SolarSoft Final Report (Oct 2011 – Sept 2013)

Publishable Summary

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Project acronym: SOLARSOFT

Project acronym: Development of Ultra Soft Copper Conductors for Crystalline Silicon Solar Photovoltaic Applications

Funding Scheme: Research for the benefit of SMEs

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The Partners:

STRIP TINNING SOLARWIRE	**STRIP TINNING LTD (SME)** Project Coordinator, Manufacturer of PV Ribbon. Birmingham, United Kingdom
FUHR	**FUHR GMBH & CO KG (SME)** Manufacturer of Copper Rolling Mills Horn Bad Meinberg, Germany
AML	**AZIENDA METALLI LAMINATI SPA (SME)** Manufacturer of Copper Products. Quargnento, Italy
UNIVERSITY OF BIRMINGHAM	**THE UNIVERSITY OF BIRMINGHAM (RTD Performer)** Metallurgical Research and Modelling Expertise Birmingham, United Kingdom
Instytut Odlewnictwa Foundry Research Institute	**INSTYTUT ODLEWNICTWA (RTD Performer)** Krakow, Poland
Plasmait	**PLASMA IT GMBH (RTD Performer)** Builder of Plasma Annealing Machines Lebring, Austria
SOLARUS Unlocking Solar Energy	**SOLARUS SUNPOWER SWEDEN A (SME)** Manufacturer of Solar Collectors Älvkarleby ,Sweden

Executive summary.

It is very important that we move more and more towards renewable energy sources to reduce dependency on the dwindling stocks of fossil fuels both from environmental and economic standpoints. Direct sunlight is an excellent source of renewable energy and the use of photovoltaic (PV) cells to produce electricity directly from the sunlight is one very effective way to harness the energy from the sun.

However, PV tends not to be competitive against fossil fuels at today's oil prices and the current state of the art for PV, due to the relatively high capital costs for manufacturing the PV collectors. The cost of the silicon wafers used in the manufacture of PV cells is a significant factor in the high cost of manufacturing PV collectors.

In this project we have made a contribution to reducing the cost of PV cells by making it possible to reduce the thickness of the silicon wafers used in PV cells. The reason that this thickness cannot be reduced further at this time is that the silicon wafers crack dues to stresses introduces in the process of soldering the copper conductors (PV ribbon) on to the silicon wafer to make the PC cells.

The SolarSoft project has produced a softer PV ribbon which means that lower temperatures can be used in this soldering process which results in reduced stress on the silicon wafer. As a result it should be possible for the PV industry to take the next step of further reducing the thickness of the silicon wafers once a supply of the SolarSoft PV ribbon is in place.

The softer PV ribbon has been achieved in the SolarSoft project on a consistent basis using a prototype plasma annealing machine which was researched, designed and built in the SolarSoft project. This project is part funding from the European Commission's Seventh Framework Programme of research and innovation funding, specifically the research for the benefit of SMEs programme.

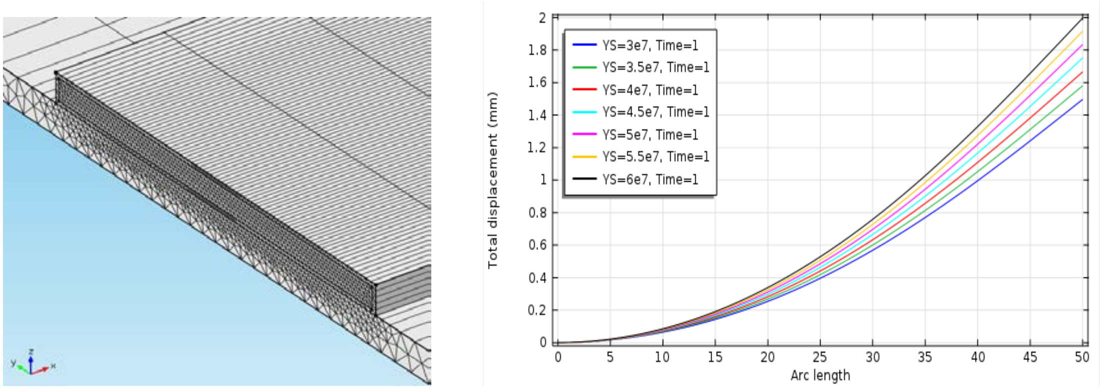
Summary description of the project context and main objectives.

