Application of Electromagnetic Fields for Enhancement of Structural Metal Performance

(EMFforMET)

Final Publishable Summary Report

The objectives of the project were (i) to transfer knowledge of electromagnetic field (EMF) treatment to the Host institution via the creation of an experimental facility for the treatment of metals in the molten and solid states and provide training courses (ii) to fulfill a series of comprehensive tests for the experimental evidence of the benefits of the treatment for the refinement of the microstructure of castings and enhancement of the corrosion and wear resistance of metals (iii) to understand the mechanisms by which improvement in metals performance is achieved and (iv) to undertake interaction with industrial companies to introduce the treatment.

During the Project the following work was performed: (i) experimental facilities for the EMF treatment of metals in the solid and molten states were developed; a generator for pulsed electric current (PEC) treatment and different types of inductors to generate a pulsed magnetic field (PMF) were assembled and facilities for the treatment of metals by application of alternating magnetic fields (AMF) and rotating magnetic fields (RMF) were designed, built and commissioned; all the required hardware and software to register the treatment parameters (magnitude of current, field, temperature, etc.) were purchased and installed; (ii) investigation of the effects of PEC, PMF and AMF treatments on the corrosion behaviour of pure titanium and its alloys; (iii) investigation of the effect of PMF, AMF and RMF treatments on the corrosion behaviour of mild steel as well as low-carbon and dual phase steels; (iv) investigation of the effect of PEC and PMF treatments on the stress corrosion cracking (SCC) of pure titanium and 70/30 brass; (v) investigation of the effect of PMF treatment on the friction and wear behaviour of bearing steel; (vi) investigation of the effect of PEC treatment on the refinement of the grain structure of A356 casting aluminium alloy, and (vii) interaction with industrial companies to introduce the treatment was undertaken.

The main results that were achieved include:

- corrosion immersion tests of CP TA2 (Commercially Pure Grade 2) titanium, titanium alloy TiAl6V4 and TiAl intermetallic in solutions of sodium and tin fluorides (these tests are critical for usage of the metals as dental implants) demonstrated a reduction of the amount of corrosion of up to 40% due to application of the PMF and AMF treatment as shown in Fig. 1;

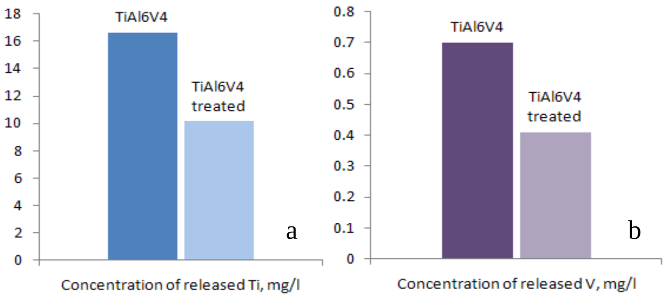

Fig. 1. Release of Ti (a) and V (b) in 0.9 % solution of SnF_2, pH 4.5 after 120 hours exposure of untreated and treated TiAl6V4.

- salt spray (5% solution of NaCl) corrosion tests of mild steel, low-carbon and dual phase steels demonstrated a reduction of the amount and rate of corrosion of more than 70% due to the use of the PMF, AMF and RMF treatments;
- SCC of cold-drawn 70/30 brass immersed in a 2% mercurous nitrate solution and CP TA2 titanium immersed in a 0.9% NaF solution was eliminated due to the use of direct electropulsing and PMF treatment as illustrated in Fig. 2;
- decrease of the wear rate and coefficient of friction (reduced by 14%) was observed for the treated AISI 52100 bearing steel following PMF treatment (data are shown in Fig. 3);
- application of direct electropulsing to molten A356 aluminium alloy (artificially enriched with 2% of iron) dramatically improved the fluidity of the alloy and its properties.

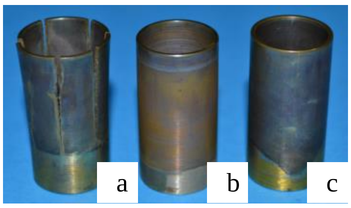

Fig. 2. Brass after 30 min exposure in mercurous nitrate: a – initial, b – annealed (330 °C, 1 h), c – treated.

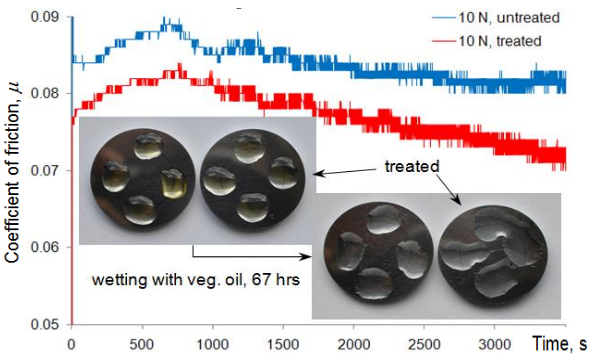

Fig. 3. Variation of coefficients of friction for untreated and treated AISI5210 steel; change of wettability of the steel due to the treatment.

