Electrospark Deposition Useful for Aerospace Repairs

Electrospark deposition applications are increasing with the development of high-temperature, high-strength, high-alloy elements, and refractory materials in aerospace

BY STEPHEN PETERKIN, NIGEL SCOTCHMER, AND ZHEN JIAO

Fig. 1 — Work helicopter blade leading edge. (Image courtesy of Rotor and Wing International.)

The aerospace industry is driving the adoption of new alloys and materials for the improvement of structural, fuselage, and engine components — Fig. 1. These new materials prioritize performance in strength, fatigue resistance, and high-temperature stability. Such improvements are achieved by the addition of alloying elements to traditional metal combinations such as aluminum, titanium, and magnesium alloys, as well as nickel- and cobalt-based superalloy systems. Refractory metals are being adopted as high-temperature and creep-resistant components and coatings.

The favorable performance of these new materials often comes at the cost of weldability. Traditional fusion welding processes result in significant discontinuities in mechanical properties, alloying element distribution, brittle intermetallic compounds, and thermal stresses.

To meet the needs of the aerospace industry, processes are trending toward higher precision, lower heat inputs, and solid-state joining and buildup technologies. Recent improvements in electrospark deposition automation and equipment has led to the development of applications in repair, coatings, surface modification, and joining of these emerging aerospace materials (Ref. 1).

Electrospark Deposition Process

Electrospark deposition (ESD) is a member of a group of processes colloquially named low-energy welding (LEW). This process is well known for its minimal heat-affected zones, metallurgically bonded coatings, minimal elemental diffusion, and its ability to weld dissimilar metals. Electrospark deposition is a micro arc welding process, where high-current, short-duration pulses melt small volumes of electrode material that impinge on the surface and deposit onto the substrate — Fig. 2. Cathodic etching of the substrate results in metallurgical bonds, and the low-per-event mass transfer results in high cooling rates, minimal heat-affected zones, and negligible thermal stresses. The high cooling rates minimize elemental diffusion and formation of brittle intermetallic compounds, and also result in a strong, finely grained microstructure.

This process was traditionally applied for the coating and surface treatment of metallic substrates with high-ceramic-content cermet materials. The fundamental benefits of the process have expanded the applications to include repair of high value, or typically unweldable, alloys and material combinations. Applications in coatings continue to evolve, with the coating of traditional metal alloys with high-hardness and wear-resistant cermet

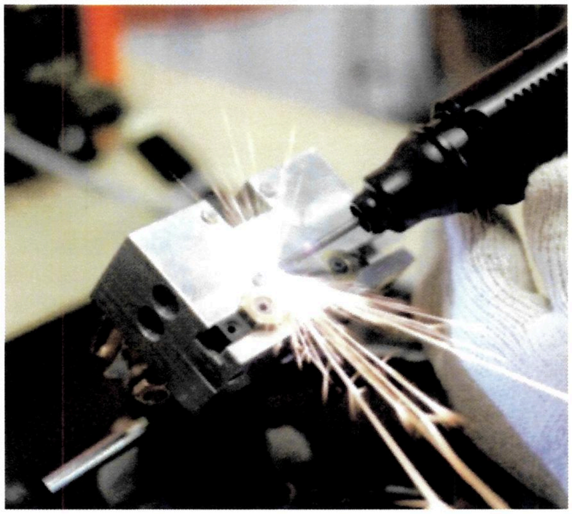


Fig. 2 — Example of a manual electrospark deposition process. (Image courtesy of Huys Industries Ltd.)

