
Executive Summary:
By combining a new surface engineering process with state-of-the-art thermal modelling, significant design and performance improvements to heat exchangers for electronic and electrical systems have been made. The designed surfaces that have been created provide an increase in surface area (allowing for smaller size heat exchanger packaging), but also enable ‘designed’ flow over a surface (which enhances its heat transfer potential). These benefits place the HeatSculptor consortium of SMEs in a position to compete against competition from countries with cheaper labour overheads, and gives the potential for charging a price premium for specialised systems, increasing their profitability and generating value in the EU economy.

There is a drive towards miniaturisation of electronic devices as well as requirements for higher power applications. The size of the heat exchangers necessary is the limiting factor for package size. By combining Surfi-Sculpt® (a European surface processing technology) with complex computational fluid dynamics (CFD) modelling, heat exchange surfaces have been customised and optimised. The result show efficient heat exchangers surfaces for the next generation of electronic cooling devices.

Conventional heat exchanger manufacturing processes are extensively developed and only small future efficiency improvements are likely to arise. The HeatSculptor project has utilised and further developed an enabling technology for heat exchangers that creates a thermal resistance of the heat exchange surface that is around 60% lower. Until now, designs have been constrained by production technologies e.g. machining or chemical etching. The new electron beam surface engineering process, Surfi-Sculpt®, has demonstrated the capability to rapidly create complex ‘HeatSculptor’ surface geometries that are not possible with existing techniques.

Project Context and Objectives:
The aim of the project was to develop electron beam enhanced surfaces for the improvement of heat transfer in liquid cooling applications for the electronics sector. The project ‘HeatSculptor’ optimised the performance of heat exchangers by developing a new surface engineering process, electron beam (EB) Surfi-Sculpt®, in conjunction with state-of-the-art thermal modelling. In combination, these offered significant design change opportunities to enable production of heat exchangers with increased efficiency and functionality that were cost competitive for a variety of applications. A new interface software was developed to enable simple operator use and improve the EB production capabilities to achieve higher volume manufacturing.

The main objectives achieved were:

- Design and establishment of processing parameters for the manufacture of HeatSculptor surfaces for prototype products which can take the technique into production.
- Manufacture heat exchangers with a target of improved product performance and greater heat transfer efficiency, of approximately 30% compared to current systems.
• Design novel surface geometries and design data that offer increased design flexibility for the manufacture of future heat transfer components.
• Smaller heat exchanger package sizes for a given performance, allowing lower cost electronic components to be used or for components to perform in more extreme operating environments.
• Take a step closer to reducing the environmental impact by eliminating the harsh chemicals and waste material which arise from current manufacturing technologies such as chemical photo-etching and electro discharge texturing.
• Plan to increase sales and production rates, through a fast and scalable manufacturing route.

Project Results:

Literature review
An extensive investigation of required features and efficiency goals of the end-users was performed. This work included both physical and geometrical considerations of the features and initial design scenarios were put forward according to heat convection theory and rules. Only Newtonian fluids and air are being investigated within HeatSculptor. The viable pressure gradient across the surface and flow rates required for liquid heat exchanger applications have been defined. Necessary physics and geometrical considerations have been detailed with the particular focus on the microelectronics device cooling applications. As a result of the review two preliminary design scenarios have been proposed from the hydraulics point of view (no thermodynamics considered).

Computer Fluid Dynamics (CFD) Analysis

On the CFD side, the forcing terms have been implemented and tested. A Python script has been written and completed to generate the two proposed geometries: Inclined cones and curved ridges. The script generates also the corresponding meshes and prepares the input files to the flow solver.

An analysis chain was integrated in the optimisation cycle, provided by the toolbox Minamo. The central part of the optimisation cycle was built around a genetic algorithm (GA). The GA provided successive groups (generations) of parameter sets (individuals). Since a large number of individuals were evaluated in each generation, the high fidelity analysis loop was not directly used for their evaluation, but replaced by a surrogate model. At the end of each GA optimisation cycle, high potential candidates were identified. At the same time, the optimisation tool also identified individuals in the regions of high uncertainty of the surrogate model. Both types of individuals were then analysed by the high fidelity tools.

The newly obtained individual data points were then used to enrich or train the surrogate model. Before the optimisation loop however, a design of experiment approach was used to identify an adequate group of individuals for an initial assessment of the design space. These individuals were analysed using the CFD loop, and then used to initialise the surrogate model. The surrogate model was then constantly enriched during the design cycles, as described above. The development of this chain obviously implies the chaining and integrating of tools. The automatised high-fidelity analysis loop essentially chained the mesh generation tool Gmsh and the CFD code Argo DG. Subsequently, this analysis chain was linked to the Minamo tools to provide the optimisation loop. The chaining was performed using python and Gmsh scripts. The main work concerned the definition and implementation of the analysis loop. The first two steps, geometry and mesh generation, required the development of adequate parameterisations for the different geometries as well as for the mesh specifications.

