Annual Report for the International Energy Agency

Of the Implementing Agreement for a Programme of Research and Development

on

Advance Materials for Transportation Applications

Calendar Year 2013

AMT Executive Committee

May 1, 2014

INTRODUCTION

The International Energy Agency (IEA) is an autonomous agency established in 1974. The IEA carries out a comprehensive programme of energy co-operation among 28 advanced economies, each of which is obliged to hold oil stocks equivalent to 90 days of its net imports. The aims of the IEA are to:

- Secure member countries' access to reliable and ample supplies of all forms of energy; in particular, through maintaining effective emergency response capabilities in case of oil supply disruptions.
- Promote sustainable energy policies that spur economic growth and environmental protection in a global context – particularly in terms of reducing greenhouse-gas emissions that contribute to climate change.
- Improve transparency of international markets through collection and analysis of energy data.
- Support global collaboration on energy technology to secure future energy supplies and mitigate their environmental impact, including through improved energy efficiency and development and deployment of low-carbon technologies.
- Find solutions to global energy challenges through engagement and dialogue with non-member countries, industry, international organisations and other stakeholders.

To attain these goals, increased co-operation between industries, businesses and government energy technology research is indispensable. The public and private sectors must work together, share burdens and resources, while at the same time multiplying results and outcomes.

The multilateral technology initiatives (Implementing Agreements) supported by the IEA are a flexible and effective framework for IEA member and non-member countries, businesses, industries, international organisations and non-government organisations to research breakthrough technologies, to fill existing research gaps, to build pilot plants, to carry out deployment or demonstration programmes – in short to encourage technology-related activities that support energy security, economic growth and environmental protection. More than 6,000 specialists carry out a vast body of research through these various initiatives. To date, more than 1,000 projects have been completed. There are currently 41 Implementing Agreements (IA) working in the areas of:

- Cross-Cutting Activities (information exchange, modelling, technology transfer)
- End-Use (buildings, electricity, industry, transport)
- Fossil Fuels (greenhouse-gas mitigation, supply, transformation)
- Fusion Power (international experiments)
- Renewable Energies and Hydrogen (technologies and deployment)

The IAs are at the core of a network of senior experts consisting of the Committee on Energy Research and Technology (CERT), four working parties and two experts' groups. For further information on the IEA, the CERT and the IAs, please consult www.iea.org/techagr.

The scope of the Implementing Agreement for a Programme of Research and Development on Advance Materials for Transportation Applications (AMT IA) is to conduct research on critical materials technologies for the development of fuel efficient, environmentally friendly cars and trucks for transportation applications. The (AMT IA) functions within a framework created by the International Energy Agency (IEA). The views, findings, and publications of the (AMT IA) do not necessarily represent the views or policies of the IEA or of all of its individual member countries. For more information about the MMT IA please consult www.iea-ia-amt.org.

CHAIR'S REPORT

AMT 2013 highlights: AMT Exco conducted a comprehensive review of its technical activities and their impact on transportation technologies. With the enactment of the new CAFÉ standards in the US, fuel economy improvement in the internal combustion engines has taken center stage around the world. AMT focuses on fuel economy improvement via friction surfaces, lightweighting, and waste heat recovery. We have concluded the Annexes on carbon fiber standards, and nanomaterials measurement techniques and have established a new Annex on multimaterial joining for optimum light weight vehicle design.

Technical highlights and milestones: We have successfully reached all the milestones planned.

