International Round Table on Thermal Plasmas for Industrial Applications

3 - 7 Mars, 2014
Marrakech, Morocco

International Round Table on Thermal Plasmas for Industrial Applications

- A small conference for open discussion of current technological trends and research needs.
- Ample time for presentation followed by discussion of a selected number of topics.
- Each session chairman prepares an introductory talk to position the topics covered by the following talks underlying their respective contribution to the selected theme.
- Limited number of attendees : around 50
- Conference locations that favors a relax atmosphere and discussions

Organising Committee 2007→ 2011
J. Heberlein University of Minnesota, USA
M Boulos University of Sherbrooke, Canada
P Fauchais University of Limoges, France

International Round Table on Thermal Plasmas for Industrial Applications

1st: Sharm el Sheikh, Egypt, January 2007: 80 participants

2nd: Alexandria, Egypt, October 2009: 60 participants

International Round Table on Thermal Plasmas for Industrial Applications

3rd : Muldersdrift, South Africa Oct.-Nov. 2011

- Conférence: 82 participants
- Cours sur les plasmas thermiques (2 jours) à l'université de Pretoria: 59 participants

4ème : Marrakech, Morocco Mars, 2014 : ~ 40 participants

International Round Table on Thermal Plasmas for Industrial Applications

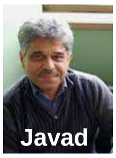
Challenges and opportunities for industrial applications of thermal plasma technology.

3 - 7 Mars, 2014
Palmeraie Hotels & Resorts
Les Jardins de la Palmeraie
Marrakech, Morocco

Organisation

Organising Committee
Javad Mostaghimi, Canada (Chair)

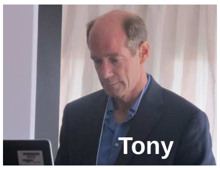
Armelle Vardelle, France
Christian Moreau, Canada
Jaco Van der Walt, Afrique du Sud
Takayuki Watanabe, Japon
Tony Murphy, Australie
Vittorio Colombo, Italie


Javad


Christian


Jaco


Takayuki


Tony

Les 6 sessions de la table ronde

1. Plasma sources

Chairs: Maher Boulos, University of Sherbrooke, Canada
Javad Mosthagimi Toronto University, Canada

2. Plasma coating

Chairs : Armelle Vardelle, Université de Limoges, France
Christian Moreau, Concordia University, Canada

3. Arc welding

Chair: Dr Anthony Murphy, CSIRO Australia

4. Arc cutting

Chair: Prof Vittorio Colombo, Universita di Bologna, Italy

5. Nano-particle synthesis

Chair: Prof Takayuki Watanabe, Kyushu University, Japan

6. Plasma Waste Treatment

Chair: Jaco Van der Walt, NECSA, South Africa

Special PCPP Issue on "Perspectives on Thermal Plasma Research for Industrial Applications": 8 articles

Dedicated to the memory of Prof. Joachim Heberlein.

Issue 3 of volume 35 (May 2015) of Plasma Chemistry and Plasma Processing

- **Thermal Plasma Sources: How Well are They Adopted to Process Needs?** J.Mostaghimi and M. I. Boulos:
- **New Methods to Look at an Old Technology: Innovations to Diagnose Thermal Plasmas** J. Schein, K. Hartz-Behrend, S. Kirner, M. Kühn-Kauffeldt, B. Bachmann and E. Siewert
- **A Perspective on Plasma Spray Technology,** A. Vardelle, C.Moreau, N J. Themelis and C. Chazelas
- **Key Challenges and Opportunities in Suspension and Solution Plasma Spraying** P. Fauchais, M. Vardelle, S. Goutier and A. Vardelle:
- **The Importance of the Arc, Unresolved Questions and Future Directions,** A. B. Murphy: A Perspective on Arc Welding Research

Special PCPP Issue on “Perspectives on Thermal Plasma Research for Industrial Applications”: 8 articles

- ***Perspectives on Research on High Voltage Gas Circuit Breakers,*** *M.Seeger*
- ***Status and Prospects on Nonequilibrium Modeling of High Velocity Plasma Flow in an Arcjet Thruster,*** *H-X Wang, S-R Sun and W-P Sun*
- ***Perspectives on Thermal Plasma Modelling,*** *A.Gleizes*

Session 1 : Plasma Sources

3 conferences

Thermal Plasma Sources : How well are they adapted to Process Needs?
J. Mostaghimi, Toronto University and M.Boulos, Sherbrooke University

- **Capabilities and Developments of re-entry plasma Ground Tests Facilities in EADS-ASTRIUM**
  Dominique Conte, Bruno Van-Ootegem, Astrium Space Transportation
- **Surface Modification of Tool Steel by Carbon Rich Plasma Jet**
  Larry Pershin, Javad Mostaghimi, University of Toronto
  Vesselin Michailov, Nikolay Doynov, Brandeburg Technical University

Thermal Plasma Sources : How well are they adapted to Process Needs?

J. Mostaghimi - M.Boulos

- In a plasma process **the plasma source is the base and most important part** of the process.

  → A wide range of plasma sources to address specific process needs

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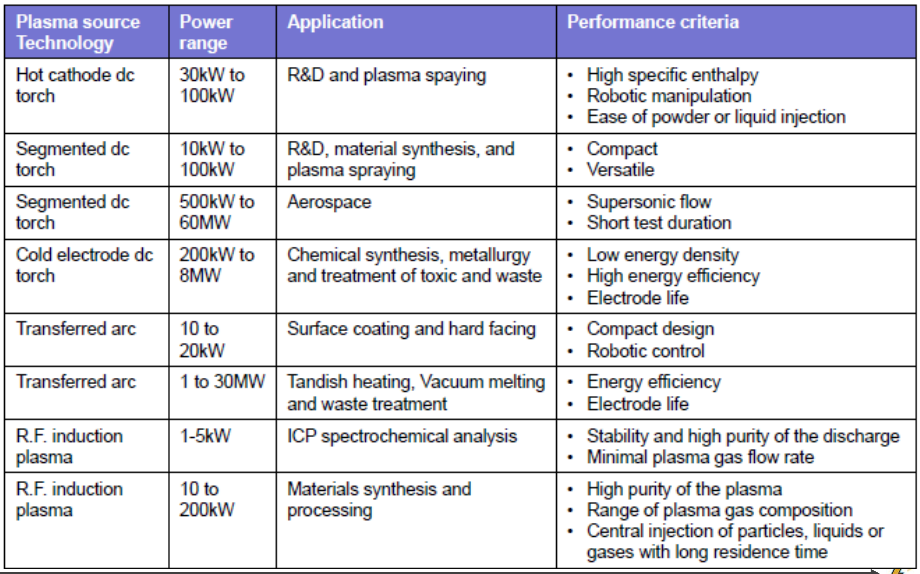
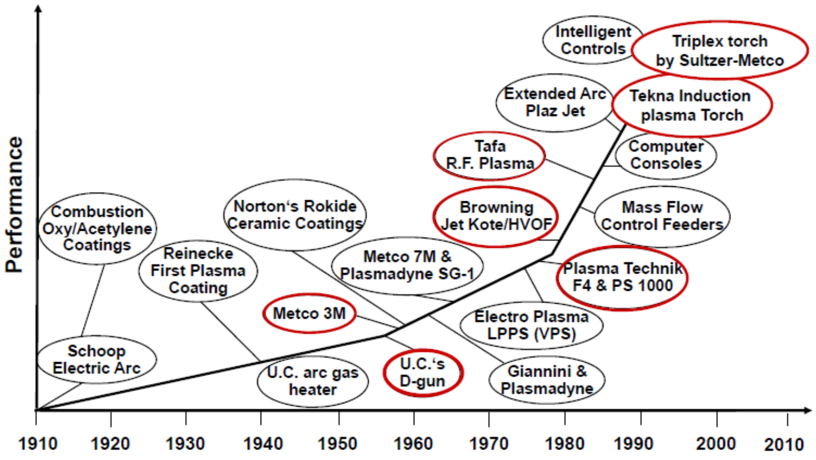
Classification of plasma sources



