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

1 Abstract

This report details the work carried out over the 42 months of the RAPOLAC (Rapid Production of Large Aerospace Components) project. The objective of the project was to investigate the additive Shaped Metal Deposition (SMD) process and develop it for use in production, where it could be particularly useful for manufacturing large, fully-dense components, or for adding features to already-existing parts. The SMD technology was initially developed by Rolls-Royce plc, but was not widely adopted for commercial production for several reasons. The TIG welding process had to be manually controlled by a skilled technician, and there was little understanding of the material properties of the parts produced by such an innovative process.

The system and process were modelled and research was carried out to determine stable parameter windows for welding the common aerospace alloy Titanium-6Al-4V and to discover the mechanical and microstructural properties of the resulting depositions and any differences in machining strategies required. Methods of automating the deposition were also investigated and the developed controller was integrated with the cell. Finally, the cost and environmental benefits of the process were compared to traditional manufacturing techniques for a number of parts. This report describes the work done by the partners to bring about the successful conclusion of the project.

2 Consortium

RAPOLAC was initiated in 2005 by the Advanced Manufacturing Research Centre (AMRC) at the University of Sheffield in collaboration with seven partners from across Europe. It was funded for 42 months between 2007 and 2010 by the European 6th Framework Aeronautics and Space Programme which aims to strengthen European competitiveness in manufacturing.

RAPOLAC brought together complementary expertise from 8 participants drawn from 3 member states and one other country (Argentina). It includes specialists in the areas of part manufacture (University of Sheffield, Footprint Tools), microstructural analysis (Katholieke Universiteit Leuven), modelling (SAMTECH, INTEC), control (Universita degli Studi di Catania), and environmental analysis (DIAD) and included the management group METEC.

Partners were chosen to have expertise in the different skills necessary to achieve the project goals; the SMD cell is operated jointly by the University of Sheffield and by local company Footprint Tools and make samples for analysis by Katholieke Universiteit Leuven in Belgium. A control system is being developed by Università degli Studi di Catania and will be embedded in the mechanical model of the robot to be developed by SAMTECH. Models of the deposition/solidification process are being developed by Intec and feed into the parameter optimisation being carried out at Sheffield. A cost/benefit analysis is being carried out by DIAD to compare SMD construction to traditional manufacturing routes and this will allow a business case to be put forward encouraging take up by SMEs. METEC performs administrative and other management tasks to ensure the smooth running of the project.

3 Objectives

The individual goals of RAPOLAC were chosen to address the problems facing the aviation industry today as set out in the sixth framework work programme. These are to:

- reduce the lead-time for new parts;
- lower manufacturing costs;
- significantly reduce the cost of inventory ;
- reduce emissions and harmful materials;

SMD meets all these criteria, as parts can be built directly from the CAD model, with no need to wait for tooling and features can be added or removed from the component as required. It will lower manufacturing costs for low-volume or one-off parts and inventory can be reduced to the wire needed for deposition. The only emission of the process is Argon, which can be safely vented to the atmosphere. However, SMD has not been widely adopted for commercial production because it had to be manually controlled and the resultant material properties were not well understood; in other words, the accuracy and repeatability of the process were barriers to take up.

The main objective of RAPOLAC was to develop the SMD process for use in production, to the point where it can reliably and repeatedly produce component geometries. This meant finding stable parameter windows which would produce material with known properties, developing a controller so that the cell could be left unattended and presenting a business case for SMD. The scientific and technical objectives of the project were:

- Reduction of 60% in the lead-time necessary to produce new parts, through the elimination of tooling and the use of SMD parts as manufacturing prototypes, particularly affecting SMEs working on small batches of parts;
- Reduction in the cost of manufacturing final products by 40%, through the reduction in raw material usage, finish machining and machining products and the elimination of tooling;
- Reduction in the cost of inventory held of 90%, since the only inventory held is wire. Parts are stored as programs and then built to order.