- The friction surface technology (Annex IV) has been demonstrated to be effective in reducing friction and avoiding wear in engine components operating in the "hot zone" using ultra-low viscosity lubricants (ULV). The use of ULV lubricant increases fuel economy of cars from 2% to 4% in vehicle tests by Japanese car companies. Wear concern poses wide spread adoption. The friction surface technology may provide a technology option to enable the use of ULV lubricants.
- Gaps in international standards and test methods for low cost carbon fibers (Annex VI) have been identified. Decision was made to conclude this activity and publish the finding.
- The activity in Annex VII on nanomaterials was concluded and the test methods developed will be released to the technical community.
- Annex VIII on thermoelectric materials has completed the robin studies on high temperature thermoelectric material. Results are being published in open literature. Annex will pursue thermoelectric modules/devices measurements to link material performance to device.
- Annex IX on model-based coatings has completed its first phase activity on testing and modeling of diamond like carbon coating. The results will be presented in the 2015 Wear Conference. The coupling of modeling with testing may lead to better coating design.
- Annex X on multimaterial joining was approved and is being organized among the member countries. US, Canada, and Germany are participating in the planning of this new activity.

Impact and significance

Materials technology is the foundation of fuel efficient technologies. The friction surface technology has demonstrated that it is feasible to harvest fuel economy benefits, thus providing a technology option. The lightweighting of vehicle is inevitable and the joining of multimaterials will accelerate the design of light weight vehicles. The improvement of thermoelectric materials measurement will enable higher efficient material for waste heat recovery in the future.

Executive Committee

The Executive committee met twice in 2013: June 4 in National Physical Lab, London, UK; Dec. 3 in City University of Hong Kong, China. The meetings focused on emerging fuel economy technologies and realign AMT activities to achieve impact. As a result of the deliberation, two Annexes were concluded and one new Annex was launched. A new subtask on shear resistant diamond like carbon (DLC) coating was organized under Annex IV.

MEMBERSHIP

AMT membership in 2013 has 9 countries (US, Canada, UK, Germany, Finland, China, Australia, Korea, and Israel). Korea was formally recognized as a member of AMT in Nov. 2013. A total of 15 Institutes now participates in various technical activities.

Country	Contracting Party
US	Department of Energy
Finland	Tekes (Finnish Funding Agency for Technology and innovation)
Canada	CANMET Materials Lab.
Germany	BAM (Bundesanstalt fuer Materialforschung und -pruefung)
China	Lanzhou Institute of Chemical Physics, Chinese Academy of Science
	Shanghai Institutes of Ceramics, Chinese Academy of Science
Australia	Western Australia University to be transferred to Curtin University
UK	University of Sunderland
Israel	Technion

Invitation letters have been sent to CISRO of Australia and City University of Hong Kong to join AMT as Contracting Parties.

ACTIVITIES

Annex IV Integrated surface technology for friction reduction in engines

Covering activities from Jan 1, 2013 to Dec. 31, 2013.

1. Overview of Scope: Within the moving parts in engines, friction consumes significant mount of energy input. Some friction resistance is essential for the safe operation of the engine but there are parasitic energy losses can be reduced to increase fuel efficiency. The Annex focuses on R&D effort on designing surface textures, DLC, and bonded chemical films on engine surfaces to reduce friction and enhance durability (high durability from very low friction levels).

2. Annex Participants

US: Led by Dr. Stephen Hsu, George Washington University, USA (Chair)
China: Led by Dr. Junyan Zhang, Lanzhou Institute of Chemical physics, CAS, China
Australia: Led by Dr. Gwidon Stachowiak, University of Western Australia, Australia
Israel: Led by Dr. Izhak Etsion, Technion, Israel
Finland: Led by Dr. Kenneth Holmberg, VTT, Finland
UK: Led by Dr. Mark Gee, NPL, UK

Germany: Led by Dr. Carsten Gachot, Saarland University, Germany

3. Activities/accomplishments

Surface textures, properly designed, can induce fluid pressure build up within the dimples to provide a lift force under lubrication conditions, hence reducing friction. When the coefficient of friction (COF) is reduced to below 0.05, a typical hydrodynamic lubrication level, there is no solid-solid contact, hence wear does not exist. This lift force on the contacting surfaces can be generated if the location, size, shape of the dimples are properly designed for the specific kinematic motions/speed/load of the contact. Under this Annex, design guideline has been developed to provide friction reduction for ring-liner, cam-lifter, and bearing contacts.