In the relentless drive for cost-competitive Renewable Energies, progressive reductions in the cost of manufacture of Crystalline Silicon Photovoltaic cells are being compromised by damage caused to the cells by the thermal strain at the interface between the increasingly thinner silicon wafers used and the soldered copper conductor. The SolarSoft project aims to solve this problem by modifications to plasma annealing and chemical-free and flux-free tinning manufacturing process to develop a novel tinned copper conductor (PV ribbon) possessing a reproducible and low proof stress, thus enabling a substantial contribution to be made towards Solar PV Technology achieving cost parity with conventional power generation and improve the environmental impact of PV ribbon production process.

Main S & T results/foregrounds.

The overall aim of the project was to design tinned copper ribbon that would have a low yield stress in order that they could be soldered to significantly thinner silicon wafers than that used currently (120 c.f. 160 – 180 μm thick) without increasing the risk of distortion / fracture of the silicon wafer. The use of thinner Si wafers would reduce the unit cost of polycrystalline-Si solar cells and so help PV-derived electricity approach grid parity.

The first work package (WP1) developed a finite element (FE)-based model to simulate the generation of thermal stresses during cooling, Figure 4.1c.1(a). The model used solder and silicon properties determined experimentally at UoB using samples supplied by STL and so representative of their product / customers' products. The yield stress of the copper and geometry, e.g. silicon thickness, number of tinned copper ribbons per cell, solder thickness, were variable inputs.



(a) (b)

Figure 4.1c.1. (a) Meshing of solder-coated copper ribbon (upper) and silicon wafer (lower) for simulation of thermal stresses during post-soldering cooling and (b) predicted wafer distortion as a function of copper yield stress.

Using the failure strain of silicon a target of 50 MPa 0.2 % proof stress for the final tinned copper was established. This model has been disseminated through the Materials for Renewable Energy conference. Industrial soldering trials were scheduled (in WP5) but could not be carried out and so only laboratory-based soldering trials have been undertaken. These have not quantitatively established the accuracy of the simulations, but the qualitative trends are established such that 50 MPa was the target strength for the rest of the project.

The rest of WP1 was taken up with modelling and initial verification of a further FE simulation of the mechanical and electrical properties of porous copper. Pores were introduced into solid copper either by mechanical methods or via a liquid route (GASAR copper). The model simulated regular (mechanical) and more random (GASAR) pore arrays with the latter coming from serial sectioning or tomography images. Simulation of porous copper tensile and electrical resistivity properties and pore stability under compression (to simulate drawing of the porous copper to ribbon) were carried out and verified against small samples (WP1, mechanical and GASAR) and larger samples (WP2, mechanical) tested at UoB. The simulations were validated quantitatively for all tests, e.g. Figure 4.1c.2 and Table 4.1c.1. These simulations have been published in the MRS Journal.

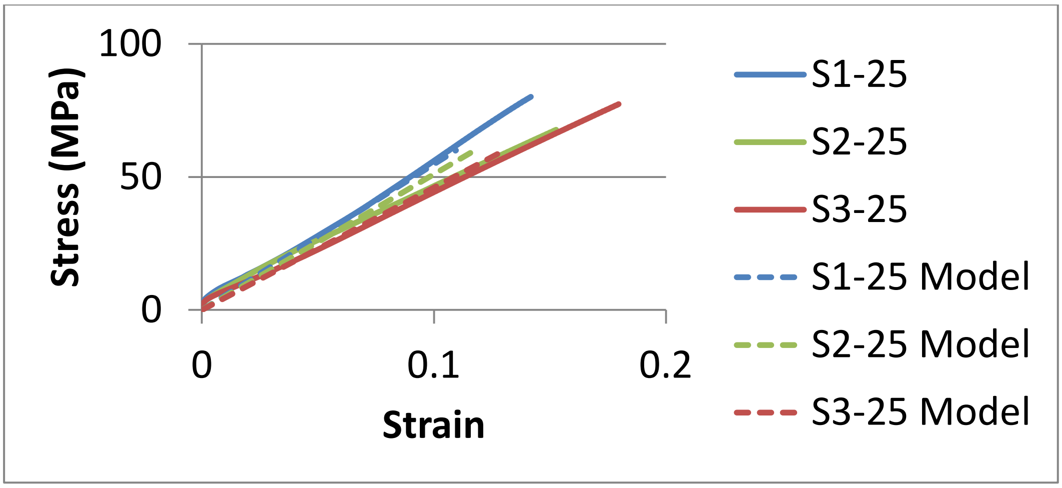


Figure 4.1c.2. Validation of FE-based model for stability of mechanically-induced pores under compression.

Table 4.1c.1. Validation of mechanical and electrical properties for GASAR porous copper.