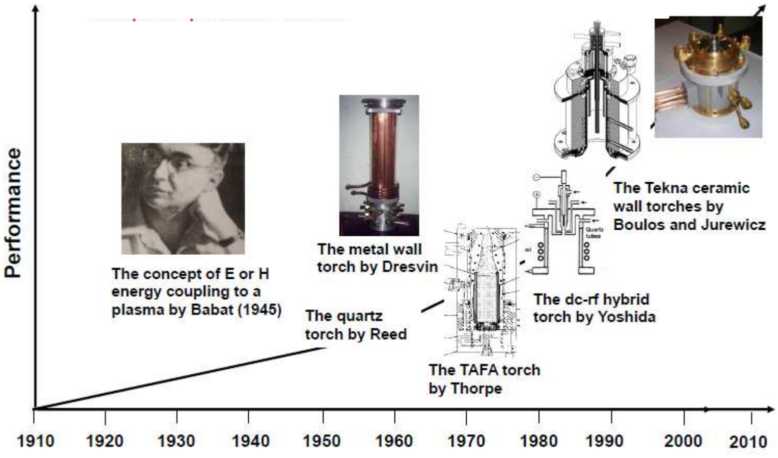
Plasma source Technology	Power range	Application	Performance criteria
Hot cathode dc torch	30kW to 100kW	R&D and plasma spaying	• High specific enthalpy • Robotic manipulation • Ease of powder or liquid injection
Segmented dc torch	10kW to 100kW	R&D, material synthesis, and plasma spraying	• Compact • Versatile
Segmented dc torch	500kW to 60MW	Aerospace	• Supersonic flow • Short test duration
Cold electrode dc torch	200kW to 8MW	Chemical synthesis, metallurgy and treatment of toxic and waste	• Low energy density • High energy efficiency • Electrode life
Transferred arc	10 to 20kW	Surface coating and hard facing	• Compact design • Robotic control
Transferred arc	1 to 30MW	Tandish heating, Vacuum melting and waste treatment	• Energy efficiency • Electrode life
R.F. induction plasma	1-5kW	ICP spectrochemical analysis	• Stability and high purity of the discharge • Minimal plasma gas flow rate
R.F. induction plasma	10 to 200kW	Materials synthesis and processing	• High purity of the plasma • Range of plasma gas composition • Central injection of particles, liquids or gases with long residence time

Milestones in the development of the DC plasma spray torch



Plasma Sources (4/13)

Milestones in the development of the inductively coupled plasma torch



The concept of E or H energy coupling to a plasma by Babat (1945)

The metal wall torch by Dresvin

The quartz torch by Reed

The TAFA torch by Thorpe

The dc-rf hybrid torch by Yoshida

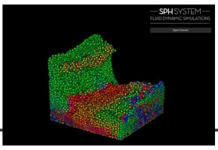
The Tekna ceramic wall torches by Boulos and Jurewicz

Plasma Sources (5/13)

Main concluding remarks of discussion

DC plasmas Torches: We have to pay more attention in developing more robust torches (e.g.; longer electrode life…)

- Development of a detailed mathematical model of arc – electrodes interaction and arc fluctuations
- Better modelling of flow turbulence in particular within the plasma torch
- For fluctuations of the arc root, an idea could be to develop Lagrangian based models, e.g., smoothed-particle hydrodynamics (SPH)?



Plasma Sources (6/13)

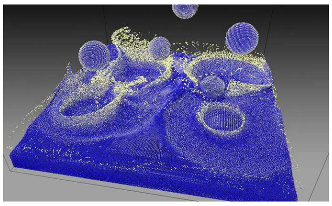
Smoothed-particle hydrodynamics (SPH)

Archives of Computational Methods in Engineering
March 2010, Volume 17, Issue 1, pp 25-76 , G. R. Liu
Smoothed Particle Hydrodynamics (SPH): an Overview and Recent Developments

Mesh-free Lagrangian method where the coordinates move with the fluid.

It works by dividing the fluid into a set of discrete elements, referred to as particles.

These particles have a spatial distance"over which their properties are "smoothed" by a *kernel function*.



The physical quantity of any particle can be obtained by summing the relevant properties of all the particles which lie within the range of the kernel. The contributions of each particle to a property are weighted according to their distance from the particle of interest, and their density.

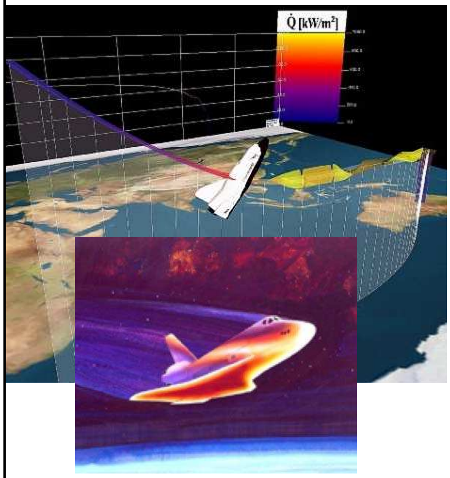
Main concluding remarks of discussion

RF plasma torches

- Scaling up of the technology to the hundreds of kW level
- Novel powder injecting techniques in order to insure the proper dispersion of the powder in the plasma flow and to distribute the thermal loading effect of the plasma on large plasma volume
  - → major improvement of the processing capabilities of the technology
  - → improvement of the process economics

Thermal plasmas for the aerospace industry

J. Mostaghimi - M.Boulos
Dominique Conte, Bruno
Van-Ootegem



Goal

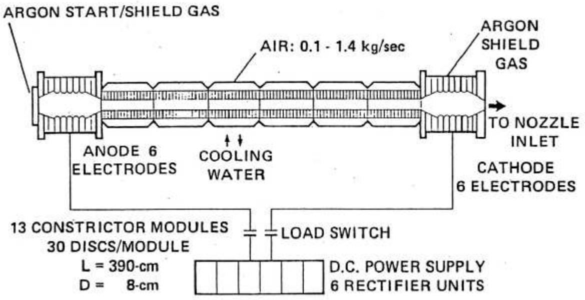
Develop thermal protection systems to protect spacecraft against high temperature and high stress during atmosphere re-entry.

- Qualification of the materials
- Basic Research on materials
- Verification of Numerical codes
- Develop diagnostic tools
- Simulate flight conditions

Wall stabilized high power arc heater (NASA)

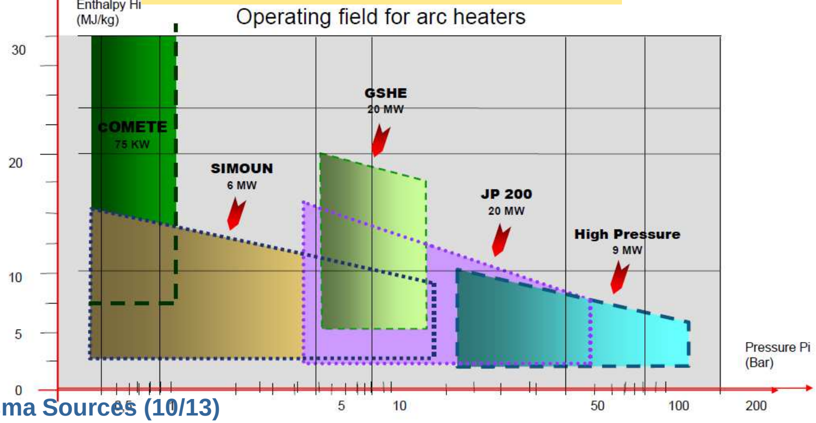
Re-entry Vehicle shield testing

60-MW Rating		
	Pressure	12 atm
	Current	5400 A
	Voltage	11000 V
	Flow Rate	1.4 kg/sec

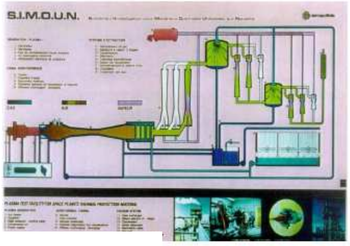


- 40 years of plasma wind tunnel experience
- From material elementary characterization to heat shield qualification
- Unique European Facility - 5 main operation facilities

Plasma Torch Facilities for Atmospheric Reentry Simulation

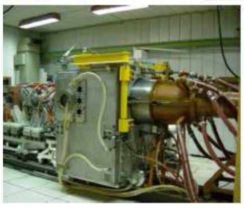


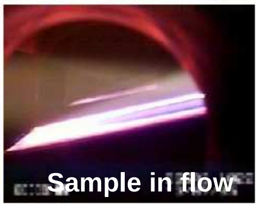
Aerospace Wind Tunnel
6 MW SIMOUN in France




Test chamber

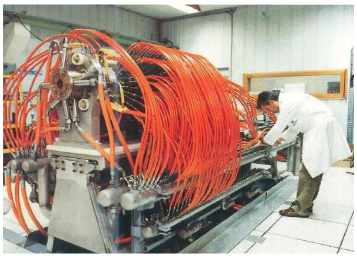
- POWER : 6 MW
- STAGNATION PRESSURE:
  1 TO 18 BAR
- STAGNATION ENTHALPY:
  4 TO 14 MJ/Kg(air)
- GAS : air, N2, CO2
- RUN TIME: a few sec. to 30 min.