In 2013, some original equipment manufacturers (OEMs) have reported significant fuel economy increase (2-4%) by using ultra-low viscosity lubricants in vehicle driving tests. While some OEMs have employed material technology to fortify their engines to be more wear resistant, this is not the case for all OEMs. A new ultra-low viscosity lubricant classification of the Society of Automotive Engineers (SAE) has been established in 2013(SAE0W-16). Surface textures may be able to alleviate the wear concern.

A Plint model TE-77 piston ring-cylinder liner wear tester was used for testing the various surface texture designs. Working with a diesel engine original equipment manufacturer (OEM), simulated engine operating conditions were used to develop the test procedure. A friction test procedure was developed to simulate the piston ring stroke cycle friction. Fig. 1a shows the effect of temperature on textured piston ring friction sliding over the cross-hatched production piston liner. The high temperature dramatically increases the friction level that wear may occur.

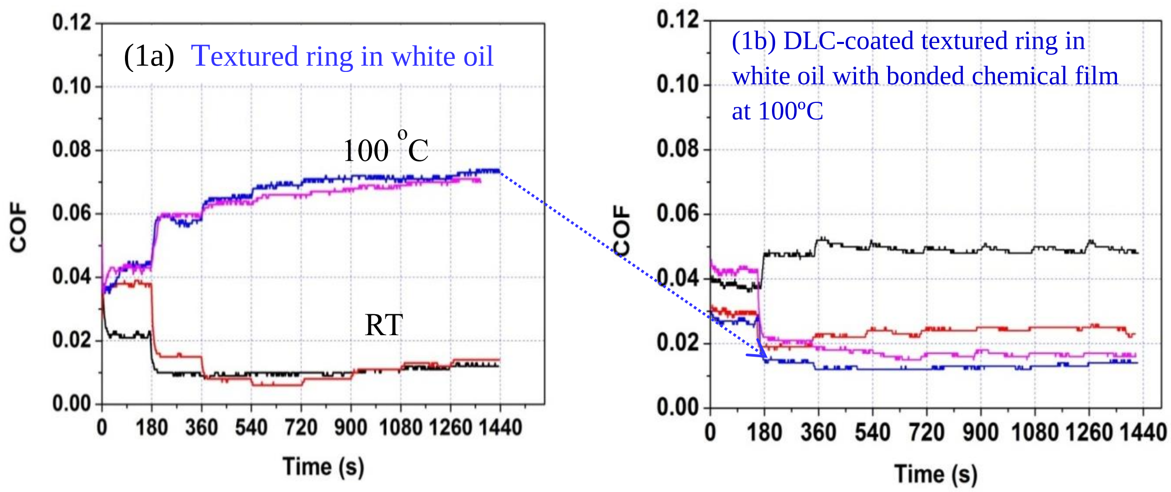

Fig. 1. The effect of temperature on the friction is shown in Fig. 1a; the effect of DLC and the bonded chemical film on top of DLC is shown in Fig. 1b.

When DLC thin film and the DLC-bonded chemical film were deposited on the textured ring surface and tested again, the coefficient of friction dropped from 0.07 to ~ 0.01 at 100°C. At a coefficient of 0.01, the probability of wear approaches zero.

With surface texture design methodology developed, there is a need to address the question of how textured surfaces can be specified for manufacturing consistency. Australia leads the effort on this aspect in the Annex. Using surface fractal mathematics, they were successful in constructing a surface image model. The methods were evaluated on computer images of self-structured surfaces with different roughness directions and patterns. Comparing the calculated image with the actual textured surface, the model was able to preserve all the critical dimensions.

Annex VIII development of thermoelectric materials for waste heat recovery

Covering the period: Jan 1, 2013 to Dec. 31, 2013

1. Overview of Scope: the objective of the Annex is to develop test methods for the evaluation of thermoelectric materials and to develop precision statements for the standardization of these methods.