	0.2 % Proof Stress (MPa)	**Resistivity (Ω.m)**
GASAR sample	24 - 26	$4.9 \times 10^{-7} – 5.0 \times 10^{-8}$
Model	20	2.7×10^{-8}

The production rate for mechanically-induced porous copper was too low for commercial consideration, whilst GASAR copper samples could not be supplied (WP3). In addition, the use of hydrogen in forming the pores in the GASAR process resulting in significant increases in the resistivity of the copper metal (Table 4.1c.1) making this process unfeasible. The characterisation of tinned copper samples in WP1 had identified that a grain size of around 70 μm for non-porous copper would give the required low proof stress and so the project looked at rapid annealing processes that could achieve such large grain sizes at a commercially viable rate (120 m/min.).

STL source copper as wire and this is then rolled and drawn down to the final ribbon dimensions prior to annealing and tinning. The cold work stored in the copper after the rolling / drawing stages drives recrystallisation and grain growth during the annealing process. As part of WP3 the stored energy of copper rolled and drawn by STL has been characterised by differential scanning calorimetry (DSC). The stored energy determined was supplemented with recrystallisation and grain growth rates determined from furnace trials, Figure 4.1c.3. Optical microscopy, scanning electron microscopy and electron back scattered diffraction characterisation have also given the recrystallisation, grain growth and intermetallic formation through all stages of the STL process. STL currently employ an early plasma annealing chamber and this has also been characterised in terms of temperature, time profiles. The combination of the validated modelling and the characteristics of the STL line indicated that the required grain size could be achieved using a plasma annealer. Other heating sources do not give fast enough heating rates that would retain the stored energy until the peak annealing temperature is reached and so drive the recrystallisation and, more importantly, grain growth sufficiently rapidly for the required production rates.

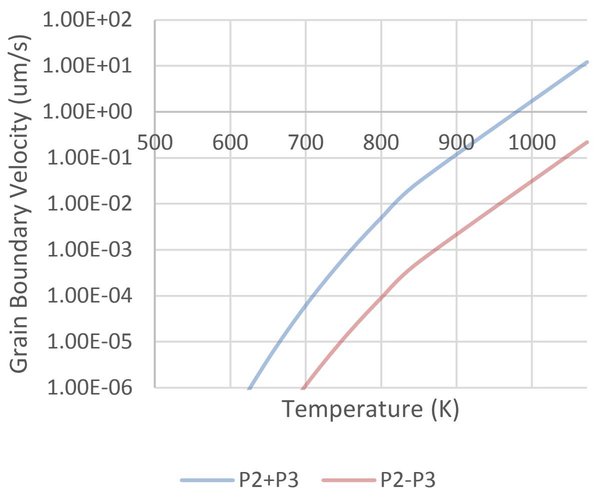


Figure 4.1c.3. Predicted grain boundary velocities for STL cold rolled and drawn copper, validated by heat treatment trials.

The target annealing treatments were then defined as a hold time of 3 – 4 sat 850 – 900 °C. These required the development of a new prototype plasma annealer as the current STL equipment was too short to hold the ribbon at temperature for more than 1 s at the desired speeds. Using a lower speed compromised production rates, but, more importantly, led to temperature control issues, so that the ribbon either broke or showed excessive scatter in properties.

Scientifically and technically, WPs 1 – 3 generated a model for strain generation during soldering of tinned copper to silicon; a validated through-process model for cold deformation and annealing of copper; and a model for the effects of plasma annealing on copper grain size that is quantitative enough to define process variables.

The new, prototype plasma annealing line was designed and fabricated during WP4. The key features that were addressed in this prototype were:

- The addition of a dwell zone after the annealing chamber to achieve the longer times at temperature for sufficient grain growth.
- Incorporation of improved seals to the plasma annealer chamber and dwell zone so that temperature control is improved, whilst temperature loss in the dwell zone is low enough

that extra heating is not required to maintain the ribbon at the target temperature for up to 4 s.

- Processing of the ribbon horizontally to improve temperature control.
- Improved temperature control through upgraded control software.
- Improved ribbon pay-off and take-up equipment along with supports to minimise the risk of ribbon work hardening before and after annealing. Pre-annealing is needed to control the driving force and so extent of grain growth, post-annealing is needed to maintain the low proof stress of the copper.
- Improved ribbon transport systems to reduce tensile stresses in the ribbon so that the risk of fracture is reduced improving production rates.

