 SOIL SCIENCE, AGRICULTURAL HYDROLOGY, WATER PROCESSES

581 SOLAR CONCENTRATING TECHNOLOGIES AND APPLICATIONS

582 SOLID STATE PHYSICS

583 SOUND ENGINEERING/TECHNOLOGY

584 SPACE TECHNOLOGY

585 SPATIAL INTEGRATION IN BUILT ENVIRONMENT

586 SPEECH COMMUNICATION

587 SPEECH PROCESSING/TECHNOLOGY

588 STANDARDISATION, STANDARDISATION OF NEW TECHNOLOGIES

589 STATISTICAL PHYSICS

590 STATISTICS

591 STRUCTURAL BIOLOGY/DETERMINATION/FUNCTION

592 SUPERCONDUCTORS

593 SURFACE CHEMISTRY

594 SURFACE PHYSICS

595 SURVEILLANCE

596 SURVEYING

597 SYNTHESIS AND NEW MOLECULES

598 SYSTEMS ANALYSIS AND MODELS DEVELOPMENT

599 SYSTEMS DESIGN/THEORY

600 SYSTEMS ENGINEERING

601 SYSTEMS, CONTROL, MODELLING, AND NEURAL NETWORKS

602 TECHNOLOGICAL SCIENCES

603 TECHNOLOGY ACCEPTABILITY

604 TECHNOLOGY ASSESSMENT AND FORESIGHT

605 TECHNOLOGY EVALUATION/MANAGEMENT

606 TECHNOLOGY POLICY

607 TECHNOLOGY TRANSFER

608 TECHNOLOGY WATCH/VALIDATION

609 TELECOMMUNICATION ENGINEERING/TECHNOLOGY

610 TELESERVICES, TELE-WORKING, TELE-PAYMENT, TELE-MEDICINE

611 TESTING, CONFORMANCE TESTING

612 TEXTILES TECHNOLOGY

613 THERAPEUTIC SUBSTANCES

614 THERMAL ENGINEERING, APPLIED THERMODYNAMICS

615 THERMODYNAMICS

616 TIMBER ENGINEERING

617 TISSUE BANKS/ENGINEERING

618 TOTAL QUALITY MANAGEMENT

619 TOWN AND COUNTRY PLANNING

620 TOXICITY AND TOXINOLOGY

621 TRACTION/PROPULSION SYSTEMS

622 TRAFFIC CONTROL SYSTEMS

623 TRAFFIC ENGINEERING/INFRASTRUCTURE/MANAGEMENT SYSTEMS

624 TRANSACTION SYSTEMS

625 TRANSGENE EXPRESSION

626 TRANSGENIC CROP PLANT

627 TRANSHIPMENT SYSTEMS

628 TRANSPORT DEMAND MANAGEMENT

629 TRANSPORT ECONOMICS

630 TRANSPORT INFORMATION SYSTEMS, FLEET MANAGEMENT

631 TRANSPORT INFRASTRUCTURE/MANAGEMENT SERVICES

632 TRANSPORT MODELLING/SCENARIOS

633 TRANSPORT OF GAS AND LIQUID FUELS

634 TRANSPORT POLICY/LAW

635 TRANSPORT SAFETY/SECURITY

636 TRANSPORT TECHNOLOGY/ENGINEERING

637 TRANSPORT TELEMATICS

638 TRANSPORT, TRANSMISSION AND DISTRIBUTION OF ELECTRICITY

639 TROPICAL AGRICULTURE

640 TROPICAL ECOSYSTEMS

641 TROPICAL FORESTRY

642 TROPICAL MEDICINE

643 URBAN DEVELOPMENT/ECONOMICS

644 URBAN FORESTRY

645 URBAN GOVERNANCE AND DECISION MAKING

646 URBAN QUALITY OF LIFE

647 URBAN SOCIOLOGY

648 URBAN TRANSPORT

649 URBAN: SUSTAINABLE CITIES AND RATIONAL RESOURCE MANAGEMENT

650 URBAN: TECHNOLOGIES FOR THE BUILT ENVIRONMENT

651 UROLOGY, NEPHROLOGY

652 USER CENTRED DESIGN, USABILITY

653 USER MODELLING

654 VACCINES

655 VACUUM/HIGH VACUUM TECHNOLOGY

656 VEHICLE TECHNOLOGY

657 VENTURE CAPITAL

658 VESSEL TRAFFIC MANAGEMENT

659 VETERINARY MEDICINE

660 VIRTUAL ORGANISATIONS

661 VIRTUAL REALITY

662 VIRUS, VIROLOGY

663 VULCANOLOGY/SEISMOLOGY

664 WASTE BIOTREATMENT

665 WASTE MANAGEMENT/RECYCLING

666 WATER RESOURCE MANAGEMENT/ENGINEERING

667 WATER TRANSPORT TECHNOLOGY, SHIPBUILDING

668 WATER: FRESH WATER ECOSYSTEMS

669 WATER: HYDROLOGY

670 WATER: MONITORING / QUALITY / TREATMENT

671 WATER: RATIONAL AND EFFICIENT USE

672 WATERBORNE TRANSPORT

673 WAVE/TIDAL ENERGY

674 WEEDS

675 WELFARE STUDIES

676 WETLAND ECOSYSTEMS

677 WIND ENERGY MANUFACTURING/TECHNOLOGIES

678 WIND TURBINE ENVIRONMENTAL IMPACT

679 WIRELESS SYSTEMS, RADIO TECHNOLOGY

680 WOMEN'S STUDIES

681 WOOD ENGINEERED PRODUCTS, PARTICLE AND FIBRE BOARDS

682 WOOD PROCESSING BY MECHANICAL MEANS

683 WORLD TRADE ORGANISATION

ANNEX 3: NACE codes for business activities

Division	Description
Section A	*Agriculture, hunting and forestry*
01	*Agriculture, hunting and related service activities*
02	*Forestry, logging and related service activities*
Section B	*Fishing*
05	*Fishing, operation of fish hatcheries and fish farms; service activities incidental to fishing*
Section C	*Mining and quarrying*
10	*Mining of coal and lignite; extraction of peat*
11	*Extraction of crude petroleum and natural gas; service activities incidental to oil and gas*
	extraction, excluding surveying
12	*Mining of uranium and thorium ores*
13	*Mining of metal ores*
14	*Other mining and quarrying*
Section D	*Manufacturing*
15	*Manufacture of food products and beverages*
16	*Manufacture of tobacco products*
17	*Manufacture of textiles*
18	*Manufacture of wearing apparel; dressing and dyeing of fur*
19	*Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear*
20	*Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials*
21	*Manufacture of pulp, paper and paper products*
22	*Publishing, printing and reproduction of recorded media*
23	*Manufacture of coke, refined petroleum products and nuclear fuel*
24	*Manufacture of chemicals and chemical products*
25	*Manufacture of rubber and plastic products*
26	*Manufacture of other non-metallic mineral products*
27	*Manufacture of basic metals*