2. Annex Participants:

USA: Led by Dr. Hsin Wang, ORNL, USA
Canada: Led by Dr. Yu-Chih Tseng, CANMET, Canada
China: Led by Prof. Lidong Chen, Shanghai Institute of Ceramics, CAS, China
Germany: Led by Dr. Jan Konig, Fraunhofer Institute for Phys. Meas, Germany
UK: Led by Dr. Alexandre Cuenat, National Physical Laboratory, UK

$$ZT = \frac{\sigma S^2 T}{\lambda}$$

3. **Activities**

International round robin study with the aim to improve the accuracy and precision of thermoelectric material properties measurement methods has been conducted, using current measurement methods. Results showed significant data scatter on thermal conductivity and other properties associated with the determination of ZT [$ZT=\sigma S^2 T/\lambda$], the figure of merit commonly used to gauge the performance of thermoelectric materials (S is the Seeback Coefficient, λ is the thermal conductivity, σ is the electrical conductivity, and T is the temperature). Round robin number 2 was subsequently launched to tighten the test procedure.

The third round-robin study (RR3) on high temperature performance consists of 11 laboratories using n-type half-heusler material was started in 2012. The temperature range of RR3 is 20-500ºC covering the automotive exhaust temperatures. As of December 2013, RR3 was completed. Figure 2 shows the specific heat results, which has been the source of variations previously, it shows much improvement.

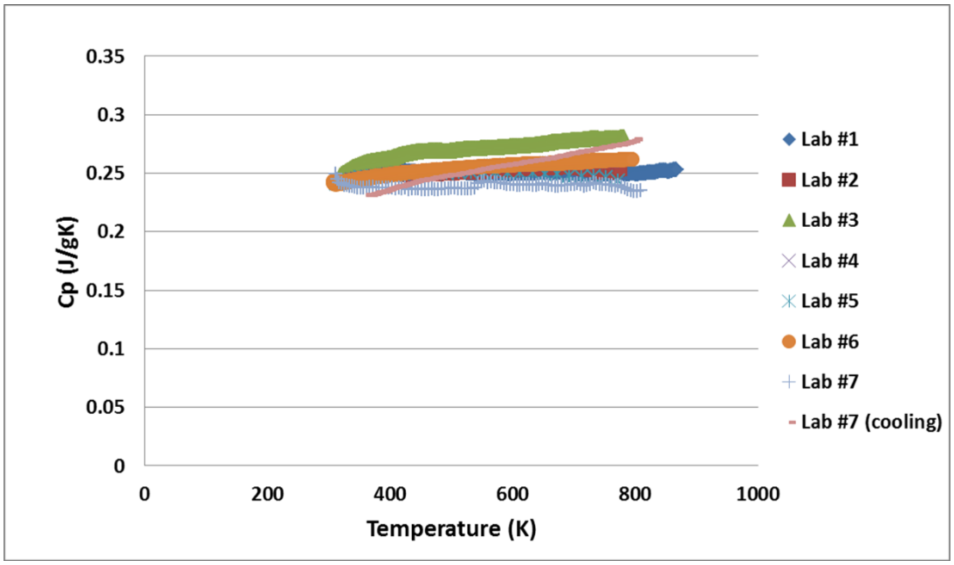

Figure 2. Results of specific heat from RR3

Figure 3 is the Seebeck coefficient results of the round-robin tests. In Seebeck coefficient results, we observed a clear difference in laboratories using 4-point measurements vs. 2-point measurements. The 4-point measurements gave consistently higher Seebeck values while the 2-point measurements gave lower values. This effect was speculated in the literature but it was the first time to be shown in a round-robin study.