Sample in flow

GSHE -10 MW : Segmented DC Torch (1992)

Designed max power : 20 MW
Designed max pressure : 17 BAR
Enthalpy: 5 → 20 MJ/Kg(air)
Plasma gas: Air
Running Time: a few sec. to 1 min.
Torch Length: 1.36-2.2 m
Typical conditions: 3000 A - 6000 V (18 MW)



New challenges for re-entry facilities

- Complex thermo-mechanical testing of materials
- Measurement techniques
    - → Accuracy
    - → Specific conditions
    - → Specific goals
- Facilities designed according to chemical specifications

B. Laub, Workshop on Planetary Probe, Atmospheric Entry Lisbon, October 2003

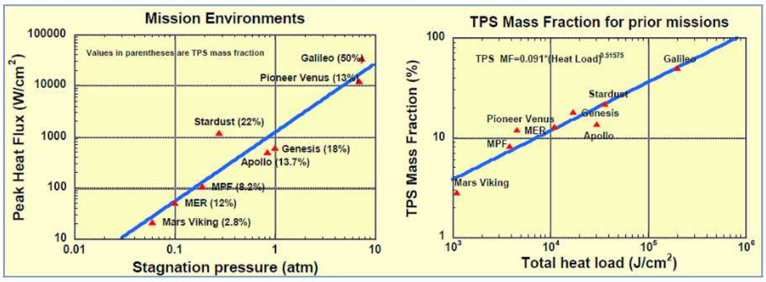


Figure 9 - Fraction massique du bouclier thermique par rapport à la masse totale du véhicule pour quelques missions de rentrée planétaire[20]

Session 2 : Plasma Coatings (1/2)

8 conferences

- **Progresses and Challenges in Plasma Coating Science and Technology,** Armelle Vardelle and Christian Moreau

Plasma Spray Processes

- **Current Knowledge and Challenges in Suspension Spraying,** Pierre Fauchais
- **The Role of Numerical Simulations in the Design and Optimization of Suspension Plasma Spray Process,** Ali Dolatabadi, Concordia University, Ca
- **An Overview of Solution Precursor Plasma Spray,** Eric Jordan
- **Theoretical and Experimental Investigation of Plasma Spraying-PVD Process Conditions,** Georg Mauer

Session 2 : Plasma Coatings (2/2)

Applications

- **Plasma Spray Deposition of Functional Materials: Fundamental Issues and Practical Considerations,** Sanjay Sampath, SUNY University, US
- **LiFePO4 Nanoparticle Synthesis and Coating Deposition by Means of Inductively-Coupled Plasma for Li-ion Battery Applications,** Jocelyn Veilleux, Sherbrooke University
- **Plasma-sprayed Coatings for Automotive Applications,** Andreas Killinger, Stuttgart University

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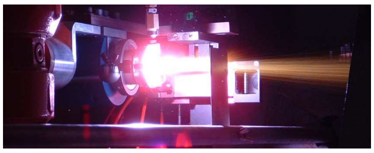
World Market of Plasma Spraying

Estimated global sales of air plasma-sprayed coatings:
in the € 2.3 billion range per year



Thermal spraying: about € 4.6 billion

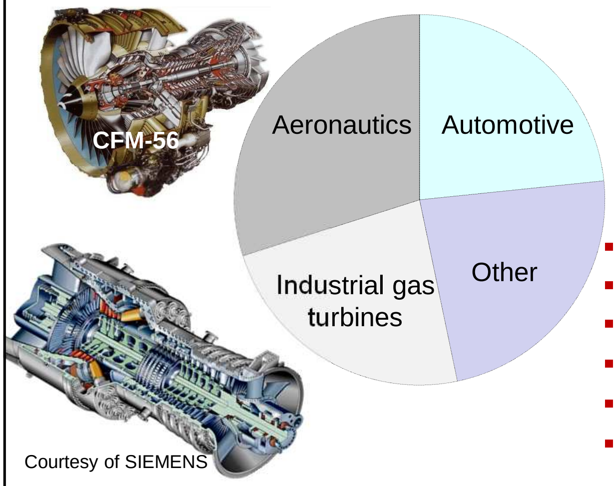
Mitch Dorfman MS&T conference, Oct. 2011

Electroplating: about € 10 billion

Report by Global Industry Analysts, Nov. 2010

Current Key Markets of Plasma Spraying

Courtesy of SAFRAN

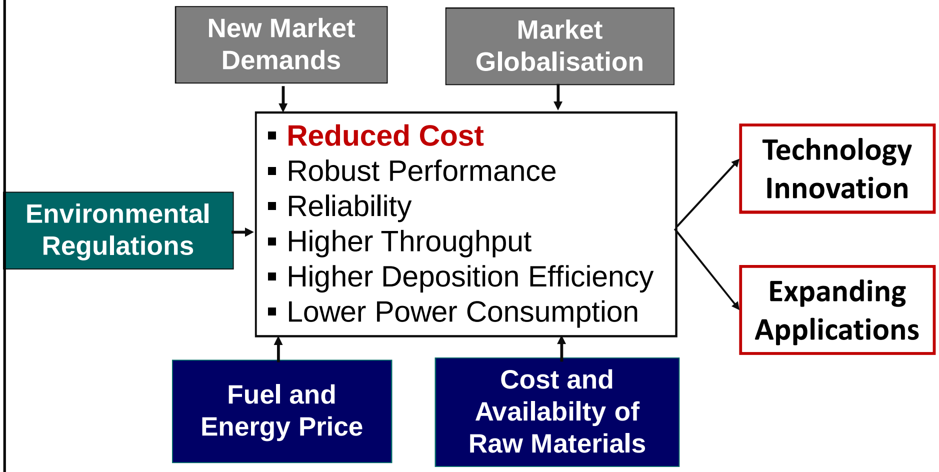


Courtesy of SIEMENS

Courtesy of Oerlikon Metco

- Printing, pulp and paper
- Biomedical
- Mining, metal processing
- Petrochemical
- Electronics
- ….

Selected Trends Driving Plasma Spray Change



New Market Demands

Market Globalisation

Environmental Regulations

- **Reduced Cost**
- Robust Performance
- Reliability
- Higher Throughput
- Higher Deposition Efficiency
- Lower Power Consumption

Fuel and Energy Price

Cost and Availabilty of Raw Materials

Technology Innovation

Expanding Applications

2014 White Paper on Thermal Spray Technology of ASM Thermal Spray Society

Addendum 4: Key Research Challenges in Thermal Spray Science and Technology

18 contributors from universities and industries

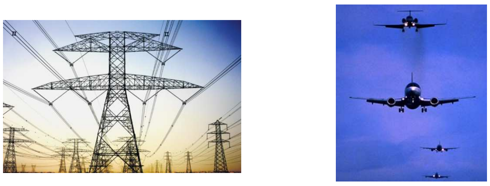
Free download from ASM international website:
English and Chinese versions available
French, German and Spanish under progress

http://www.asminternational.org/documents/17679604/17892455/Addendum+4+final_Challenges.pdf/d46ff5d0-09b0-4154-9127-34aa71a96194

A Key Market and New Challenges

- World electricity consumption: rise by 2.2 % per year till 2040

International Energy Outlook Report 2013 US Energy Information Administration



- Airline passenger traffic: nearly doubled in the next 20 years

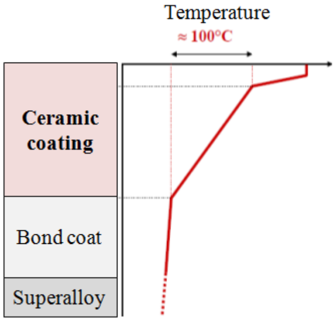
Federal Aviation Administration, Press release 12 March 2012

→A Key market for plasma spraying
Land-based and Aero Gas Turbines

Thermal Barrier Coating

Plasma spraying mostly used to produce **T**hermal **B**arrier **C**oatings (**TBC**) in combustor and turbine sections

- → **Increase in operating temperature**
- → Greater fuel efficiency
- → Lower NOx emissions
- → Higher power and thrust



Current standard for plasma-sprayed **topcoat**:
Porous or dense vertically cracked
Yttria **S**tabilized **Z**irconia (7YSZ) (1200≤°C)

Competitive technology for advanced gas turbines:
Electron beam Physical Vapor Deposition (EB-PVD):
Columnar microstructure from vapor phase

Land-based and Aero Gas Turbines

Main new challenges

1. **Increased firing temperature and service life of components**
2. **Fuel flexibility**: syngas, heavy fuel, natural gas, …
3. **Processing of larger and more complex parts**
4. **Global shortage of “rare” Materials:** Y, Yd, Helium gas, ...

