Perspective: Challenges in the Aerospace Marketplace and Growth Opportunities for Thermal Spray

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Abstract The market needs for increased engine efficiency and environmentally friendly solutions remain the key drivers for the aerospace industry. These efficiency gains will be achieved by meeting the challenges of higher engine operating temperatures, weight reduction, and novel surface solutions for increased component longevity. A critical question to address is if the thermal spray (TS) industry can continue to meet the challenges and demands seen by the airlines and the engine manufacturers. In addition to non-aerospace influences, the COVID-19 pandemic has dramatically affected the landscape of industry growth, not only directly on airlines but also on the associated supply chain. This article reviews this market, its suppliers, and identifies the challenges and opportunities for future growth. Primary focus is on technology and what will be required to bring about reliable, robust, and cost-effective TS solutions into the marketplace. Several issues affecting the global landscape of the aerospace industry are discussed including (1) sustainability, (2) technology, (3) cost of ownership, (4) evolving marketplace, (5) workforce and behavior, and (6) supply chain vitality. An important question to address is if the TS industry can accelerate development with its supply chain and have the ability to commercialize technology more efficiently. Despite the market setbacks from the pandemic and previous issues with the Boeing 737 MAX fleet, the aerospace industry is poised to make significant advancements. These will create new opportunities for thermal spray technology in materials, equipment, and processes. To deliver on them, the implementation of Industry 4.0 along with the investment in human resources is more critical than ever. Based on the findings, the authors project a bright long-term future for both the aerospace and thermal spray industries.

Keywords aerospace · clearance control coatings · environmental barrier coatings · ITSC 2021 keynote · sustainability · thermal barrier coatings · thermal spray

Introduction

Many international organizations have identified global warming and climate change as critical concerns for the future of our planet (Ref 1-6). To address these concerns, actions will be needed to reduce carbon emissions going forward. The aerospace industry is taking this issue seriously and has already planned several evolutionary and radical steps to reduce carbon emissions over the years ahead. In particular, the utilization of biofuels and the potential for hydrogen/hybrid battery propulsion are seen as key areas of development and growth. Other sustainability efforts are well documented which present a significant challenge for the aerospace industry and all its suppliers. Specifically, engine manufacturers will need to
increase engine efficiency. These efficiency gains will be achieved by meeting the challenges of higher engine operating temperatures, new lighter weight components, and implementing advanced surface engineering solutions to sustain component longevity. Advanced surface solutions will be discussed in greater detail later in this paper. It is clear that in order to meet the challenges of new fuels entering the market, new and innovative material designs pertaining to advanced thermal barriers, oxidation-resistant bond coats, clearance control, wear resistance, and environmental barriers will be required. Robust and predictable processing routes will also be necessary to achieve such solutions.

It is important to understand how these challenges in the aerospace industry influence new short- and long-term opportunities for the thermal spray market. From this perspective, there are six main categories: (1) sustainability, (2) technology, (3) cost of ownership, (4) evolving marketplace, (5) workforce and behavior, and (6) supply chain vitality that will define the thermal spray market and drive technology growth in the near future (Fig. 1). One also has to bring into the context the past successes and failures along with the factors that are needed to achieve technological advancements. For example, the development of superalloys was critical to the success of new aerospace engines, but this could not have been possible without improvements in process engineering, manufacturing processes, and new air-cooling designs (Ref 7). It was a slow and steady evolution of technology advancement that required decades to achieve, and such evolution also stands true for the development and advancement of thermal barrier bond and topcoats.

Today, in our growing digital world, a few relevant questions to be addressed are:

- Will the time required for commercialization of new technologies could be shortened by implementing sensor technologies, harvesting “Big Data”, refining engineering-based modeling techniques, and/or improving collaborations between organizations such as original equipment manufacturers (OEMs) and their supply chains?

From a thermal spray point of view, the important questions include:

- Will the utilization of sustainable biofuels and/or hydrogen fuels result in new growth opportunities for TS aerospace coatings?
- Will we be able to meet the goals of Industry 4.0?
- Will the traditional concept of “spray-and-pray” be replaced with true science and predictive engineering concepts?