Analysis of the initial product from the prototype whilst still at Plasmait indicated that the annealed material had a 0.2 % proof stress of < 50 MPa, but that increased to > 60 MPa on tinning and spooling. This was partly associated with excessive intermetallic formation due to high metal entry temperatures and use of impure tinning alloy (established by tensile testing and microscopy studies at UoB). The mechanical deformation during spooling accounted for the rest of the strength increase. Tighter control on tin bath composition and copper entry temperature at STL removed hardening with larger spools and take-up systems being used to reduce that source of hardening.

The final scientific task was to determine the algorithm linking annealer power and metal speed with annealing time and temperature, which was established and validated using the plasma annealers at STL. This algorithm has been formulated as software for use at STL based on four inputs, listed below and shown in Figure 4.1c.4.

1. The initial product – The user is able to select the draw ratio used on the received wire, the final rolled dimensions and the solder system/dimensions that will be added during tinning. These parameter will cover the range of possible inserted products into the new plasma annealing line.
2. Target properties – Previous work packages have looked at the influence of line speed and power on the proof stress of the copper. However in this case, it is proof stress that is needed and the speed and power are controllable variables. Assuming that the ribbon is produced at a set speed. Then the power for this combination can be predicted (further details on how this is predicted will be described later in the report).
3. Power value – States the predicted power value need to obtain the properties from (2).
4. Error – This value states the range in proof stresses that could be expected due to normal variance. This value is associated with the maximum error seen for a particular ribbon/solder system. Through usage this error will become more refined at predicting the error for a particular system and speed/power settings.

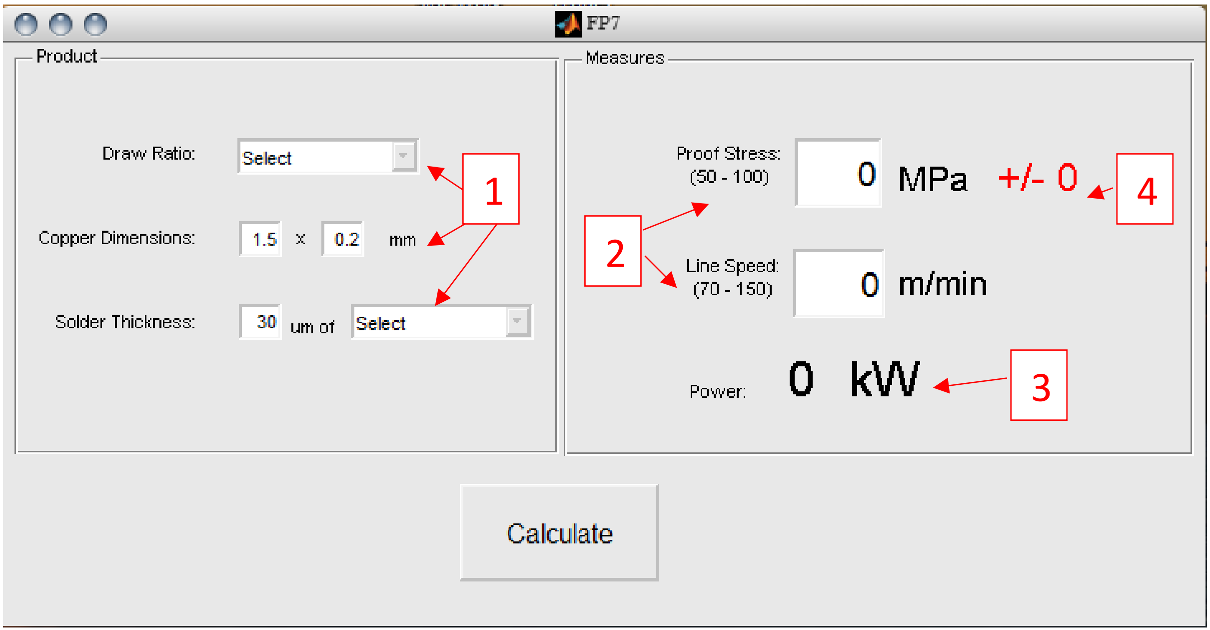


Figure 4.1c.4. Screenshot of the interface for the annealer control software. The boxed red numbers represent different areas of the model that will be explained further.

Potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and the exploitation of results.

NEXT STEPS:

After the end of the SolarSoft project, further validation testing is continuing on getting the prototype operating conditions improved further so that it can achieve market demands for 50Mpa PV strips on a more consistent basis.

COMMERCIAL IMPACT:

Partner 1 Strip Tinning Limited's MD and SolarSoft project coordinator, Richard Barton has recently stated: "

"Whilst automotive remains our largest market, the new prototype line has the potential to really accelerate our expansion into the solar panel sector.