Land-based and Aero Gas Turbines

Addressing the challenges

- **Improved and new plasma torches**
  e.g. increase of deposition efficiency (→80%)
  to reduce the use of strategic materials

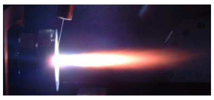
- **New materials and/or architecture**

→ new deposition processes?

Emerging Plasma Spray Processes

- **Suspension and Solution Precursor Plasma Spray**

Liquid Feedstock



- **Very Low Pressure Plasma Spray: < 1000 Pa**

Mostly Powder Feedstock

→ Finely- and even nano-structured coatings
→ Various microstructures tailored to meet in-service requirements
e.g. columnar microstructure
→ Possibility of thinner coatings ~ 5-100 µm

- Alternative to EB-PVD coatings
- Alternative to thin film technologies : PVD, CVD
- Alternative to electroplated coatings

One-order higher deposition rate

Emerging Plasma Spray Processes

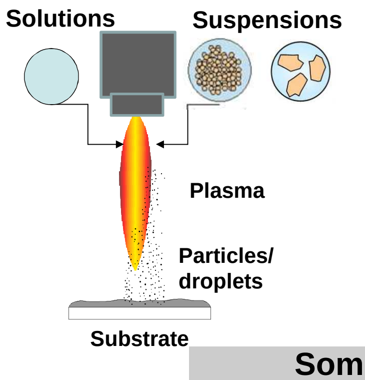
Very active fields of research
involving academia and equipment manufacturers

However : Technologies not mature enough to meet industrial standards

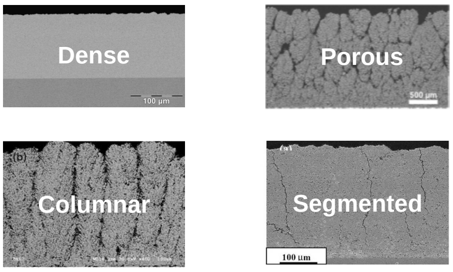
→Need broad **understanding of process** to improve:

- Deposition Efficiency
- Reliability
- Robustness
- Ease to use
- **Deposition Cost**

Suspension and Solution Plasma Spray

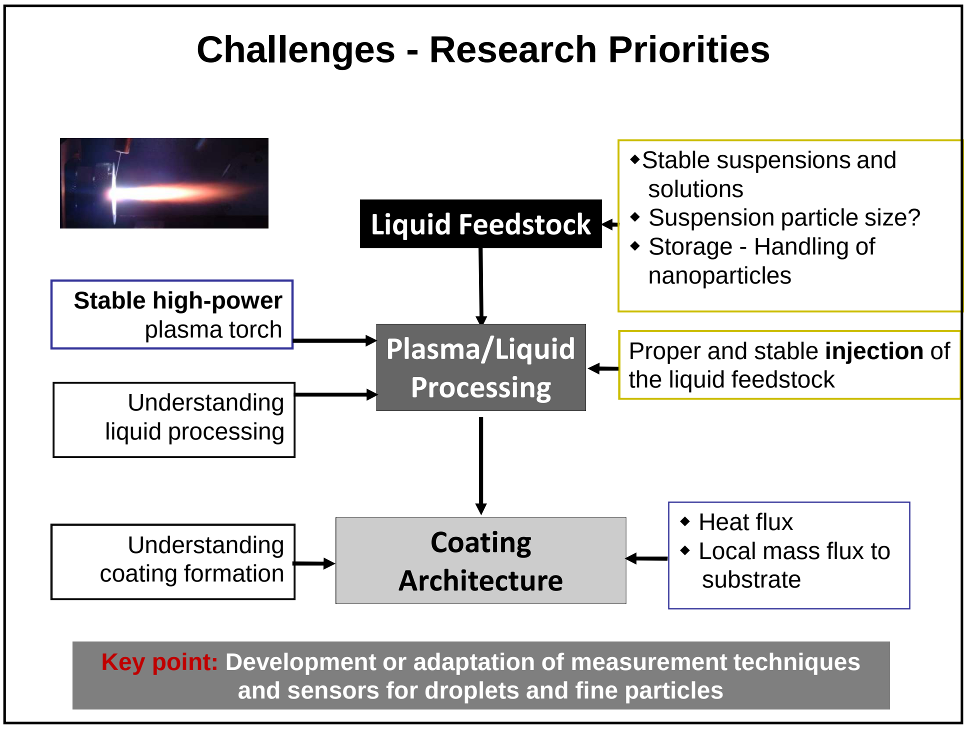


Microstructures



Some potential applications

- Thermal barrier coatings for aerospace and gas turbines
- Fuel cells and electrocatalysis
- Photocatalytic materials
- Anti-microbial coatings and biomaterials



Challenges - Research Priorities

Liquid Feedstock

- Stable suspensions and solutions
- Suspension particle size?
- Storage - Handling of nanoparticles

Stable high-power plasma torch

Understanding liquid processing

Plasma/Liquid Processing

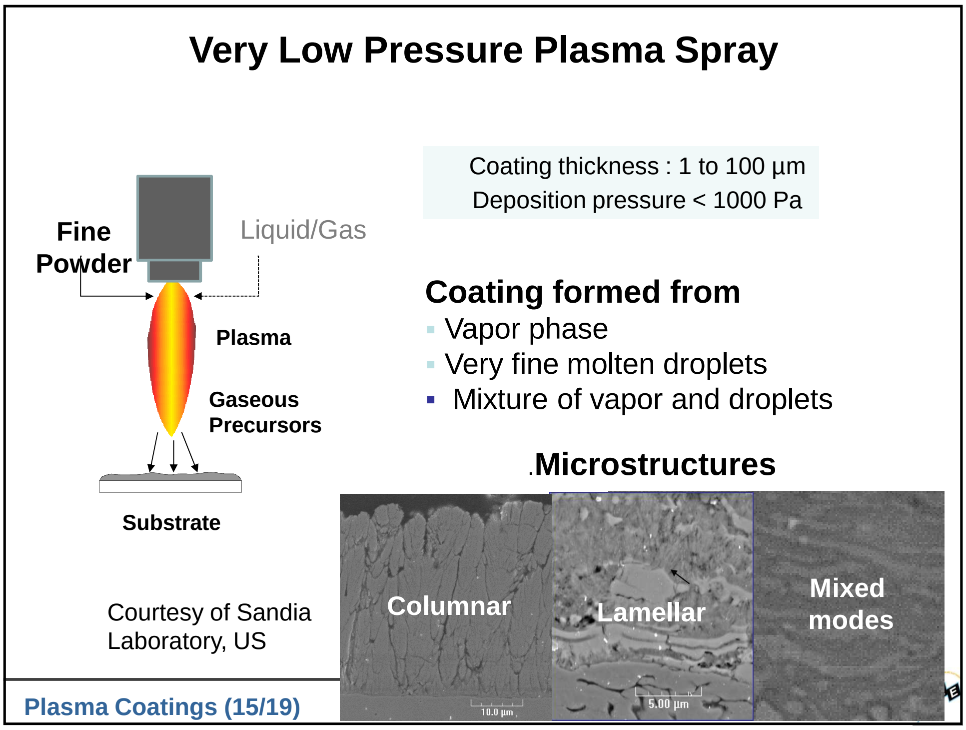
Proper and stable **injection** of the liquid feedstock

Coating Architecture

Understanding coating formation

- Heat flux
- Local mass flux to substrate

Key point: Development or adaptation of measurement techniques and sensors for droplets and fine particles