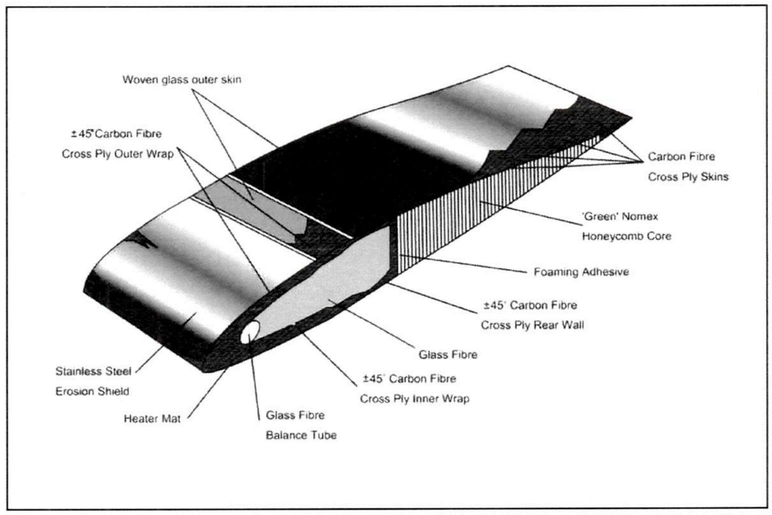


Fig. 3 — Cross section of helicopter rotor blade. Example of thin-skinned metal composite structures (Ref. 2).

coatings, with alloying elements and refractory materials to improve the corrosion, oxidation, and temperature sensitivity at the surface. Where thin or dissimilar materials need to be joined, ESD can be used to build up the joint between two incompatible materials, or to build up a low-heat-input interlayer to be later processed by a traditional welding method. New ESD equipment and research are tailored to meet the unique needs of the aerospace industry and the adoption of difficult-to-weld high-strength, long-life, and extreme-service alloys and metals.

Aerospace Repairs

Electrospark deposition is well suited for the repair of thin-walled and heat-sensitive aerospace components. Applications in the repair and refurbishment of thin, sensitive, and skinned composite-filled parts are common. Such components are exposed to extreme conditions and suffer from impingement, wear, cracking, corrosion, and other defects. The low-heat input resulting in minimal heat-affected zones and low thermal stresses paired with metallurgically bonded depositions in ESD make it one of the few welding processes capable of handling a variety of sensitive repair cases — refert to Fig. 1 and 3.

Nickel superalloys such as MAR, Inconel®, Hastelloy®, and others are heavily used in the aerospace industry. These alloys exhibit high-temperature

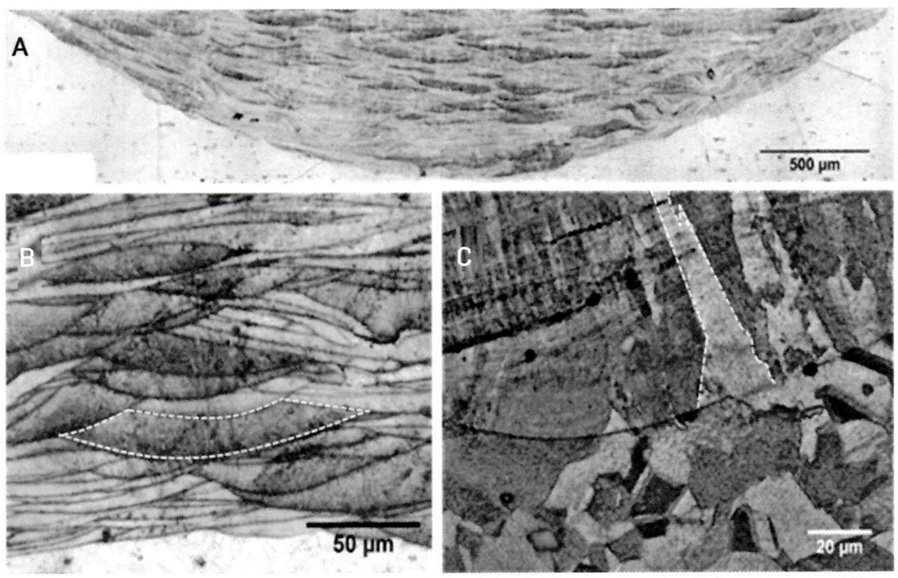


Fig. 4 — ESD Inconel 718 repairs: A — Stitched cross-section image; B — highlighted ESD; C — solidification structures (Ref. 5).

corrosion and oxidation resistance, paired with high strength and fatigue resistance. These materials are well suited for the extreme conditions experienced inside jet engines, and are often used as the material of choice for turbine blades. To achieve these mechanical properties at high temperatures, increasing and varying alloying elements are added to the nickel matrix, along with strengthening heat treatments (Ref. 3).