To achieve these goals, RAPOLAC had 3 main research strands:

- Process modelling at micro- and macro- scales;
- Investigation of part microstructure and material properties;
- Process control;

with the exploitation of the results leading to another 2 strands:

- Integration of the process controller
- Development of a business case for SMEs

The main outputs of RAPOLAC were:

- Stable parameter sets for the materials chosen;
- Known material properties for a given parameter window and part geometry;
- A prototype control system integrated with the main SMD cell;
- A cost and environmental comparison of SMD and traditional production processes;
- A business plan for SMD;
- Example parts with different geometries for dissemination purposes;

Section 4 describes the work carried out during RAPOLAC. Section 4.1 gives details of materials and methods used and the assumptions and limitations of the work. The current state of the art in SMD is described in section 4.2 below which also describes improvements to the physical cell developed as part of the RAPOLAC project. Section 4.3 covers the work done to develop parameter windows and section 4.4 describes the resultant material properties. Section 4.5 gives details on the mechanical and weld models used and the control system developed.

4 Technical Work (methodology, approach, achievements)

4.1 Methodology

Research in RAPOLAC was carried out in 5 main technical strands as described above. A Design of Experiments (DoE) approach was used to organise the work and to ensure that the maximum amount of data was gained from each trial. This allowed stable parameter windows to be found and the mechanical and microstructural properties of parts deposited with these parameters were investigated. The consortium investigated methods of monitoring and hence controlling the deposition to allow the cell to be automated. Thermo-metallurgical models were developed which can predict microstructure and stresses and were integrated with the results from the DoE approach to create and SMD calculator which can be used to predict properties from input parameters or to offer parameter options which will produce the required material properties.

Early on in the project, the common aerospace alloy Ti-6Al-4V was chosen as the main focus of the project as SMD is most beneficial for components made from expensive alloys where there is high material waste. Standardised test pieces (walls, cylinders and beads as well as more complicated dissemination pieces) and procedures were defined which would allow the results of different trials to be compared and which would enable partners to obtain the maximum amount of information. Suitable geometries and dimensions were chosen for testing which could be produced from a single SMD bead. Various methods of monitoring the weld were used (thermocouples, pyrometers) to provide information to the controller and to validate the thermo-mechanical models developed.

Figure 1: (top left) heat-treated and part-machined sacrificial wear part (top right) standard features SMD part with cylinder, polygon, flange and boss (bottom left) hybrid part with as-deposited SMD flange and boss deposited onto bar (bottom right) hybrid part after finish machining

The parts developed for dissemination purposes (Figure 1) were used to measure the cost and environmental implications of the process. Due to constraints on part size imposed by the robot reach, deposition times and cost, the dissemination parts are scaled down versions of standardised geometries which has the added advantage of making them more portable. However, comparisons are carried out for full-sized parts.

4.2 SMD and Cell Development

The SMD cell at Sheffield (Figure 2) contains a 6-axis KR16 Kuka robot linked to a 2-axis DKP400 turntable. The robot carries a TIG-welding head which is linked to a wire feeder and Hitachi weld unit (outside the cell). During depositions, the cell can be purged with Argon. Monitoring

RAPOLAC Proprietary Information.

equipment includes a Redman weld vision camera and, a Systech Oxygen monitor, a Triton AMV4000 weld monitor, two Raytek non-contact pyrometers which between them cover a temperature spectrum of 300° - 3,000°, twelve thermo-couples and a thermal camera. Of these, only the Redman camera and the Oxygen monitor were in place before the project start.

Figure 2: SMD Cell at Sheffield

This equipment allows the weld-pool and arc gap to be measured and ensures that the gas purity in the cell is maintained. It also means that the current, voltage and wire speed values can be monitored and recorded and the temperature evolution at any point can be monitored.

A rotary coupling was developed to allow the non-contact pyrometers and the thermocouples to monitor the temperature evolution of a single point on the deposition; this was required as many depositions are carried out through movement in the turntable rather than in the robot arm which is attached to the system which feeds the welding wire to the torch head. A ceramic cylinder is used to insulate the wires from the heat of the weld torch but heat build-up and the fact that it is only possible to rotate the turntable through one axis using this set-up, restricts the parts which can be monitored in this way during the build.

Due to cell and reach constraints, the working envelope is around 1.6 m^3; however this can be increased for production machines as required. To improve robot reach, an extension arm was developed to change the relative location of the robot tool centre point (TCP).