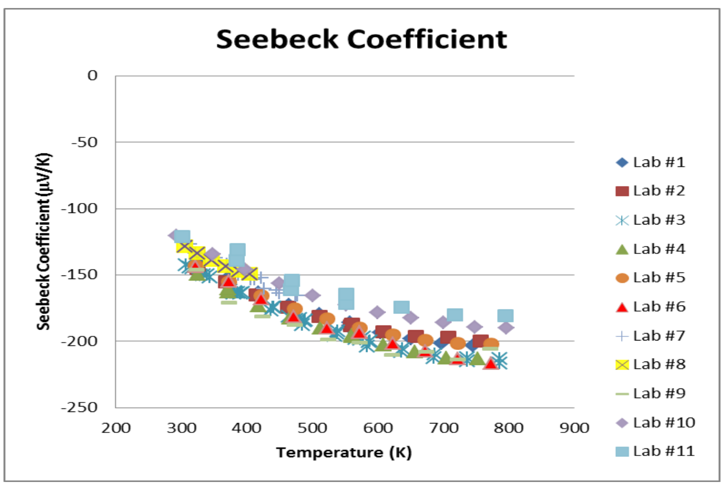

Figure 3. Results of Seebeck coefficient from Round Robin 3

The round robin study of thermoelectric materials is the first of its kind. The study reveals fundamental measurement problems in the laboratories around the world, leading to reporting of many “high efficiency” thermoelectric materials. The Annex now plans to standardize the test procedure through the ISO, paving the way for accelerating the discovery of effective materials.

Annex IX Model based design of tribological coating systems
Covering the period: Jan 1, 2013 to Dec. 31, 2013

1. Overview of Scope: the objective is to integrate modeling and coating testing to guide the development of next generation of advanced coatings for energy efficiency and durability in engines.

2. Annex Participants

Finland:	Led by Dr. Kenneth Holmberg, VTT, Finland (Chair)
Australia:	Led by Dr. Gwidon Stachowiak, University of Western Australia, Australia
US:	Led by Dr. Stephen Hsu, George Washington University, USA
Israel:	Led by Dr. Izhak Etsion, Technion, Israel
China:	Led by Dr. Junyan Zhang, State Key Lab of Solid Lubrication, Lanzhou, China
UK:	Led by Dr. Mark Gee, National Physical Laboratory, UK
Germany:	Led by Dr. Carsten Gachot, Saarland University, Germany
Hong Kong:	Led by Dr. Lawrence Li, City University of Hong Kong, Hong Kong

3. Activities
For the past year, DLC coated samples have been produced and distributed to participants for characterization and testing. The results of the characterization measurements provide the in-put parametric values into the model. Six different surfaces are studied. They are uncoated and DLC coated rough (Ra = 0.2 – 0.4 μm), average (Ra = 0.03 – 0.05 μm) and smooth (Ra = 0.004 – 0.008 μm) surfaces. The coating is a magnetron sputtered PVD diamond-like carbon (a-C) amorphous coating. The variation in roughness has been shown in the literature to have a profound effect on friction and wear.

The roughness was measured by Curtin University in Australia, VTT in Finland, Saarland University in Germany, and the NPL in UK, the techniques used include conventional stylus measurement, dual white light interferometry analysis and fractal measurements. Each measurement method has specific scale significance. To model the wear process, the model needs detail information on surface material structure, the topography, and the detailed wear process and mechanism. A unique real-time pin-on-disc tester at NPL was used to visualise the wear initiation and propagation processes. The wear was observed to initiate from the surface behind the sliding contact as shown by a video camera (4 images/revolution). The penetration depth of the ball into the disk was measured by a depth sensor, and any electrostatic charge generated by the wearing interface was measured by an electrostatic probe. The coefficient of friction was recorded using the lateral and vertical loads, as shown in Fig. 4. As anticipated, the rough surfaces show higher friction and wear.