It was shown that PMF treatment can be referred to as “non-thermal” because it leads only to a low increase of temperature to just about 100°C and can promote changes in the microstructure of metals leading to the generation of a uniform network of dislocations as shown by the transmission electron microscopy (TEM) images in Fig. 4. After PMF treatment, dislocations were no longer pinned at grain boundaries, but they were homogeneously distributed within the grains and had textured (ordered) appearance (Fig. 4b). Further investigation using atomic force microscopy (AFM) manifested micro-plastic deformation of the metal surface after PMF treatment as well as an increase of the scatter of the values of the surface electrical resistance; this observation can be promoted by the generation of new dislocations. The increase of dislocations in PMF treated metals also was confirmed by the differential scanning calorimetry (DSC) results that were obtained. Overall, it was apparent that the EMF treatment led to the development of a more homogeneous microstructure. This was further supported by the observation that the scatter of the hardness values was substantially reduced for all investigated metals (from 20% for CP TA2 titanium to 70% for AISI 52100 steel) indicating greater homogeneity of the microstructure. This was beneficial for the reduction of electrochemical corrosion because the potential difference between anodic and cathodic areas on metal surface is likely to decrease and thus the driving force for the corrosion is decreased. In addition, it was observed that the EMF-treated samples exhibited a higher value of the corrosion potential as shown in Fig.5.

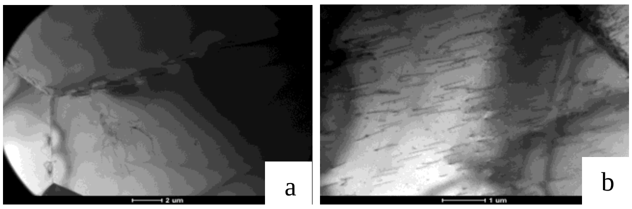

Fig. 4. TEM patterns of untreated (a) treated (b) CP

In the case of AISI 52100 bearing steel, the mictrostructural homogeneity that resulted from EMF treatment was critical in reducing the coefficient of friction and the wear rate of the steel. An additional observed benefit of the registered treatment was the increase of the wettability of the steel for oil and other fluids. These observations are summarised in Fig. 3. The EMF treatment leads to an increase of dislocation mobility and the dislocation removal from the grain boundaries by annihilation thereby also reduces the residual stresses in the materials causing the observed elimination of SCC of cold-drawn 70/30 brass and CP TA2 titanium.

The effect of direct electropulsing of on molten A356 aluminium alloy (artificially enriched with 2% of iron) resulted in the fragmentation of the $Fe_2Si_2Al_9$ blades that are responsible for the coarsening of the microstructure (it should be noted that gradual iron accumulation is a huge problem for recycled aluminium alloys as it promotes unwanted coarsening of the microstructure). The fragmentation of the $Fe_2Si_2Al_9$ blades allows the desired refinement of the microstructure and leads to improvement of the mechanical properties. In addition, a significant decrease in the porosity levels was achieved by the use of EMF treatment. The average measured hardness also increased from 70 HV up to 118 HV (increase of about 70%).

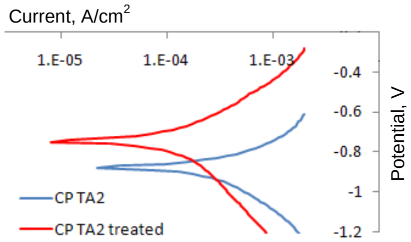

Fig. 5. Potentiodynamic polarization scans for untreated and AMF treated CP TA2 in 0.9 % NaF, pH 6.0.

Conclusions and further potential

1. The application of various types of EMF leads to (i) beneficial effects on the corrosion resistance of structural metals, (ii) improvements in the wear resistance of steel and (iii) microstructural changes of A356 alloy.
2. The developed experimental facilities and transfer of knowledge from the Research Fellow to the Host institution staff and researchers strengthens the competence and expertise of the Host institution in the field of the PEC/PMF/AMF/RMF treatment of metals and creates an environment to obtain further support from industry and funding bodies for implementation of the results and for further developments and findings.
3. The experimental results of the EMF treatments can serve as a scientific basis for new advanced processing technology extending the corrosion resistance of structural metals and reducing the coefficient of friction and the wear rate of bearing steel. The main advantages of the technology are: (i) it can be applied to large structures as well as for small parts like human implants; (ii) it can be applied locally or for critical parts; (iii) it is non-thermal and is applied at ambient temperature and (iv) due to its low-energy consumption, it is cost-effective and environmentally-friendly.
4. The experimental results of PEC treatment of molten 356 aluminium alloy can serve as a scientific basis for new advanced technology for more effective utilization of scrap of aluminium alloys.
5. EMF-based technology will extend the lifetime of materials and reduce costs and thus it will potentially have an important economic impact. For example, an increase of the corrosion resistance of human implants which can be achieved will lead to fewer operations to replace corroded ones and reduce the burden on EU health services, while the contribution to the quality of life for the ageing European population is virtually immeasurable. This demonstrates the main socio-economic impact of the Project.
6. It is anticipated that the main users of the above technology will be the aerospace, automotive and defence industries as well as manufacturers of human implants. Contact with industry (including MBDA-UK, Jaguar-Landrover, C4 Carbides) has taken place and further collaborative work is planned.

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