4.3 Parameter Optimisation

The parameters used to control SMD via the Kuka pendant are current, travel speed, step height and wire feed speed. Generally speaking, once the arc-gap is set, current, travel speed and step-height are specified then the wire-feed is used to fine-tune the deposition. The exact settings of these parameters are critical to allow continuous deposition to be maintained; as the parameters vary, the deposited geometry and material properties also vary in terms of part shrinkage, wall thickness, hardness, surface roughness and some metallurgical aspects of Ti-6Al-4V. To commercialise the SMD process, it was necessary to find stable parameter windows which produce known geometries with good material properties.

Brainstorming sessions were held to decide the parameters to be varied and the ranges through which the parameters could be moved without compromising the build. A number of different parts were built, measured, sectioned and analysed and the results were used to narrow down the parameter range. The models produced can predict process outputs with an error of less than 10%. Different possible beads are shown in figure 3.

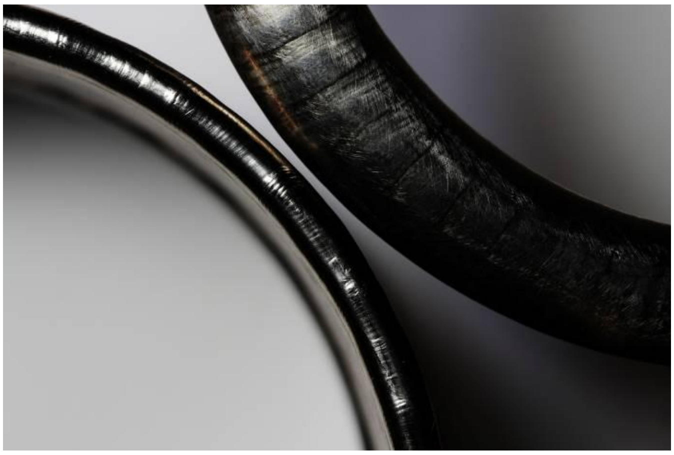


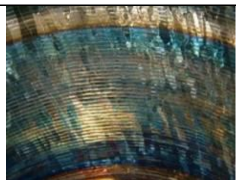
Figure 3: Different wall widths obtained after optimisation

Once parameter windows had been determined for parts made wholly from SMD, a similar exercise was carried out to determine critical parameters which affect deposition onto an already-existing part. Substrate temperature and thermal expansion play an important role in obtaining good results with a minimum of necking and associated stress at the join. Experiments were carried where thermocouples were embedded in a plate and pyrometers measured temperature evolution for autogenous passes and simple builds. The models developed (section 4.5) were used to determine the optimum substrate temperature and FEA analysis can then be carried out to determine the substrate expansion. These parameters can be used when creating the robot program to adjust the path dimensions and the pre-heat time.

4.4 Mechanical and Microstructural Properties

Once best-practise for SMD depositions was established, a number of parts were build which were used to carry out research into the microstructure and mechanical properties of SMD parts and compared to AMS4999A, the standard for additive materials. An initial concern from end-users was that SMD parts are always slightly discoloured. In traditional welding, this indicates O_2 contamination. Analysis of SMD parts (Table 1) shows that the material has the same composition as the wire used and meets the standard for the Grade V Titanium alloy. Parts built with a low current show less discolouration but have lower tensile strength. Additionally, a pressure decay test is carried out before each build to ensure that the cell is airtight and it is kept at a slight positive pressure during the build.

Table 1: Oxygen and Nitrogen Levels in Typical SMD Parts

As-built part:								
	O %wt	N %wt	O %wt	N %wt	O %wt	N %wt	O %wt	N %wt

RAPOLAC Proprietary Information.

Wire Used	0.142	0.003	0.142	0.005	0.145	0.008	0.145	0.008
SMD Build	0.160	0.004	0.150	0.002	0.150	0.004	0.150	0.002
Grade 5 (MAX)	0.200	0.050	0.200	0.050	0.200	0.050	0.200	0.050

Generally, the deposited material is fully dense, but it does contain a few spherical pores (<200µm); these are within the limits allowed by AMS4999A. The material morphology shows a layered structure due to the deposition technique used. This also encourages the growth of large epitaxial, elongated grains which are inclined towards the weld torch. A cross section of the material shows that the final 10mm of the build has a different microstructure where the parallel bands visible throughout the part are absent (Figure 4a). The bulk of the SMD material has a coarse Widmanstätten structure with acicular α phase lamellae in a retained β phase, whereas the final section of the build contains bundles of fine lamellae needles growing perpendicular to the surface (Figures 3b,c).