This article will answer these questions based on the authors’ perspectives.

**Evolving post-pandemic market conditions**

The years 2019-2020 will go down as some of the worst financial years in the history of the aviation industry. This was not only due to the COVID-19 pandemic but also the technical issues related to the grounding and certification of the Boeing 737 MAX fleets (Ref 8, 9). The entire supply chain was affected by significant reductions in the number of people flying, and the number of engines and aircraft which were built and delivered to airlines. Many companies used this downturn to invest in their own futures by realizing that the aerospace industry recovery will be a potential for a “new normal”. They invested in their infrastructures, whether by investing in efficiency-driven manufacturing equipment and internal processes or developing new future technologies, R&D programs, and training employees.

Many experts in the thermal spray industry believe that once the aerospace market has rebounded the first area of business opportunity would be on the maintenance, repair, and overhaul (MRO) side—as opposed to original equipment manufacturers (OEMs). In August 2020, Forecast International™ reported that the industry will face a slow recovery of up to 5 years to reach pre-pandemic levels, however, with a bright future of continued aerospace growth (Ref 8, 9). Additionally, a publicly released report from Boeing indicated an optimistic future growth of air travel, specifically in China and Asia Pacific regions. It was anticipated that over the next 20 years these regions will share approximately 40% of aircraft deliveries (Fig. 2) (Ref 10).

The total thermal spray market is estimated to be 10 billion USD with approximately 60% in turbine-related activity involving industrial gas turbines (IGTs) and aircraft engines (Ref 11, 12). Of its 6 billion USD share in the turbine industry, the greatest portion of the business comes...
from coating services, with the balance linked to TS material and equipment consumables. With both IGT and aerospace markets expected to expand, the growth of thermal spray products and services is given. Besides reports from airlines, it also seems clear that there are thermal spray technology shifts into the Asia Pacific regions. The trends in the number of patent applications and technical publications in the field of thermal spray in these regions clearly support this shift. Countries like India have seen significant growth in past years and China continues to be aggressive in the thermal spray field (Ref 13, 14).

**Technology**

In addition to a constant need for efficiency improvements, over the past two decades, additional criteria have been added arising from stricter environmental legislation, with particular focus on reduced noise, gas, and particle emissions. The result has opened the door for new technical challenges as well as opportunities. To address these issues researchers are working to develop high-temperature, lightweight engines along with high-strength, lightweight environmentally friendly airframes and landing gear. In some aerospace applications, components are being fabricated by new manufacturing processes (e.g. additive manufacturing) and materials (e.g., ceramic matrix composites). In many of those cases, surface engineering solutions will be critical for technical success. From the thermal spray point of view, the key areas of advancement in the engine are the fan-, low- and high-pressure compressor, the combustor, and the low- and high-pressure sections of the turbine (Fig. 3) (Ref 15, 16). In recent years, landing gear has also seen the transformation from traditional hard chrome plating to the more environmentally friendly thermal spray process (Ref 17-19). Design requirements for thermal spray wear-resistant coatings for landing gear applications are complex. Coatings need to have a suitable balance of wear and corrosion resistance along with adequate bond strength and optimized residual stresses so that the coating can easily meet the demanding thermo-mechanical stresses in service. In most cases, properties and performance are dependent on the landing gear material of construction, surface preparation, finishing requirements, the deposition process, and the surface temperatures reached during spraying. More information on landing gear applications will be discussed later in this paper.

**Growth of Advanced Thermal Barrier Coatings**

With higher engine operating temperatures more creative material designs will be required. Thermal barrier coatings (TBCs) will not only require low thermal conductivity, phase stability, sintering resistance, and long thermal cyclic life but will also need to exhibit resistance to attack from calcia-magnesia-alumina-silica which is also known as CMAS (Ref 20). CMAS is basically molten sand that, when ingested impacts thermal barrier coating surfaces at temperatures greater than 1150 °C. This phenomenon significantly impacts the coating integrity and performance. Current legacy 7-8 wt.% yttria-stabilized zirconium oxide (YSZ) thermal barrier coatings will not withstand these harsh, environmental conditions at advanced temperatures. Although this challenge is associated with almost all aircraft engines, military aircraft operate under even harsher conditions, making them more prone to CMAS ingestion resulting in significant downtime for maintenance and repair. Figure 4(a) shows photographs of a military helicopter operating in a desert environment, leading to the
engine components covered with the re-solidified CMAS sand, and the resulting damage (Fig. 4b) (Ref 21, 22).