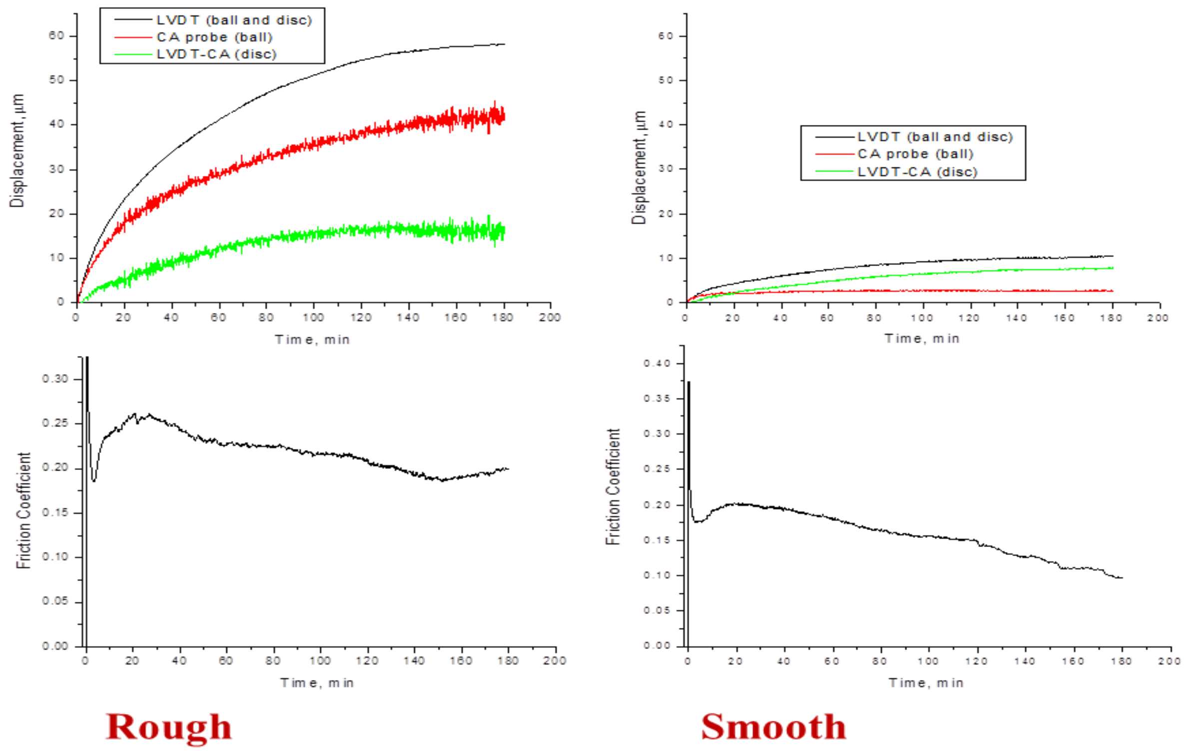

Fig. 4. Real-time pin-on-disk contact analysis of a rough and a smooth DLC coated surface carried out by National Physical Laboratory, UK.

The data collected in Fig. 4 will be compared to modeling study to understand the physics and the contact mechanics of the DLC coating. The goal is to gain fundamental insights into the structures of the coating and how it influence the friction and wear performance. This would provide a powerful tool to guide the next development of coatings. The technical analysis is ongoing and the result will be reported in the next AMT annual report.

Annex X Multi-Material Vehicle Lightweight Structures, Materials Joining Technology

Covering the period: Jan 1, 2013 – Dec 31, 2013

1. Overview of scope

This Annex was approved by the IEA AMT Executive Committee meeting in London, UK on June 4 2013. The objective of this Annex is to develop joining methods of various light weight materials to enable the assembly of an optimum light weight vehicle with high energy efficiency

2. Annex Participants

Canada: Led by Dr. James Chen, CANMET Materials, Canada (Chair)
US: Coordinated by Jerry Gibbs, US Department of Energy, USA

3. Activity

2013 is the first year that this Annex begins to operate. Germany has proposed to undertake tasks on NDE of carbon joints. The aim is to explore and share knowledge of the physical, mechanical and corrosion behaviour of a series of multi-material joint structures and to evaluate the performance of various joints against the baseline joining methods. The first activity on multi-material joining method development for specific combinations of steel, aluminum and magnesium was agreed to between the US and Canada. A friction stir spot welding (FSSW) of metal couples of DP600 steel/AA6063 T6 aluminum was launched. These materials are particularly relevant since high strength steels are used for improved passenger safety through enhanced crash energy absorption. The ability to join these high strength steels to aluminum will allow for aluminum structures and panels to be incorporated in the automotive body-in-white and will allow for optimum lightweighting of the overall structure. The use of the friction stir spot welding technique is being explored to determine whether it could be deployed using existing electrical spot welding infrastructure at comparable processing rates.