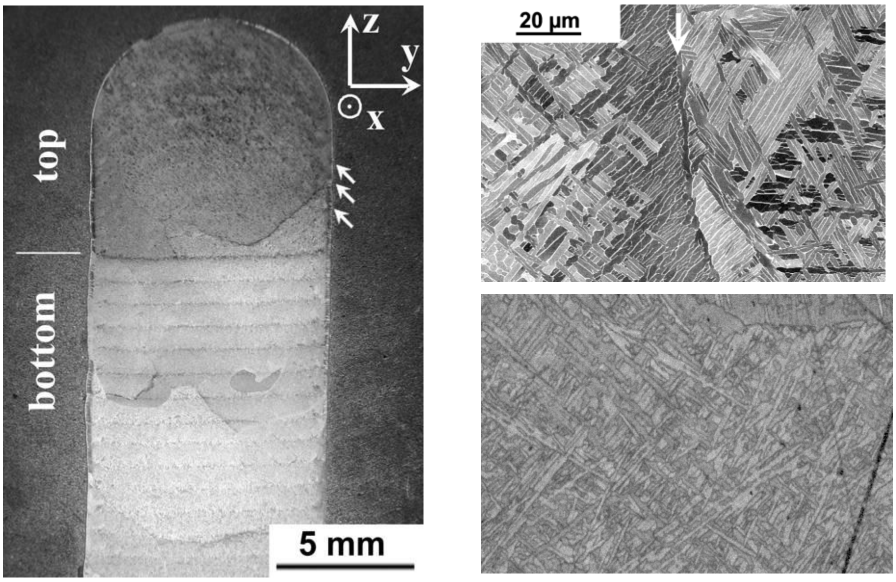


Figure 4: (a) Meso-structure of SMD material; (b) Widmanstätten structure and grain boundary; (c) fine lamellae

SMD parts are anisotropic, with the mechanical properties varying with the orientation of the deposited layers. These are shown in table 2 below:

Table 2: Mechanical properties of Ti-6Al-4V SMD material

	Along the layers	**Perpendicular to the layers**
UTS	1014 MPa	936 MPa
Ductility	6% - 11%	14% - 21%
Young's Modulus	117 GPa	
HCF	770 MPa	

Young's Modulus is similar to low-oxygen Titanium while the High Cycle Fatigue (HCF) is superior to wrought Titanium. The SMD material meets AMS4999A for all criteria except for ductility horizontal to the build direction. They have similar microstructure to components made through laser deposition but SMD has slightly improved surface roughness and ductility.

4.5 Modelling and control

4.5.1 Mechanical and Mechatronic Models

The robotic system used for SMD was modelled to allow system behaviour to be analysed and stiffness and precision to be improved by tuning the robot controller. Different modelling techniques (rigid, super-element and full finite element) were used to create a library of parts for the robot and a master model was created, which picks the most appropriate element type for the analysis. It was found that a mixed model using rigid models for all components except the hand, arm and wrist which used super-elements and the link bar which was a full finite element model, allowed the dynamic behaviour of the system to be investigated whilst reducing computational time. This mechanical model was useful to analyse system behaviour and vibration modes.

Topology optimisation was then used to redesign the extension arm and reduce vibrations caused by low vibration frequencies. This led to reduced spatter during deposition

A mechatronic model was also developed which includes the force controllers for each joint and which was used to calculate the optimum robot control sequence for deposition. When creating parts, it is important that the tool-tip follows the trajectory smoothly. The joint positions created using the mechatronic model eliminate tool-tip oscillations and overshoot and reduce transient errors leading to a fast rise time.

4.5.2 Thermo-mechanical models

Thermal and metallurgical models of the SMD process were developed, based on finite elements limited to the solid domain. The model was solved with hexahedral measurements, tri-linear interpolation of displacements and interpolation of stresses. A double-ellipsoidal heat-source was used to represent the TIG-torch. These models were validated using temperature evolution measurements during depositions and cut-ups of the parts produced. The model can correctly predict the size of the top region of the build with the finer microstructure as microstructural evolution is considered during the build. The sequential heating and cooling cycles are also modelled and this allows the percentage of martensite, grain-boundary α and Widmanstätten microstructure in the part to be estimated. Observations of micrographs of SMD material made using different parameter matched model predictions well.