To mitigate the problems caused by CMAS attack, many new coating solutions have been developed and designed by engine OEM’s. For example, gadolinium zirconate and high-yttrium oxide containing zirconium oxide top layers are being used, but not without some additional design challenges. Many systems today require multilayered TBCs, in order to meet several necessary features into one package. Current efforts are being made to develop robust, reliable, and cost-effective systems that, ideally, are simpler than multilayer applications.

Clearance Control Coating Systems

Another critical area of development and growth for thermal spray coatings is in clearance control systems, also referred to as abradable coatings. These systems contribute overall engine efficiency improvements of approximately 2% for a typical civil aero engine. Engine sections where clearance control systems are applied are the low- and high-pressure compressor and the high-pressure turbine (Ref 23-25). Technically, there are many design requirements which depend on several factors, such as erosion resistance, ability to cut against specific rotating blade materials, blade geometry, operating environment (temperature and location in engines), blade speeds, incursion rates, and compatibility with substrate materials. Figure 5 illustrates the various solutions used in different sections of the engine. It is important to realize that the optimization of all of these technical variables in an engine may require many years of development. However, the potential efficiency gains are significant.

From an application point of view, a few of the many challenges with abradable coating systems are robustness, reliability, and process economics. Over the years, many conventional combustion sprayed coatings have been replaced by air plasma sprayed coatings which significantly addressed these challenges. In recent years, air plasma processes along with sensor technology and new, creative material-powder manufacturing design concepts have continued to improve the reliability and economics of TS abradable coatings.
Environmental Barrier Coatings and Ceramic Matrix Composites

Engine manufacturers are developing and optimizing the use of ceramic matrix composites (CMCs) (Fig. 6a) to replace existing superalloy components. CMCs not only offer weight reduction but also withstand the significant increase in temperature (Ref 26, 27). The technical and manufacturing challenges of CMCs are its relatively high cost and vulnerability to water vapor-rich combustion environments. To address the later challenge, CMC components require environmental barrier coatings (EBCs) (Fig. 6b) which are more resistant to water vapor attack. Critical areas of development include the bond coat and designing new ceramic topcoat layers which provide water vapor stability, thermal expansion compatibility, and phase stability over time and temperature (Fig. 6b). Similar to TBCs, CMAS and erosion issues also need to be accounted for in any EBC design. Various research programs, both in academia and in industry, are underway to develop reliable and robust EBC coated components for 1480 °C, and eventually 1650 °C, operating temperature targets. Today EBCs are used in some commercial engines but there is significant potential for growth over the next 5-10 years.

To reach a wider scale implementation, EBC development will need to consider three factors: (1) how alternative fuels impact performance, (2) cost and repairability, and (3) component geometry and the need for hermetic intermediate layers. The latter point may result in the use of processing technologies other than thermal spray (e.g., physical vapor deposition).

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FIG. 6 (a) Cross-section of a typical CMC (Ref 26), (b) a schematic highlighting the design requirements of a typical EBC.

FIG. 7 Importance of alloy development on wear and corrosion resistance. The map identifies various classes of carbides currently used for wear and corrosion-resistant applications.

Development and Growth of Landing Gear Materials

Over the past decade, thermal spray technology has replaced hard chromium plating. The main drivers for this process change are environmental health and safety requirements and the cost of hazardous waste disposal. Today, aircraft landing gears are coated with thermal spray-based coatings, but this has taken several years of extensive research, testing, and validation. Critical design requirements include, but are not limited to, corrosion—wear resistance, surface finishing capability, fatigue resistance, and residual stress. Although many materials have been tested for these applications, tungsten-carbide-cobalt-chromium powders have demonstrated success when the correct thermal spray parameters are used (Ref 28, 29).