28	*Manufacture of fabricated metal products, except machinery and equipment*
29	*Manufacture of machinery and equipment n.e.c.*
30	*Manufacture of office machinery and computers*

31	*Manufacture of electrical machinery and apparatus n.e.c.*
32	*Manufacture of radio, television and communication equipment and apparatus*
33	*Manufacture of medical, precision and optical instruments, watches and clocks*
34	*Manufacture of motor vehicles, trailers and semi-trailers*
35	*Manufacture of other transport equipment*
35.1	*Building and repairing of ships and boats*
35.2	*Manufacture of railway and tramway locomotives and rolling stock*
35.3	*Manufacture of aircraft and spacecraft*
a	*Manufacture of helicopter*
b	*Manufacture of aeroplanes for the transport of goods or passengers, for use by the defence forces, for sports or other purposes*
c1	*Manufacture of parts and accessories of the aircraft of this class*
d2	*Others*
36	*Manufacture of furniture; manufacturing n.e.c.*
37	*Recycling*
Section E	*Electricity, gas and water supply*
40	*Electricity, gas, steam and hot water supply*
41	*Collection, purification and distribution of water*
Section F	*Construction*
45	*Construction*
Section G	*Wholesale and retail trade; repair of motor vehicles, motorcycles and personal and household goods*
50	*Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of automotive fuel*
51	*Wholesale trade and commission trade, except of motor vehicles and motorcycles*
52	*Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods*
Section H	*Hotels and restaurants*
55	*Hotels and restaurants*
Section I	*Transport, storage and communication*

[1] Includes: major assemblies such as fuselages, wings, doors, control surfaces, landing gear, fuel tanks, nacelles, airscrews, helicopter rotors and propelled rotor blades, motors and engines of a kind typically found on aircraft, parts of turbojets and turbopropellers

[2] This includes: manufacture of gliders, hang-gliders, manufacture of dirigibles and balloons, manufacture of spacecraft and spacecraft launch vehicles, satellites, planetary probes, orbital stations, shuttles, manufacture of aircraft launching gear, deck arresters, etc.
manufacture of ground flying trainers However 35.3 should **exclude**:manufacture of parachutes, military ballistic missiles, ignition parts and other electrical parts for internal combustion engines, instruments used on aircraft, and air navigation systems.

60	*Land transport; transport via pipelines*
61	*Water transport*
61.1	*Sea and coastal water transport*
e	*Transport of passenger or freight over water*
f	*Operation of excursion, cruse or sightseeing boats*
g	*Operation of ferries, water taxis, etc.*
62	*Air transport*
h	*Transport of passenger or freight by airlines*
63	*Supporting and auxiliary transport activities; activities of travel agencies*
63.1	*Cargo handling and storage*
63.2	*Other supporting transport activities*
i	*Operation of terminal facilities such as harbours and piers, waterway locks etc.*
j	*Airport and air-traffic control activities*
63.3	*Activities of travel agencies and tour operators; tourist assistance activities n.e.c.*
63.4	*Activities of other transport agencies*
k	*Forwarding of freight*
64	*Post and telecommunications*
Section J	*Financial intermediation*
65	*Financial intermediation, except insurance and pension funding*
66	*Insurance and pension funding, except compulsory social security*
67	*Activities auxiliary to financial intermediation*
Section K	*Real estate, renting and business activities*
70	*Real estate activities*
71	*Renting of machinery and equipment without operator and of personal and households goods*
72	*Computer and related activities*
73	*Research and development*
l	*Research and experimental development on natural sciences and engineering*
m	*Research and experimental development on social sciences and humanities*
74	*Other business activities*
Section L	*Public administration and defence; compulsory social security*
75	*Public administration and defence; compulsory social security*
Section M	*Education*
80	*Education*
Section N	*Health and social work*

85	*Health and social work*
Section O	*Other community, social and personal service activities*
90	*Sewage and refuse disposal, sanitation and similar activities*
91	*Activities of membership organisations n.e.c.*
92	*Recreational, cultural and sporting activities*
93	*Other service activities*
Section P	*Private households with employed persons*
95	*Private households with employed persons*
Section Q	*Extra-territorial organisations and bodies*
99	*Extra-territorial organisations and bodies*

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