4.5.3 Control

The consortium also developed a closed-loop welding controller and integrated it with the SMD cell at Sheffield. The controller was based on the parameters described in section 4.3, i.e. current (heat source), wire feed (mass of material), travel speed and step height. For any given combination of current, speed and arc-gap, there is a wire-feed rate which will produce a good weld. A number of different ways of measuring the arc gap were investigated and a visual method (CCD) selected; the voltage can be obtained from the weld-controller. A number of different image processing methods were applied to the CCD output to allow the weld-pool and arc gap size to be measured. The hub of the controller is a PC which connects to the control unit and weld monitoring systems and alters the wire-feed to maintain a constant arc gap using set-points which is calculates. It is also possible for the operator to override the controller if required.

The controller was integrated with the SMD cell and a number of depositions were carried out. It could be seen that parts built using the controller had fewer wire-feed interventions and showed a more even build profile leading to improved surface finish. Operator interventions can clearly be seen in the curves for the manual cylinder (Figure 5) at 2s, 10s and 14s.

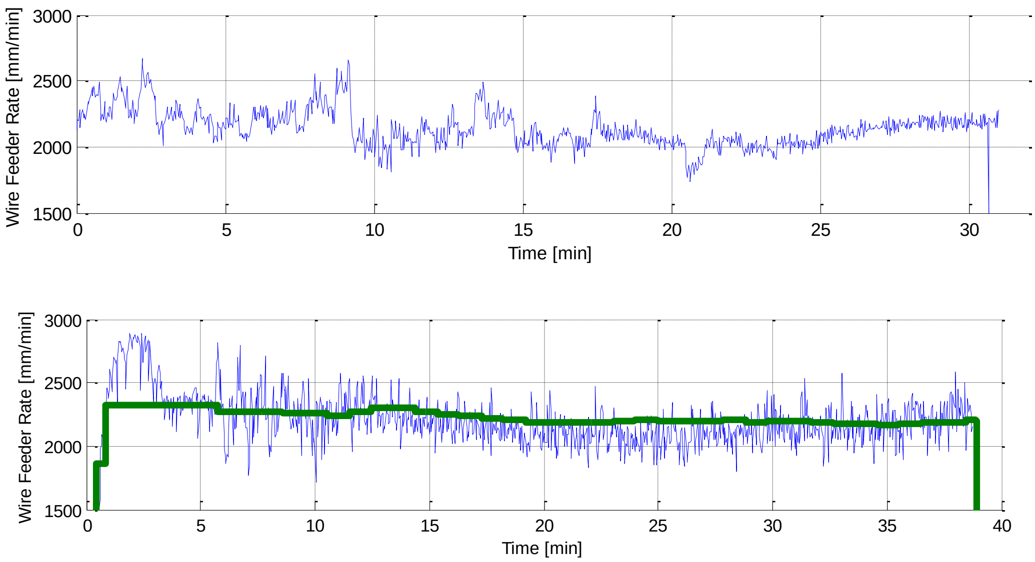


Figure 5: Comparison of wire-feed over time for (top) manual- and (bottom) controlled-build

Parts were then sectioned for analysis; no differences (surface roughness, porosity, and microstructure) were found between the two methods of deposition. A microstructural comparison between manual and automatic depositions is shown in Figure 6.