Very Low Pressure Plasma Spray

Courtesy of Sandia Laboratory, US

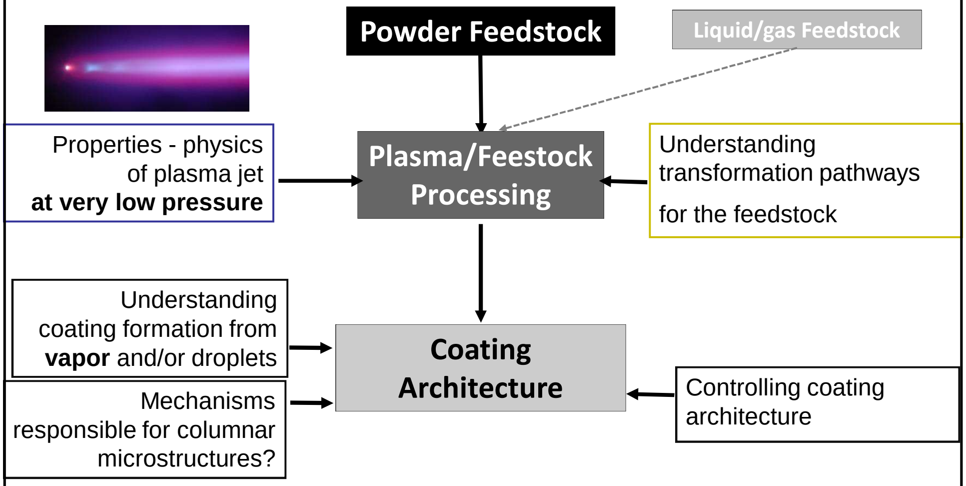
Coating thickness : 1 to 100 µm
Deposition pressure < 1000 Pa

Coating formed from

- Vapor phase
- Very fine molten droplets
- Mixture of vapor and droplets

Microstructures

Challenges - Research Priorities



Powder Feedstock

Liquid/gas Feedstock

Properties - physics of plasma jet **at very low pressure**

Plasma/Feestock Processing

Understanding transformation pathways

for the feedstock

Understanding coating formation from **vapor** and/or droplets

Mechanisms responsible for columnar microstructures?

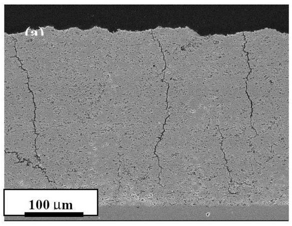
Coating Architecture

Controlling coating architecture

Key point: Process should benefit from the experience gained vacuum film deposition techniques

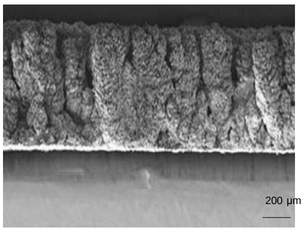
Thermal Barrier Coating by Emerging Processes

Solution Precursor Plasma Spray



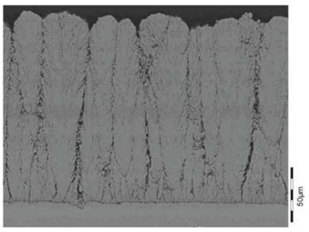
Courtesy of Gell & Jordan
University of Connecticut, US

Suspension Plasma Spray



Courtesy of Vassen
Forschungszentrum Julich, G

Plasma Spray at Very Low pressure



Courtesy of *Von Niessen*
Oerlinkon-Metco

Opportunities and Application Areas

Greening the Thermal Spray Processes

→ **Cost and environmental load reduction**

- Efficient energy and resource utilization
  - → minimizing the total energy use per gram of deposited material
  - → Minimizing waste and emissions
  - → Efficient methods for the recovery and recycling of overspray

Life cycle assessment (LCA) of thermal spray processes and products

"Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 14040)

Plasma Spray Markets

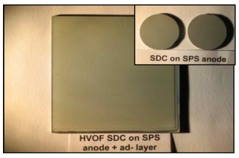
Opportunities and Application Areas

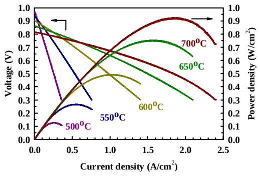
Functional surfaces

- Superhydrophobic
- Catalytic

Device manufacturing

- Thermoelectric Energy Converters
- Alkaline Water Electrolysers
- Solid Oxide Fuel Cells
- Membranes
- Batteries
- Sensors





Courtesy of NRC

Potential Areas

- Electronics Industry
- Energy Conversion and Harvesting

Session 3 : Arc Welding

5 conferences

- **Arc welding research : Progress and Challenges,** Tony Murphy, CSIRO, Australia
- **A Wind of Smart Arc Welding Technology in Japan,** Manabu Tanaka, Osaka University
- **Investigation of TIG arcs with a non-equilibrium model and optical diagnostics,** Dirk Uhrlandt, Greifswald, Germany
- **Experimental description of welding,** Erwan Siewert, Linde Gas, Germany
- **Experimental und numerical investigations on the influence of different shielding gases in GMA welding,** Martin Hertel, Technische Universitat, Dresden

Arc Welding Research: Progress and Challenges

T. Murphy

Arc welding fundamentally concerned with joining metals.

→ the great majority of arc welding research directed towards **the properties of the metals** :
changes to the microstructure and development of residual stresses as a consequence of heating and cooling during the welding process.

Problem 1 : The importance of arc

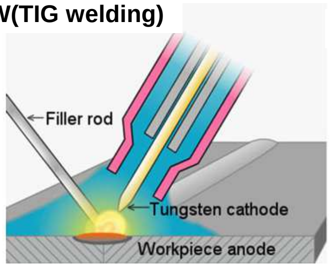
'An Iconoclast's View of Arc Welding – Rethinking Old Ideas' by Thomas W. Eagar, MIT (1993) : The arc temperature is not that important

Problem 2 : Gas Metal Arc Welding (GMAW) is used much more widely than Gas Tungsten Arc Welding (GTAW)

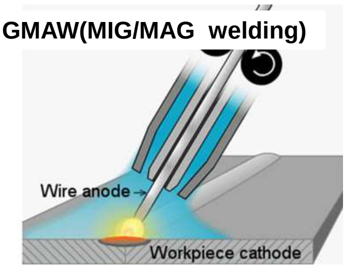
TIG was extensively studied by researchers

MIG/MAG more complex. It has ben studied widely only recently .

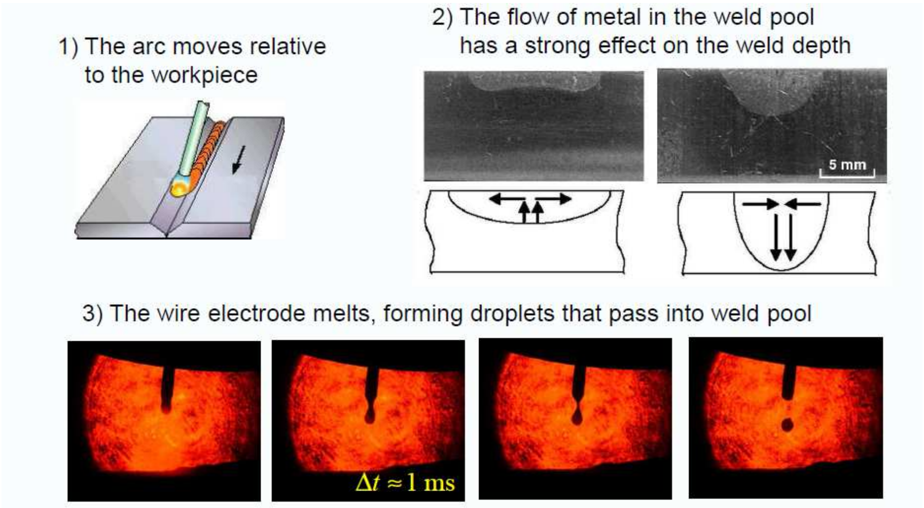
GTAW(TIG welding)



GMAW(MIG/MAG welding)



Problem 3: Gas Metal Arc Welding is a complex process

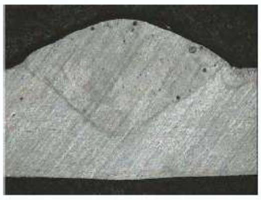


1) The arc moves relative to the workpiece

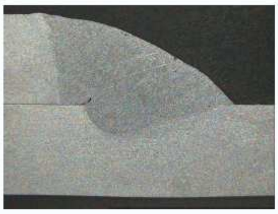
2) The flow of metal in the weld pool has a strong effect on the weld depth

3) The wire electrode melts, forming droplets that pass into weld pool

4) The surface of the molten weld pool is not flat



5) The geometry is fully 3-D (fillet weld)

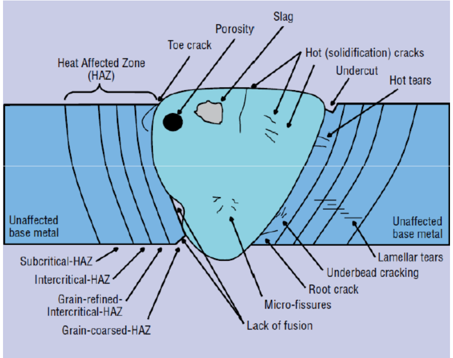


6) The weld has a start and an end

7) Metal vapour can strongly affect the arc and weld pool

Arc Welding (5/19)