In order to simplify the convergence of the numerical simulations to a steady state, the fluid thermodynamic properties were assumed in this study. The fluid used was an ethylene glycol and water mixture. The thermodynamic properties were assumed for the fluid to give a Prandtl number of unity.

The inclined cones and the curved ridge features were shown not to be very effective with respect to more common features found in the literature. A number of iterations were carried out to optimise the geometries to enhance the heat transfer
characteristics. Results show that the inclined cone shape is the most effective when inversed.

Design and production of electron beam enhanced surfaces
The Surfi-Sculpt process utilises a computer controlled intense electron beam to melt and move the material in a controlled manner in the surface of the substrate material to produce a range of 3D features that cannot be produced with the conventional manufacturing techniques.

Surfi-Sculpt pattern design software was used by TWI in conjunction with their experience in pattern development to produce surfaces. A range of surfaces were produced on flat plate aluminium in order for the effects of different feature types to be assessed and measured. Six of these surfaces came from designs requested by the SMEs within the consortium with the final two were suggested and produced by TWI. Extensive trials have been completed on one aluminium alloy (Al6082-T6) in 6mm thick plate.

The designs are described as:

- Design 1: Pin-like features.
- Design 2: Staggered ridge features.
- Design 3: Long ridge features.
- Design 4: Fin-like features.
- Design 5: Inclined cone features.
- Design 6: Curved ridge features.
- Design 7: Pins in a curved array.
- Design 8: Square based pin features.

Development of the test samples
Surfi-Sculpt trials were carried out to ensure that patterns were developed such that the required feature height was achieved without perforating the base material. The movement of the electron beam to produce the features has been designed to minimise the depth of cavities. TWI has also investigated post-milling the surfaces to remove the channel left on Design 6 between each row of features. Results were encouraging but the process proved to be cumbersome, so emphases were put on improving the automation of the system.

Optimisation of the electron beam surface treatment
Variable heights of Surfi-Sculpt features were produced ranging from under 2mm, up to 6.1mm. The density was varied from less than 2.7 features/cm² up to 3.9 features/cm², with the aim to vary it to allow for the surface to be optimised for improved heat transfer.

TWI showed that the EN AW 6101B T7 grade of aluminium (Al6101b) material produced much better surfaces than the originally investigated Al6082 and was more suitable for processing by Surfi-Sculpt given its lower silicon content. Other participants also confirmed that Al6101b had better thermal conductivity which would also benefit the performance of the ultimate product. A batch of samples was manufactured in the following optimised designs:

- Design 5: Inclined cone features.
- Design 6: Curved ridge features.

The processing equipment was considered and it was determined that, a lower power electron beam (EB) machine (60kV, 4kW), as opposed to 150kV, 6kW, could be used to generate the required features. The benefit being a lower capital cost equipment, leading to a lower barrier to uptake.
TWI produced the optimised surfaces on a designed part for initial lab testing with a dummy heat load. This allowed initial assessment of the best designs (Designs 5 and 6) and to validate the CFD.

The CFD modelling showed that there could be significant benefit in inverting Design 5 (inclined cones) to go with/against the flow. These inverse inclined cones were produced ready for testing (modified Design 5).

The equipment requirements to produce an enhanced treatment area of 200mm x 200mm without the need to move the workpiece, using solely the deflection of the beam, was investigated. It was based on the novel approach of using cosine-theta coil winding in the deflection coils used to manipulate the movement of the electron beam in the Surfi-Sculpt process. Further processing trials were performed on the 60kV machine to compare the results against a 150kV machine in order to determine if the process would be viable on the lower power, lower cost machine. It was shown that approximately 3mm high features could be achieved for Design 5 using a 60kV EB machine compared to approximately 6mm high Design 5 features on the 150kV EB machine; the 3mm height being viable and appropriate for the heat exchange application.

Automation of the electron beam treatment process
Work was carried out to specify and produce a user interface. A design specification was agreed and a bespoke CAD ADD-ON software in both 32-bit and 64-bit for the CAD software (SolidWorks) was written. It assists with the production allowing the pre-stored program templates to be called upon in SolidWorks and positioned on a component part. The output includes the co-ordinates of the enhanced area which can then be used by the CNC capability on the 60kV EB machine to place the treatment accurately on the part. Any of the eight different designs produced in HeatSculptor are available in the software.

The 60kV EB machine was updated and improvements made to the control system. A bespoke jig to HeatSculptor’s requirements was also manufactured to enable the production of parts

A prototype liquid cold plate was designed and manufactured from aluminium Al6101b with the modified Design 5 enhanced treatment area as predicted by the CFD to give the best results.