The dilution and heat-affected zone from traditional welding processes significantly weaken the properties of the nickel superalloy components, rendering some of the more advanced alloys unweldable. Beyond the difficulty in joining nickel superalloys, the components that operate inside the jet engines, such as the turbine blades, are subject to extreme conditions and significant wear. Electrospark deposition has been shown to be capable of repairing numerous nickel superalloy materials with minimal effects on the base material. With this technology, the damaged turbine blades and components can be repaired and refurbished to extend the part life (Ref. 4).

Studies to determine the effects of ESD repair on Inconel 718 parts, as well as the effects of different ESD parameters, have been detailed extensively

(Ref. 3). Damaged specimens were able to be restored, depending on the ESD parameters, to 97% and 104% of the initial yield strength of the parts. Variance in the performance of the repaired parts was related to the ESD parameters used in the repair (Ref. 5) — Fig. 4.

While the ESD parameters share that there is a good metallurgical bond and minimal heat-affected zone, the fundamentals of the ESD parameters have an affect on the deposition size and internal microstructure, and correlate directly to the resultant mechanical properties of the repair.

Further research was done into recovering the microstructural properties of the ESD-repaired Inconel 718. Direct aging was tested to normalize the mechanical and microstructural properties of the ESD repair, when compared to the substrate material — Fig. 5. This process was effective in normalizing the hardness values across the ESD repair and into the substrate. Continuity of mechanical properties is critical to the fatigue life of repaired components (Ref. 6).

Refractory Metals

Refractory materials are well known for their high operating and melting temperatures as well as excellent chemical corrosion resistance. Tungsten has long been used for its high density as ballast components, and molybdenum has long been used as an alloying element for improved corrosion resistance. Tantalum and niobium are being explored as refractory components and as coatings for the aerospace and defense industries (Ref. 7). Refractory materials often exhibit poor weldability, and now current ESD technology is being used to deposit refractory materials along with other solid-state joining technologies.

Electrospark deposition has been shown to be capable of depositing refractory materials and has potential in repair and coating applications. Research into the coating effects of molybdenum on 304 stainless steel produced interesting results — Fig. 6.

Initial ESD passes with pure molybdenum electrodes on 304 stainless steel substrates resulted in surface alloying, with an approximately 30% by weight composition of molybdenum alloyed with the 304 stainless steel. This surface alloying coating proved very effective at increasing the corro-

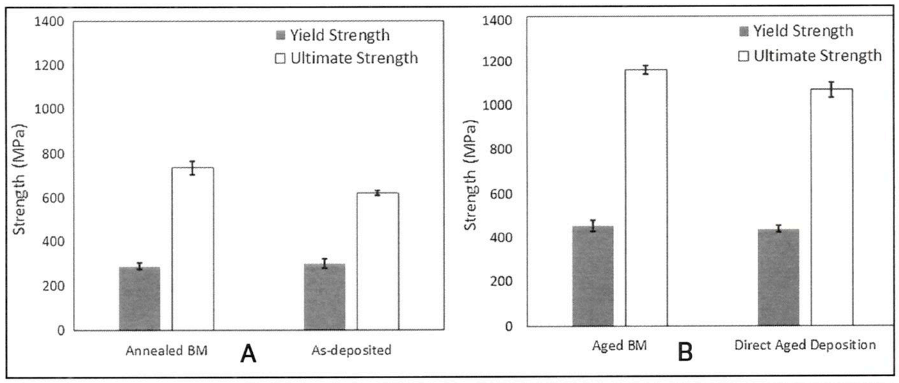
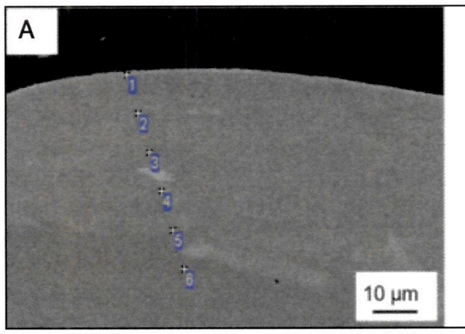