Initial trials investigated a simple aluminum/aluminum joint to assess the functionality of a specialized friction stir spot welding apparatus that allows for backfill or refill of the tool impression which offers considerable strength and fatigue durability enhancement over traditional systems. The refill FSSW operation is shown in Fig. 5.

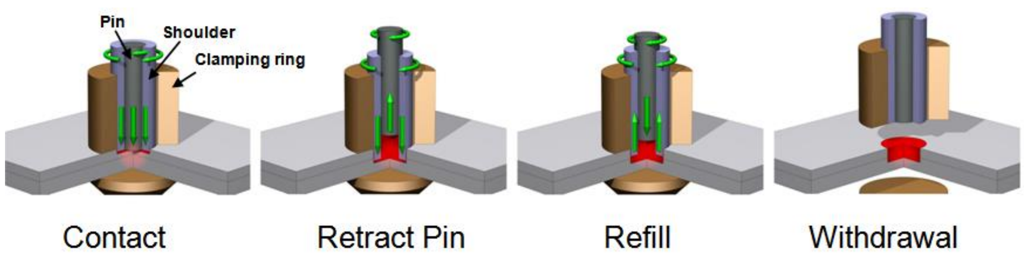

Fig. 5. Schematic diagram of the friction stir spot welding operation

A series of spot welds were prepared using advanced equipment from our academic partners at the University of Waterloo, Waterloo, Ontario, Canada. A sample of welds made using the technique under varying operating conditions of plunge depth and weld time are shown in Fig. 6.

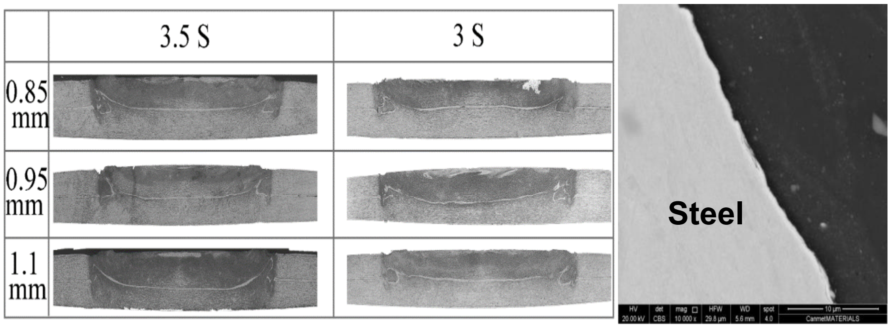

Fig. 6. Friction stir spot welding micrographs showing the weld interface

The weld interface is shown to be extremely discrete as shown in Fig 6. Further analysis indicates that there is no indication of brittle phases formed in the interface. This is particularly important since fusion methods for joining would inevitably produce gross amounts of brittle phases and the joints would be structurally incapable of meeting vehicle design requirements.

While the technical work progresses, the organization of the Annex proceeds with the possible German participation forming some subtasks.

AMT PLAN FOR NEXT YEAR

AMT ExCo committee continues to evaluate existing activities as the transportation sector transforms itself towards more fuel efficient, carbon neutral future. The link between technology options and policy mandates has been increasing. AMT is fully aware of this trend and has been deliberating on ways to increase the potential impact of our technological activities. For the coming year, we plan to implement some changes in the following activities:

1) Create a working group on Technology Assessment and Policy Implications in the AMT ExCo committee to monitor technology changes and examine its implications on materials issues. Provide feedback and reports to the ExCo for consideration of potential changes.