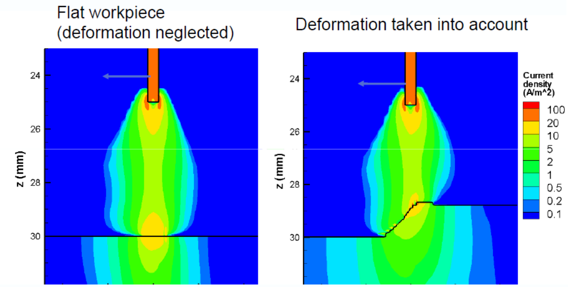
Problem 4: Welders worry about things like microstructure, porosity, stress and defects



1. Is the arc plasma important?
2. What can we already do?
3. What is there still to do?

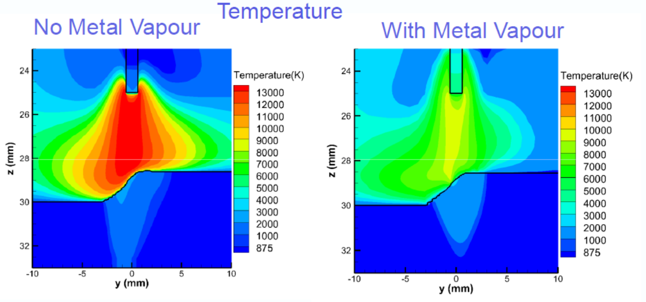
Arc Welding (6/19)

1- Is the arc plasma important?



Example 1:
The weld pool surface profile affects the current density at the surface

95 A arc, 15 mm/s welding speed, Al alloy AA 5754 workpiece



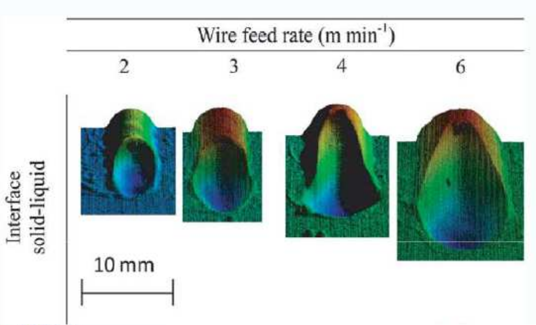
Example 2:
Metal vapor affects the arc temperature and current density

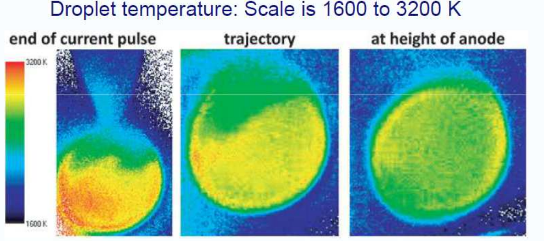
I = 95 A, VW = -0.9 m/min,
Vfeed = 4.3 m/min,
fdrop = 93 Hz, AA 5754

2- What can we already do?

Measurement of

- arc temperature
- droplet temperature
- weld pool temperature
- weld pool shape…





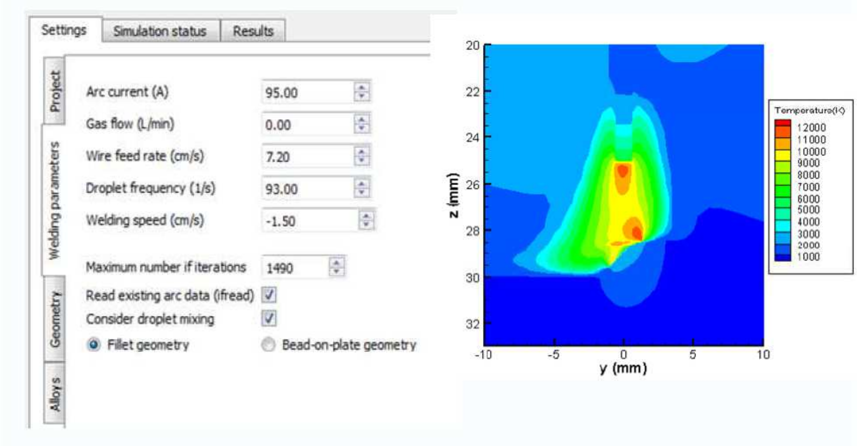
E Siewert, J Schein, G Forster, J Phys D: Appl. Phys. **46 (2013) 224008**

Modelling can take into account all the main arc and weld pool phenomena

- Three-dimensional
- Two way coupling between arc, electrode and weld pool
- Arc motion
- Complex geometries
- Weld-pool surface deformation and flow of liquid metal
- Effect of droplets
- Metal vapor
- Mixing of droplets with weld pool

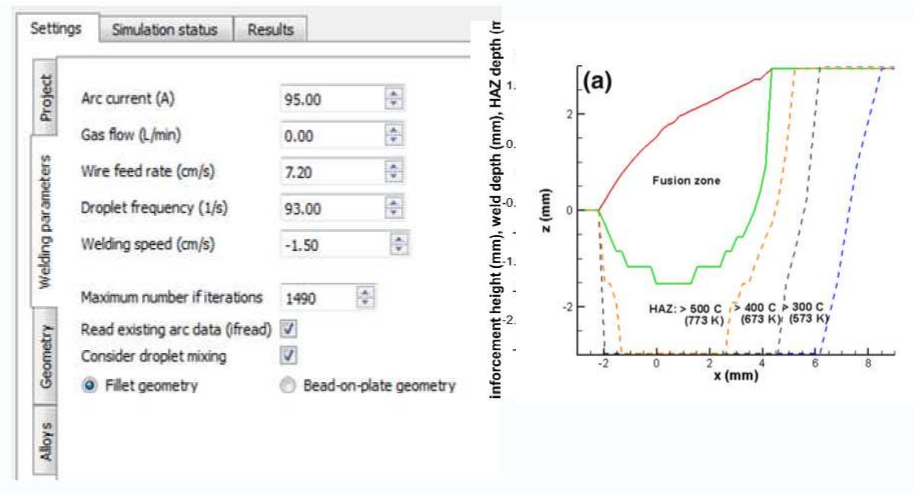
→ **Using arc welding models 'on the factory floor'**

Using arc welding models 'on the factory floor'



Arc current (A) 95.00
Gas flow (L/min) 0.00
Wire feed rate (cm/s) 7.20
Droplet frequency (1/s) 93.00
Welding speed (cm/s) -1.50
Maximum number if iterations 1490
Read existing arc data (ifread) ☑
Consider droplet mixing ☑
● Fillet geometry ○ Bead-on-plate geometry

Using arc welding models ‘on the factory floor’



Arc current (A) 95.00
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Welding speed (cm/s) -1.50
Maximum number if iterations 1490
Read existing arc data (ifread) ☑
Consider droplet mixing ☑
● Fillet geometry ○ Bead-on-plate geometry

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3. What is there still to do?

Improved diagnostics

- Measurement of current density

Improved models

- Fast and accurate model of droplet transfer
- Deviations from LTE and LCE near electrodes

Extended range of application of models

- Coupling arc models to models of microstructure, porosity …

Improved processes

- Reduced fume formation
- Improved productivity
- Increased range of applications

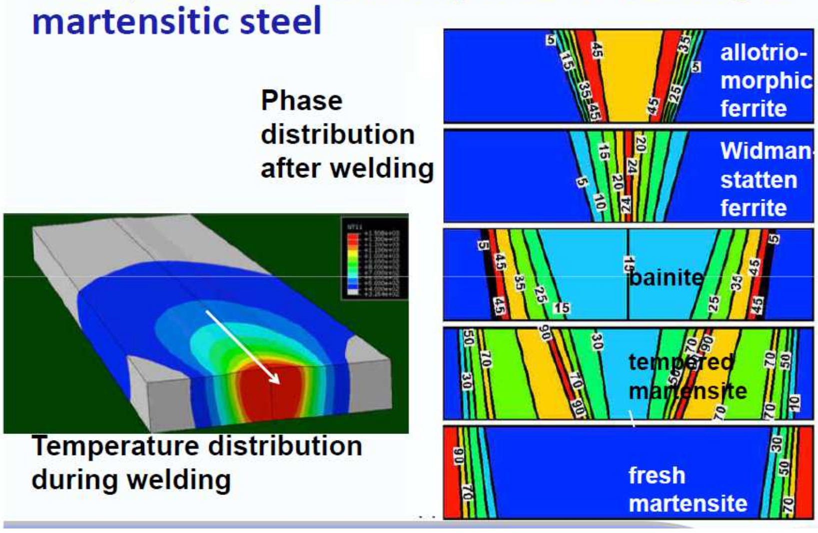
More specific requirements (1/2)