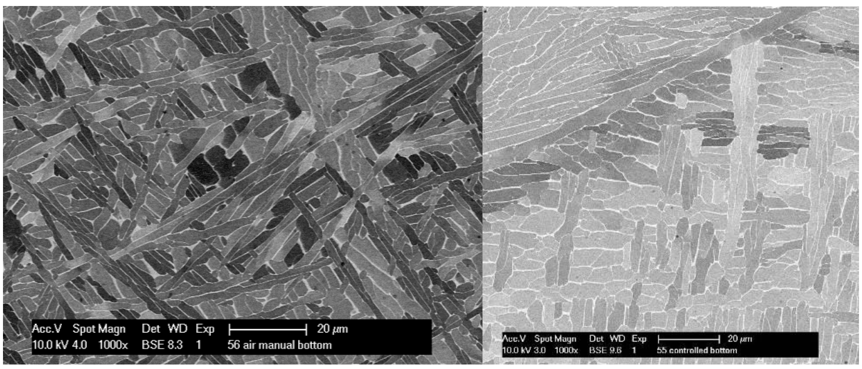


Figure 6: Microstructure of (left) manually- and (right) automatic-control

An operator console was developed and linked to the controller. The console comprises a quadcore computer to run the weld controller, screens showing the output of the cameras and pyrometers and a screen showing data from the Triton weld monitor. The user interface shows arc voltage, wire feed rate and arc gap and shows the number of layers already deposited and the position of the torch in relation to the build. This console is shown in Figure 7.

Figure 7: Operator Console

5 Disseminations and Impact

The benefits of SMD depend on many factors such as material used, part geometry, batch size and current method of manufacture. During RAPOLAC, comparisons were made for low-volume aerospace parts where around 95% of material stock is removed and which require large tooling to produce. Using traditional methods, there is a nine-month lead time to create such parts, but with SMD they can be produced in under a month. This makes SMD ideal for prototyping, and one-off or short production runs.

The consortium carried out life-cycle analysis for SMD parts, taking into account wire production and transportation and waste from finish machining as compared to production of forgings and subsequent machining. The parts used for the calculation were standard-feature engine-casing parts. Although wire production is less environmentally friendly and more expensive than the creation of ingots, because less material is used, overall there is net environmental and cost gain for the SMD component; it required only half the energy to produce and CO_2 and NO_x emissions were reduced by 20% over the whole manufacturing chain. This makes SMD competitive for parts where a large amount of material is removed from the stock, or for small batches which require expensive tooling, such as low-volume parts or spares. SMD can also be used in conjunction with tradition processes to add features to the stock or to add material to out-of-conformance forgings or castings. It is envisaged that the main market for SMD will be in this area.

A website (www.rapolac.eu) for the project was launched in time for the kick-off meeting. The website has been updated on a monthly basis in this period. A RAPOLAC YouTube channel has been set up and RAPOLAC pictures have been posted on the popular photo-sharing site, Flickr, and tagged. Videos have been produced showing the operation of the SMD cell, modelling and robot operation. A longer video was also produced summarising project results. These are available on the website through YouTube and on the RAPOLAC channel. They are also being shown on the Sheffield MANTRA lorry.

MANTRA (The Manufacturing Technology Transporter) is a specially modified HGV packed with the latest machinery and simulators. The truck visits shows, businesses and schools to demonstrate manufacturing and assembly line technology of the future and help inspire young people to take up careers in engineering. As of the project end, 3,600 people had been through the door at 244 companies and 8 trade fairs.

A RAPOLAC board showing results from all the partners was set up at USFD and visitors to the facility have been shown the SMD cell and RAPOLAC exemplar parts. As the project progressed, the board was updated with the latest results. In this way, the project technical aims have been disseminated to world-class aerospace companies; six feasibility studies have been carried out with an aerospace company and further work is pending. A RAPOLAC banner was also produced which is used on MANTRA (Figure 8).

Figure 8: RAPOLAC on the Road

Mid-term and final press releases were put out, leading to a number of articles on RAPOLAC in technical and general publications. Partners have published over 30 papers and generated 6 magazine articles, 4 articles in the local press, and 3 press releases. Two patents have been applied for and partners were nominated for an award in engineering.

6 Summary and further research

The achievements of RAPOLAC can be summarised as follows:

- Improved cell design
- Dedicated data-capture equipment
- Temperature measurement equipment
- Understanding of temperature evolution
- Mechatronic models developed
- Weld models developed
- Automatic control of welding process
- Defined mechanical properties
- Understanding and prediction of microstructure
- Knowledge of welding parameter windows
- Understanding of shrinkage
- Optimisation of pre-heat parameters
- Build recipes for hybrid parts

- Machining characteristics well understood
- Environmental advantages of SMD characterised
- Business case for SMD developed
- Exemplar parts manufactured
- SMD training modules developed
- Increased awareness of SMD

7 List of Publications

- Anca A, Fachinotti V, Escobar-Palafox G and Cardona A, 2010, "*Computational Modelling of Shaped Metal Deposition*", **International Journal for Numerical Methods in Engineering,** in press, 2010**.**
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