Figure 7 illustrates an overview of the carbide size versus grain size and the corrosion and wear performance benefits of various matrix materials. Besides tungsten carbide materials, in the future, alternative materials could potentially include lightweight, hard, and wear-resistant materials such as boron carbide or other unique carbides, borides, or nitrides. The objective is to reduce the passive load on the aircraft with lower density, wear-resistant materials.

The challenges that have been addressed to bring TS coatings to landing gears were not only material
composition but the process reliability. Application of these coatings is now seeing extension from stainless steel to titanium-based substrates. Besides outer diameters, many applications are requiring internal diameter coatings, which adds an additional level of processing challenges.

Technology Trends

New Material systems

Thermal spray solutions for aircraft engines have been experiencing a constant emergence of additional application opportunities. On one hand, classic variants of known TBC and MCrAlY bond coat materials have been satisfying the evolving technical challenges for aircraft engines, while on the other hand, research and developments on disruptive material concepts, such as EBCs, are also pushing the engine efficiency limits. The authors would also like to mention two additional emerging concepts for next-generation coating materials.

MAX Phases

MAX phase materials ($M_{n+1}AX_n$) are unique due to their crystal structure where a combination of the best attributes of both metals and ceramics are utilized (Ref 30). Here, $M$ is an early transition metal, $A$ is an A-group element (mostly IIIA and IVA, or groups 13 and 14) and $X$ is either carbon and/or nitrogen. This class of materials is oxidation resistant, lightweight, machinable, high-strength, corrosion-resistant, and exhibit high thermal and electrical conductivity. There are many combinations of MAX phase regimes, but the three key compositions researched are $Ti_2AlC$, $Ti_3SiC_2$, and $Cr_2AlC$. Studies have demonstrated the potential of $Cr_2AlC$ as a high-temperature bond coat for TBCs. Challenges remain with the fabrication of these materials and determining the best application method which sustains the material chemistry and characteristics during the thermal spraying process. It has been reported that these phases can operate up to approximately 1200 °C, which is well above the capabilities of conventional MCrAlYs.

High Entropy Oxides (HEOs)

HEOs are part of a new class of materials, known as high-entropy alloys, which consist of 5 or more principal elements ranging from 5 to 35 at.% (Ref 31, 32). HEOs are of interest for advanced TBC applications due to their unique properties which are attributed to the higher number of components in a given crystal structure (i.e., high configurational entropy) and highly strained crystal lattices. These design principles open up a door to numerous combinations of TBC materials that can address future requirements. Among other properties, HEOs have demonstrated in early research low thermal conductivity and improved phase stability at elevated temperatures compared to other advanced TBC systems.

Alternative Substrate Materials

Complex Refractory Alloys (Niobium, Molybdenum, and Tantalum)

Besides the growth of CMC technology in the turbine industry, various government-supported programs are actively involved in the development of substrate materials based on refractory alloys. In the USA, these programs are supported by government agencies such as DOE (Department of Energy) and ARPA (Advanced Research Project Agency) (Ref 33). Europe is also leading similar development programs on these materials, and in fact, they are defined as “critical” materials (Ref 34). The objective is to develop new materials for power generation and aerospace that can operate up to 1300 °C (2372 °F) without cooling and coating designs, and up to 1800 °C (3272 °F) with coatings and internal cooling. These advanced materials will ultimately need to be fabricated into turbine blades.

Oxide/Oxide (O/O) Ceramics

These ceramic composite systems are lightweight combinations of alumina and/or mullite fibers embedded in an alumina matrix (Ref 35, 36). They are potential high-temperature alternative solutions to superalloys and silicon-based ceramic matrix composites. Research and development will need to improve material strength, fabrication, and perhaps the process for their repair.
Compatibility of protective coatings for these O/O ceramics will be dependent on many factors such as thermal expansion mismatch and the ability to achieve adhesive bonding necessary for application.