"It is our fantastic team that is driving our business forward and this gives us the confidence to follow JLR to China, hence the opening of a sales office and distribution centre in Shanghai."

SME, Solarsoft project partner 7 R&D Manager, João Gomes has recently stated:

"The highly competitive solar market has driven the price of PV cells down by reducing the amount of silicon used in the manufacturing of the cells. As a result, PV cells breakage rates during manufacturing go up. Cell breakage during the process of soldering the cells strings of the Solarus PVT collector is today a critical issue for Solarus, like for most PV manufacturing companies.

"Apart for the cell breakage, the soldering process (when the cell is connected to the coated copper busbar) is also vital for the lifetime of the PV or PVT module.

"By using softer PV ribbon, as the SolarSoft ribbon, the cell breakage rate can be reduced significantly which is expected to improve the profitability."

SOCIOECONOMIC IMPACT:

As a direct result of the results of the SolarSoft project we now have the expertise and equipment in place which with further development work will strengthen our position with existing customers and open up access to additional customers due to the increasing demand for softer PV ribbon. This will have the following socioeconomic outcomes:

1. **Improved competitiveness**. This gives us the ability to access customers currently being supplied by Companies outside Europe which supply soft PV ribbon using a different technology which is a more expensive process than the one we have developed, giving us a competitive advantage to access these customers.

2. **Employment protection**. Of the 39 jobs in StripTinning, 10 are related to the production of ribbon. **These 10 jobs will be made secure** due to the requirements of existing customers to source softer copper than we can produce with the original technology and equipment.

3. **Employment generation – 2014-2015**: Strip Tinning are in negotiations with two customers which are at an advanced stage an which will mean that we will need to increase output significantly over the next two years from the current 200 tonnes per year to about 500 tonnes by 2015 and this should lead to the generation of an **additional 7 jobs** over the period 2014-2015.

4. **Further Employment generation – 2016-2017.** Strip tinning has opened an office in Shanghai this year and from this platform they expect to add new customers and they project that the

additional output of 300 tonnes of PV ribbon required to service this market should lead to **another additional 7 jobs** at their plant in the UK during 2016-2017

5. **Indirect Employment:** The extra direct employment expected to be generated between now and 2017 is 14 jobs by 2017 and this should also generate an **additional 70 indirect jobs** in the Birmingham area of the UK.

DISSEMINATION:

Progress of the project and communication results to the SMEs has been achieved through the participation of the SMEs in project tasks and at the various technical and management meetings of the consortium.

A practical tool to assist in achieving optimum operating conditions in the form of an executable software program has been supplied from partner 4 UoB to partner 1 STl (Deliverable 6.2) to allow plasma annealer power settings and ribbon speeds to be selected for a range of target properties based on degree of cold deformation (shape of ribbon).

Dissemination to the general public including SMEs outside the consortium has been achieved using various means including

- SolarSoft web-site (http://www.solarsoft.org),
- SolarSoft Facebook page (https://www.facebook.com/solarsoftpv)
- SolarSoft also features strongly on the Strip Tinning Facebook page (https://www.facebook.com/pages/Strip-Tinning-Limited/308110685999573).

We have also prepared a press release it has been published by targeted relevant media such as

- BBC News
- The Birmingham Press
- BDaily
- Manufacturing Advisory Service
- Solar Power Portal

Events:

Strip Tinning had a stand at the SNEC PV POWER EXPO 2013 – (The 7th International Photovoltaic Power Generation Conference & Exhibition) in Shanghai with a major focus on the SolarSoft project in May 2013 heralding the opening of the Strip Tinning sales office and distribution centre in Shanghai in August 2013. This Shanghai office is being used to service the Chinese PV market, where they already have a number of customers. Simon Wong, a director of Strip Tinning, has moved from Birmingham to Shanghai to manage the Chinese market for Strip Tinning.

Richard Barton, MD of Strip Tinning has recently stated: “The new prototype line has the potential to really accelerate our expansion into the solar panel sector”.

Scientific publications include:

- Peer reviewed publication: “Modelling the effects of pore arrays on the electrical and mechanical properties of copper” by Dr Carl Slater and Martin Strangwood (Journal of Materials Research, Vol. 28, No. 17, Sep 14, 2013, PP 2539-2544).
- Abstract and slides of proceedings entitled “The influence of copper yield strength on the warpage of silicon wafers for photovoltaic applications” which was presented by Dr Carl Slater of partner 4 (UoB) to the International Congress on Materials and Renewable Energy (MRE 2013) held in Athens in July 2013.

Public website address

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The Prototype Plasma Annealing Line installed at Strip Tinning