- Development of methods for the measurement of current density and heat flux distributions for MIG/MAG arcs; such measurements are critical for benchmarking computational models and understanding the energy transfer;
- Confirmation (for example by laser scattering) of spectroscopic measurements of the local temperature minimum caused by metal vapour in MIG/MAG arcs;
- Development of techniques to simultaneously measure the properties of the electrode, droplets, weld pool and arc, to allow welding dynamics to be tracked with time;
- Models treating diffusion of multiple gases, such as vapours from different alloy components;
- Fast and reliable modelling treatments of droplets and weld pool deformation;

More specific requirements (2/2)

- Modelling treatments of the periodic extinction and reignition of the arc in short-circuit transfer;
- A better understanding of the sheath, and methods of integrating the sheath into arc models; in particular:
- Extensions of simple treatments analogous to the ‘‘LTE–diffusion’’ approach that can be used reliably for shielding gases other than pure argon and when metal vapour is present;
- An understanding of the non-thermionic cathode sheath;
- A resolution of the different approaches used for thermionic cathode sheaths;
- A detailed understanding of the influence of metal vapour on the sheath.

Example: predictions of phase in welding of martensitic steel



Phase distribution after welding

Temperature distribution during welding

Investigation of TIG arcs with a non-equilibrium model and optical diagnostics

Dirk Uhrlandt

Magneto-hydrodynamic approach:

Arc plasma close to LTE *but no thermal, chemical or ionization equilibrium is assumed (valid approach in arc column and pre-sheath regions)*

- Conservation equations for mass, momentum, heavy particle energy, electron energy, heavy particle species (excited / ionized species) in the plasma
- Treatment of individual collision processes and species diffusion (non-equilibrium plasma chemistry)
- Heat balances in the electrodes
- Ohms law (current conservation) and Maxwells equations in the whole solution area

Unified description of the cathode and anode sheath:

- pre-sheath – a part of the plasma model
- space-charge sheath – collision less, treated as 0D interface
- total current density

$$j_t = j_i + j_{em} - j_p$$

- thermionic current $j_{em} = A_R {T_{c,a}}^2 \exp(-\frac{e\phi_c}{k_B T_{c,a}})$, work function $\phi_c = \phi - \Delta\phi$
- electron back current $j_p = \frac{e n_e}{4} v_{e,th} \exp(-\frac{eU_d - e\Delta\phi}{k_B T_e})$
- ion current $j_i = e n_s \sqrt{k_B (T_i + T_e)/M_i}$
- voltage drop U_d from energy balance at the sheath-pre-sheath edge

$$a j_{em} = b j_p + c j_i$$

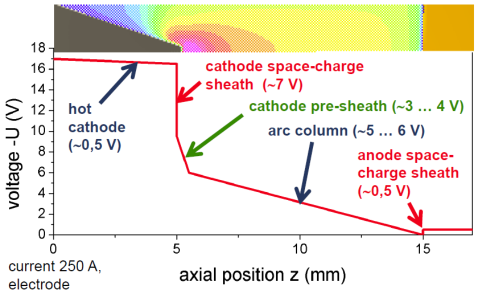
$$a = U_d - \Delta\phi - \left(3.2T_e - 2T_{c,a}\right)\frac{k_B}{e}, b = U_d - \Delta\phi - 1.2T_e \frac{k_B}{e} \quad ,$$

$$c = E_{ion} + (2T_i + 0.5T_e)\frac{k_B}{e} + \left(3.2T_e - 2T_{c,a}\right)\frac{k_B}{e}$$

- energy flux to the cathode / anode

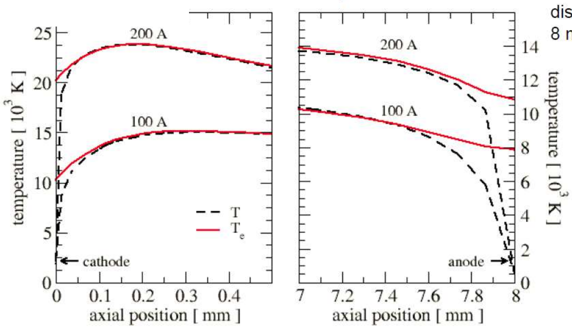
$$\Gamma_{eff}{}^{c,a} = \frac{j_p}{e}(2k_B T_e + e\phi_c) - \frac{j_{em}}{e}\left(2k_B T_{c,a} + e\phi_c\right)$$
$$+ \frac{j_i}{e}\left(2k_B\left(T_i - T_{c,a}\right) + 0.5k_B T_e + e(U_d - \phi + E_{ion})\right) - \epsilon_c \sigma_{SB} {T_{c,a}}^4$$

Arc Welding (17/19)



current 250 A, electrode distance 10 mm

and electron temperature



electrode distance 8 mm

- Tg # Te in arc column
- Significant deviations in electrode regions
- Non-LTE sheath width near cathode smaller than near anode

Arc Welding (18/19)

Main concluding remarks

- Model clearly shows the deviations from equilibrium state in the electrode sheath regions.
- Non-equilibrium models enable consistent description of the electrode regions and the potential structure.
- Results reproduce well the measured temperature and arc voltage.
- Spectral selective high-speed images can be used to estimate the 2D temperature profile.

Next steps

with NLTE model: systematic studies of

- cathode shape and material
- interaction with anode (workpiece)

with the optical diagnostics:

- 2D temperature and metal vapour profiles
- study of time-dependent processes

Session 6 : Plasma Waste Treatment

Jaco van der Walt

- **Very small plasma gasification system**, Jaco van der Walt, NECSA, SA
- **Tetronics'– High Specific Value Materials Recovery in Modern Circular Business Models Employing Tetronics' Plasma Technology,** D.E. Deegan, Tetronics UK

Very small plasma gasification system,

Jaco van der Walt

Current waste treatment technologies

- Incineration (mass burn)
  - Controlled burning
  - Excess air
  - CO_2, H_2O, NO_x, SO_x, HCl, dioxins and fly ash
- Pyrolysis
  - Heating in absence of air
  - Char, tar, volatile gases
- Conventional gasification
  - Burning in partial oxygen feed and steam if needed
  - Syngas (H_2, CO), CH_4, CO_2 and H_2O
- Plasma gasification
  - Heat source is a plasma
  - Syngas and small quantities of CH_4 and CO_2

Comparison of waste treatment options

	Pyrolysis	**Conventional gasification**	**Plasma arc gasification**	**Incineration**
Operating temp (°C)	650 – 1200	800 – 1500	4 – 7000	540 – 1200
Efficiency (%)	57	68	81	54
Net energy to grid (kWh/t)	571	685	861	544
Capital cost ($ million)	87	80	101	115
Operating cost ($ million/a)	7.2	6.8	7.4	8.2

Industrial scale plasma waste treatment plants

Company	Location	Description
Plasco Hera JV	Castellgali, Spain	5 t/d research pilot plant. MSW, alternative (unspecified) feedstocks
Plasco Energy Group	Trail Road, Ottawa, Canada	100 t/d demonstration plant processes post-recycled MSW, producing 1MWh/t
Phoenix Solutions Corporation (PSC)	Minneapolis, MN, USA	Plasma equipment supplier. Furnace design and manufacture.
Enersol Technologies Inc	Springfield, Virginia, USA	Plasma Enhanced Gasification System (PEGS^{TM}): Petroleum coke, Coal waste, Biomass, MSW.
Bellwether Gasification Technologies Ltd	Hennigsdorf, near Berlin, Germany	IMG (Integrated Multifuel Gasification). Plasma equipment supplied by Phoenix (PSC). Turnkey plant under construction in Brasov, (100 000 t/a), Turnkey plant, (90 000 t/a) for Vaslui, Basic and detail engineering for 60 000 t/a MSW gasification plant, Bals, Romania.
Air Products/ AlterNRG/ Westinghouse	Teesside, UK	1000 t/d MSW-to-energy. Westinghouse plasma gasifier and torches. Commissioning: 2014
AlterNRG	Wuhan, Hubei, China	150 t/d biomass gasifier. Electricity and FT liquid fuels. Commissioning late 2012
AlterNRG	Mihama-Mikata, Japan	20 t/d MSW + 4 t/d sewage sludge. Commissioned 2002. Produces heat for feedstock drying.