Fig. 5 — Effect on yield and ultimate tensile strength of direct aging annealed and aged ESD-repaired Inconel 718 (Ref. 6).



B

Spectrum	Cr	Fe	Mo	Ni
1	11.01	51.64	32.03	5.32
2	9.51	51.25	34.98	4.26
3	10.55	50.14	35.92	3.39
4	9.87	47.85	36.18	5.10
5	10.96	63.44	19.74	5.86
6	15.05	76.03		8.92

Fig. 6 — A — SEM image of Mo ESD-coated 304 stainless steel and EDX spectrum locations; B — EDX spectrum results in wt-% (Ref. 8).

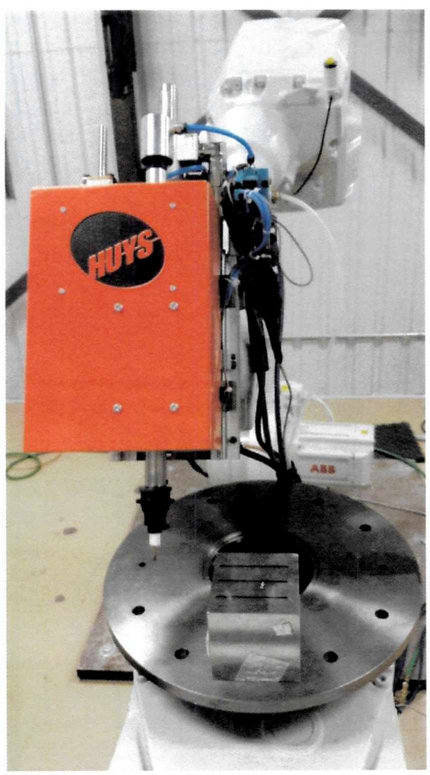


Fig. 7 — Robot-mounted automated ESD cell. (Image courtesy of Huys Industries Ltd.)

Fig. 8 — Huys portable ESD automated system. (Image courtesy of Huys Industries Ltd.)

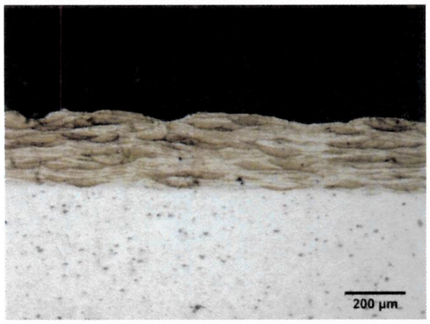


Fig. 9 — Cross-section etched microstructure image of automated ESD Inconel 718 buildup. (Image courtesy of Huys Industries Ltd.)