Production of the test parts
The CFD analysis showing that inversed inclined cones (modified Design 5) performed better than the inclined cones (Design 5) therefore the part to be processed by Surfi-Sculpt was changed from the thin cover plate to the thicker (16mm) base plate.

Five blank prototype liquid cold plates manufactured from Al6101b, with nominal dimensions of 20mm x 76mm x 170mm, were designed and machined. The enhanced Surfi-Sculpt area was designed to be 95mm x 32mm. Three of those were processed with the modified Design 5 enhanced treatment surface ready for testing.

Validation
Experimental work was carried out using a water-glycol mixture as the working fluid. Test data was compared with the current liquid cold plate design that Cooltech produces for the market. The test sample was prepared as a liquid cold plate, where temperature and pressure were recorded at the inlet and the outlet. Thermo-hydraulic testing was performed on a variety of heights of features of the modified Design 5 liquid cold plate, using a 50:50% mix of de-ionised water and ethylene glycol. The results showed that 2.2mm high inverse inclined cones achieved a heat transfer coefficient of between approximately 10,000 and 12,000W.m-2.K-1. This heat transfer coefficient was higher than the 8000 W.m-2.K-1 set as a project objective. It was also shown that the modified Design 5 prototype’s thermal resistance was approximately 60% lower compared to an existing CT product, ‘Turbolator’.

Testing has been performed using a heat load that was composed of a resistive electronic device and the modified Design 5 (2.2mm high features) enhanced treatment. The results showed that thanks to the improvement of the cooling capacity provided using the Surfi-Sculpt technology we have obtained the possibility to drive the example component with more power; allowing use at the maximum power rating without any damage. The air cooling testing did not show a significant
improvement under natural air cooling and only minor improvement under forced air cooling; it should be noted that the surfaces were designed for liquid cooling primarily.

It was shown that a more economical (in terms of capital cost) 60kV, 4kW EB machine could produce the required features for HeatSculptor compared to a 150kV, 6kW EB machine. This has made the HeatSculptor process much more commercially attractive due to the lower upfront costs of the 60kV machine.

Conclusion
The project conclusions included:

• The Surfi-Sculpt process is efficient to produce a range of surface modifications for heat transfer improvement that cannot be achieved with conventional techniques.
• A reduction of the thermal resistance by 60% compared to the products that the SMEs supply into market has been achieved.
• The technique is efficient and cost effective for improvement of thermal performance in liquid cooling application for the electronics industry.

Future work
Consortium has been impressed with findings that this project has produced and is looking for opportunities to integrate the electron beam treatment process in their product lines.

Potential Impact:
Design guidelines for initial heat exchange surfaces have been developed with commercial and technical benefits over existing surface production techniques. A new modelling optimisation strategy using genetic algorithms has been written.

Eight novel Surfi-Sculpt surfaces for heat exchange applications were generated, trialled and initial optimisation was carried out on Al6082-T6 aluminium alloy. Analysis of these surfaces has been completed. Two were selected by the SMEs to carry forward within the project.

HeatSculptor has manufactured and performed validation testing of a prototype novel Surfi-Sculpt liquid coldplate using an electron beam machine integrated with the HeatSculptor developed improved control/interface sub-system. The results have shown significant improvement in the performance of this novel heat exchanger.

The most significant results from a socio-economic perspective as a result of the development of a 20% to 30% increase in cooling rates are:

• Production cost; much less energy is utilised by the process used to make heat exchangers
• Maintenance cost; failures as a result of overheating can be minimised.
• Waste, recycling and environmental issues; reduced as a result of significantly longer electronic component life expectancies.
• Environmental issues; large reduction of waste as a result of longer life.

A presentation entitled ‘Numerical analysis of the heat transfer performance of two novel types of pin-fin and plate-fin heat sinks’ was given at the ASME-ATI-UIT 2015 Conference on Thermal Energy Systems: Production, Storage, Utilization and the Environment in May 2015. As a result of the presentation we were invited to submit a paper entitled ‘Thermal and hydrodynamic efficiency investigation of two new types of pin- and plate- fins for efficient heat sinks’ to the Journal of Applied Thermal Engineering. The abstract was accepted on 9 September 2015. We have also had an abstract entitled ‘Optimisation of electron beam generated inclined conical pin fins for efficient heat sinks ‘accepted into the 14th International Conference on
List of Websites:
The project website has been kept up to date with information exchanged by the partners, in the partner only area. A project video was produced summarising the developments in the project and its results. The video is available on the HeatSculptor website at [www.heatsculptor.eu/video](http://www.heatsculptor.eu/video) or on YouTube at [http://tinyurl.com/heatsculptorvid](http://tinyurl.com/heatsculptorvid).

**Related information**

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