2) With the friction surfaces activity (Annex IV), we plan to create a subtask on advanced lubricants which including the ultra-low viscosity lubricant to meet the fuel economy needs of the automotive industries world-wide. A vertically integrated technology including surface textures, thin films, and advanced lubricants focusing on fuel economy increase will provide effective technology options for OEMs, and decision makers.

3) Annex VIII on thermoelectric materials will conclude the third round robin study on high temperature thermoelectric materials and will publish the results in open literature. The fourth round robin on module and device will be organized.

4) The activity on Annex IX on model based coatings will continue their work trying to link the model insight to performance.

5) For the multimaterials joining, Annex X, additional subtasks will be organized to have more countries participating. Development of other joining methods such as hybrid welding brazing of bi-metallic spot and/or linear joints will be considered and there is interest in exploring polymer composite joints and associated damage development mechanisms in the composite by non-destructive testing techniques.

6) Recruiting new member countries remains as one of the priority items. CSIRO of Australia and City University of Hong Kong had been sent invitation letters and will monitor its progress.

COMMUNICATION

Internal communication

1) Annex IV meeting was held in Lanzhou, China on June 1, 2014 in conjunction with the AMT ExCo meeting

2) Annex IX meeting was held in Turin, Italy Friday 13.9.2013 in conjunction with the World Tribology Congress.

3) December 2013, Annex site visit by Hsin Wang to Shanghai Institute of Ceramics, Chinese Academy of Science and Material Institute, Tsinghua University in Beijing; December 2013, Hsin Wang visited AIST in Tsukuba and attended an AIST workshop on thermoelectric. The possibility of AIST representing Japan to join IEA_AMT was discussed.

External communication

AMT participates in the transport contact group meetings organized by the EUWP Vice Chair and interacts with other transport IAs via email exchanges and circulate newsletters from AMF and HEV to our participants.

We have revamped our website to be more communicative and begin publishing Special Topical Reports as some technical activities mature.

As we have been practicing over the past years, every ExCo meeting has a full day open technical symposium to introduce AMT activities to local technical community.

Publications:

1. H. Wang, W. D. Porter, H. Böttner, J. König, L. Chen, S. Bai, T. Tritt, A. Mayolett, J. Senawiratne, C. Smith, F. Harris, P. Gilbert, J. Sharp, J. Lo, H. Kleinke, L. Kiss, "Transport Properties of Bulk Thermoelectrics – An International Round-Robin Study, Part I: Seebeck Coefficient and Electrical Resistivity," ***Journal of Electronic Materials***, Volume: 42 Issue: **4** Pages: 654-664 April, 2013.

2. H. Wang, W. D. Porter, H. Böttner, J. König, L. Chen, S. Bai, T. Tritt, A. Mayolett, J. Senawiratne, C. Smith, F. Harris, P. Gilbert, J. Sharp, J. Lo, H. Kleinke, L. Kiss, "Transport Properties of Bulk Thermoelectrics – An International Round-Robin Study, Part II: Specific heat, Thermal Diffusivity and Thermal Conductivity," ***Journal of Electronic Materials***, Vol. 42 No. 6, pp1073-1084 May, 2013.

FINANCING

AMT is a task-shared Implementing Agreement. Every participant in each country receives funding from the government agencies, universities, and industries on specific Annex activities or related projects. AMT does not have a common fund.

EXECUTIVE COMMITTEE MEMBERS

Mr. Jerry Gibbs, Department of Energy, Forrestal Building, Washington DC, USA (Chair)

Dr. Stephen Hsu, George Washington University, Washington DC, USA (Vice Chair)

Dr. Alan Wheatley, University of Sunderland, UK (Secretary)

Dr. Juergen Lexow, BAM, Berlin, Germany

Dr. Mark S. Kozdras, CanmetMATERIALS, Hamilton, Ontario, Canada

Dr. Hsin Wang, Oak Ridge National Lab, Oak Ridge Tennessee, USA

Dr. Pasi Viitanen, Tekes, Finland

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Dr. Hee Woong Lee, Korea Electrotechnology Research Institute (KERI)

CONTACT INFORMATION

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