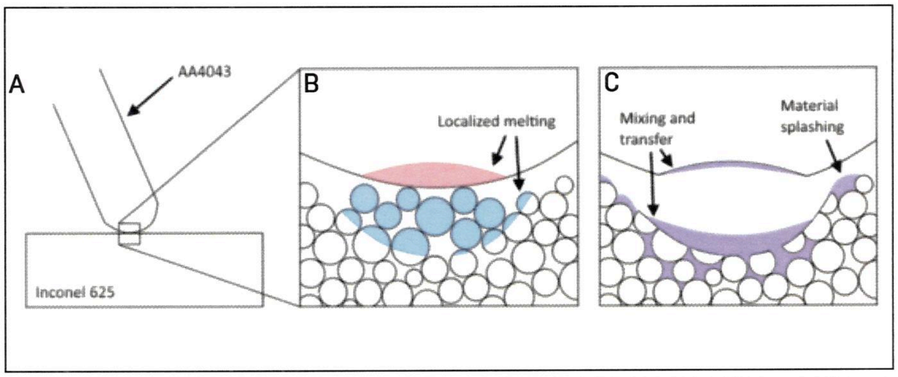


Fig. 10 — Schematic of ESD surface treatment for additively manufactured parts (Ref. 9).

sion resistance of the 304 stainless steel by more than 350× when tested using a Tafel test and 5% NaCl solution (Ref. 8).

Additive Manufacturing

Electrospark deposition can be classified as a metal additive process, due to the distinct depositions and minimal erosion and heat effect into the substrate. The benefits of the ESD process require that the thermal mass per deposit is low and material can be built up over time with subsequent passes.

Improvements in ESD automation equipment and systems have opened the potential for additive manufacturing and the ESD processing of larger areas and thicker coatings. With these systems, the quality and repeatability of the ESD process can be closely controlled and monitored — Figs. 7, 8.

Automated ESD coatings and repairs exhibit higher microstructural quality and repeatability when compared to manual coatings and repairs (see Fig. 4). They offer better surface conditions, better position control, and long-duration coatings. Previously, labor-intensive manual repairs and coatings required intermittent inspections, grinding, and peening to continuously build up materials. The proper selection of ESD parameters paired with the precise control provided by the automated ESD systems mitigates grinding and peening, while repeatably maintaining consistent coating quality — Fig. 9.

In addition, ESD can be used to deposit coatings and modify the surfaces of traditional additive manufacturing processes such as powder bed and powder fed laser processes. In addition to the traditional ESD hard and wear-resistant coatings, recent applications show that ESD can be used to densify the surface of typically porous additive parts; during that consolidation, specific electrodes can be used to improve surface properties with alloying (Ref. 9).

Studies in surface modification binder jet additive manufacturing parts of 625 Inconel demonstrated that ESD posttreatment was effective in reducing the high near-surface porosity. This reduces the need for subtractive finishing processes such as machining for BJAM parts. When treating the surface of the parts with AL4043 allows for the formation of a nickel aluminide intermetallic coating that has the benefit of reducing hot corrosion and oxidation — Fig. 10 (Ref. 9).

Electrospark deposition (ESD) is a member of a group of processes colloquially named low-energy welding (LEW).

Summary

Electrospark deposition equipment, research, and applications are expanding along with the adoption of new metal alloys and processes in the aerospace industry. The unique ability of the ESD process to work with advanced repairs, coatings, surface modification, and joining, with minimal heat-affected zone, metallurgical bonds, and ability to join difficult-to-weld metals, makes this process a prime candidate for tackling evolving issues in aerospace materials.

Advanced aerospace materials have the advantage of high operating temperatures, corrosion resistance, oxidation resistance, high strength, and good fatigue life. Such materials are achieved through the addition of large amounts of elements to existing material matrices, such as nickel superalloys; cobalt superalloys; aluminum, titanium, and magnesium alloys; as well as specific microstructural distributions achieved through heat treatments. Such complex microstructures and alloying elements make these materials very heat sensitive and susceptible to significant degradation when exposed to traditional welding and joining techniques.

The adoption of additive manufacturing processes lends itself to the development of light, hollow, and high-strength structures. These structures are highly susceptible to thermal stresses and blow through when working with traditional welding processes.

Electrospark deposition can be used to repair advanced aerospace alloys; work with refractory materials; provide wear-, heat-, and corrosion-resistant coatings; and surface alloying. The development of new ESD power supplies and equipment, advances in automation, research into material combinations, and parameter studies, is focused on matching the innovations in the aerospace industry. WJ

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