Waste Treatment (4/9)

Industrial scale plasma waste treatment plants

Company	Location	Description
AlterNRG	Westinghouse Plasma Centre, Madison, PA, USA.	48 t/d plasma gasification demonstration and test facility. In operation since 1984. More than 100 different feed stocks tested. Syngas produced for various applications (e.g. ethanol production, Coskata bio-fermenter).
PEAT International (PTDR)	Kaohsiung City, Taiwan	Medical and hazardous wastes MSW gasification
InEnTech (PEM)	Columbia ridge Landfill, Arlington,	Processing of MSW, industrial, medical and hazardous waste
PyroGenesis		Mobile/shipboard systems for general waste destruction.
APP/Tetronix	Test Facility: Swindon, UK	"Gas plasma" process: fluidised-bed gasification of reuse derived fuel (RDF). Tetronix supplies plasma torches and technology.
Europlasma/CHO Power	Morcenx, France	~51 500 t/a. Sorted/recycled. Generates 12 MWe +18 MWth as hot water. Crude syngas "polished" in plasma reactor.
Solena Fuels	London, UK	500 000 t/a MSW to 73 ML of jet fuel, 49 ML of naphtha/a, 40 MWe
Millenium Technologies	Prague, Czech Republic	Plasma gasification systems and engineering services (5 t/h, 20 t/h)
Rentech	Commerce City, Colorado	Biomass-to-liquid fuels. Silvagas and ClearFuels gasifiers, Fischer-Tropsch (F-T) technology. >2 000 h operation; Rentech F-T >13 000h operation; Integrated process >1 000 h operation

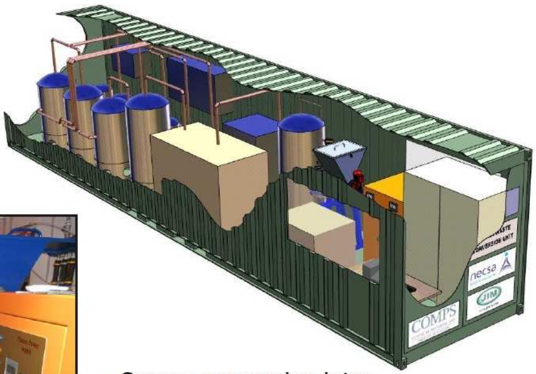
Waste Treatment (5/9)

Very small waste treatment plants

- Municipal land fill sites (sorted municipal waste)
- Delocalized municipal waste sites (under developed communities, shopping malls, big company buildings, etc.)
- Farming plant waste
- Farming animal manure (fumier) waste
- Renewable feedstock (bamboo, trees, Hyacinths, etc.)
- Tyre waste
- Medical waste
- Toxic waste

Very small waste treatment plants

- Containerised plasma gasification system
- 0.2 – 1 tpd waste treatment
- 10 – 50 kW plasma



- Syngas conversion into:
  - Electricity
  - Synthesis products
  - Steam/hot water

Economic viability

I.J. van der Walt, J.T. Nel, D. Glasser, D. Hildebrandt, L. Ngubevana, An Economic Evaluation For Small Scale Thermal Plasma Waste-to-energy Systems, ISPC 21, Cairns, Australia, 4 –9 Aug, 2013.

Waste type	Current waste treatment cost ($/kg)	Plant cost for 1 tpd ($`000)	IRR for 1 tpd (%)	Products	Min viable size (tpd)
Organic waste	0	400	0	Electricity, fuel	10
Municipal waste	0.01	400	0	Electricity, fuel	7
Tyre waste	0.012	500	0	Electricity, fuel	6
Hazardous waste	3	500	158	Electricity	0.2
Medical waste	4	500	207	Electricity, steam, hot water	0.1

Very small waste treatment plants

Session 4 : Arc Cutting

Vittorio Colombo

3 conferences

- **Modeling and diagnostics for high current PAC torch design**
  Emanuele Ghedini, Universita di Bologna, Italy
- **Hafnium cathode evaporation for an oxygen plasma cutting arc,**
  Leander Schleuß, Thomas Richter, Ralf Ossenbrink, Vesselin Michailov,
  Brandeburg University of Technology,Germany
- **Numerical investigation on the effect of cathode holder shape on hafnium cathode evaporation for an oxygen plasma cutting arc,** Yasunori Tanaka, Kanazawa University, Japan

Arc Cutting (1/1)

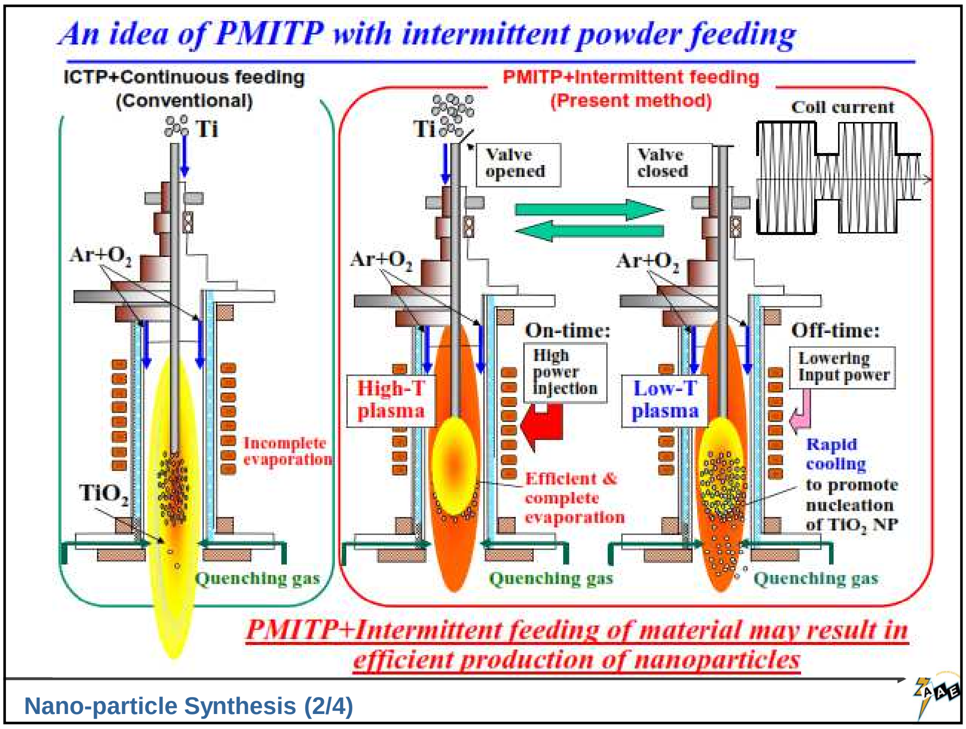
Session 5 : Nano-particle synthesis

Takayuki Watanabe

6 conferences

- ***A model of welding fume formation*****,** Tony Murphy, CSIRO, Australia
- **Models of Nano-powder formation in thermal plasma synthesis**
  Masaya Shigeta, Osaka University, Japan
- **Large scale synthesis of functional nanopowder using modulated induction thermal plasmas with time-controlled feedstock feeding,** Yasunori Tanaka, Kanazawa University

Nano-particle Synthesis (1/4)



An idea of PMITP with intermittent powder feeding

PMITP+Intermittent feeding of material may result in efficient production of nanoparticles

Development of a large amount synthesis method of Al doped TiO$_2$ nanopowder

Methodology: PMITP + Intermittent powder feeding + Quenching gas

Synchronized for complete evaporation of Ti+Al feedstock

Efficient nanopowder production & particle size control

#Feedstock feeding rate : *g*=12 g/min @20 kW
→ A large amount of Al-doped TiO$_2$ nanopowder can be synthesized with *d*=53-66 nm (it can be controlled by SCL conditions).
→ The production rate was higher than 400 g/h@20 kW.

#Reducing SCL (larger modulation) provides smaller nanoparticles.
From XRD, EDS mapping and %R results,
Al doped TiO$_2$ nanoparticles were synthesized.
Synthesized Al doped TiO$_2$ nanoparticles
have a little photocatalyst efficiency for UVA light.
→Suppression in reactive oxygen species (ROS) production.

Session 5 : Nano-particle synthesis

- **Three-dimensional modeling of Silicon nanoparticle synthesis in a radio-frequency inductively coupled plasma system with quenching ring,** Paolo Sanibondi, Universita di Bologna, Italy
- **Silicon nano-powders synthesis by RF induction plasma : optimization by diagnostics and modelling for process scale-up** Paolo Sanibondi, Universita di Bologna, Italy
- **Fullerene synthesis in radio-frequency inductively coupled thermal plasmas,** Emmanuel Ghedini, Universita di Bologna, Italy