**Ceramic Matrix Composites (CMCs)**

Previously discussed, the benefits of CMCs over traditional superalloys are their lightweight and high-temperature capability. However, challenges remain in terms of cost and their dependence on coatings to prevent water vapor attack (Fig. 8).

**Carbon Fiber Reinforced Plastics (CFRPs)**

CFRPs are gaining more and more use on airframes to replace traditional metallic alloys such as aluminum (Ref 29). Although their cost is relatively higher, their strength and lightweight benefits have led these materials to be used on Boeing 787 aircraft.

**Legacy Materials (Superalloys, TiAl, Al)**

Many traditional aircraft components are also being evaluated using alternative manufacturing technologies (Ref 29). Additive manufacturing is just one example. The values of this technology are reduced time, ease of manufacturing complex parts, and reduced waste of machining components. A key challenge is an ability, when needed, to design and implement surface engineering solutions such as thermal spray coatings.

**Sustainability**

Over the years it has become increasingly clear that climate change is resulting in global warming which has mostly been attributed to CO₂ emissions (Ref 6, 37-40). The transportation industry, along with new government regulations, is constantly challenged to reduce carbon emissions. Although the industry is composed of many sectors (auto, ships, buses, trains, and aerospace); aviation, even though not the largest, remains one of the most important sectors. The technology commercialized in this market sector has influenced other markets through the decades creating new products and services.

According to the International Air Transport Association (IATA), commercial aviation is responsible for 2-3% of global carbon emissions. In 2009, the industry established three targets to address climate change: (1) improvement in fuel efficiency of 1.5% per year from 2009 to 2020, (2) cap on net aviation carbon dioxide emissions, and (3) reduction in net aviation carbon dioxide emissions by 50% by the year 2050. The aviation industry has set a number of evolutionary short-term and radical long-term goals to meet these targets. One recent example is seen in the CFM International RISE (Revolutionary Innovation for Sustainable Engines) program which sets a target of more than 20% lower emissions, 100% compatibility with alternative fuels, with a technology roadmap detailing CMC composite fan blades and more (Ref 41).

Some key facts to consider when thinking of aviation and its sustainability goals for the future are:

(a) The world population is growing and living longer. Additionally, people will become increasingly mobile, and more people will be flying.

(b) It is projected that more of the world population will be living closer to cities and airports.

(c) Air transportation is expected to grow over the next 10 years, with China and Asia Pacific regions seeing the greatest expansion, irrespective of the current pandemic

(d) Market drivers which will lead to technical advancement in aviation.

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Fig. 9 (a) Engine efficiency improvements over the years with advanced coating and base material technologies (Ref 42). (b) Chart identifying a few select engine types with improved efficiencies
Typical aircraft generations, succeeding each other, are seen every 15-20 years.

Technologies continue to evolve with the intent of improving fuel efficiency. Between 2005 to 2030, it is estimated that an improvement of approximately 30% can be achieved.

Historically the market pull from aviation also leads to accelerated growth of new products and services in surface engineering solutions including, but not limited to, thermal spray technology.

Despite all the sustainability goals listed above, it is yet to be seen how the growth of the aviation market will deviate from the earlier predictions (Fig. 2).

Figure 9(a) is an example of how technology improvements, over time, lead to increases in surface temperatures (Ref 42). This has occurred through the lessons learned in materials and manufacturing technology of superalloys and internal air-cooling designs, along with thermal barrier coating systems (Ref 43). The need for lighter-weight materials has resulted in alternative substrate and coating systems, however, their technical, manufacturing, and commercial successes are challenging. Figure 9(b) identifies a few types of past, current, and futuristic aero engines and how they address the efficiencies. Will radical shifts in direction be made to transition aircraft toward battery hybrid/electrical propulsion-based systems? Will fossil fuels be replaced by sustainable biofuels or hydrogen-based fuels in the future? What will this mean for the design and development of new coating systems and substrate materials? All of these potential outcomes remain to be seen in the future, however, these changes that are redefining the conventional propulsion system will offer many new opportunities (Ref 41).

Workforce and Behavior

The pandemic caused a significant loss of business in the aerospace marketplace. The subsequent impact on the supply chain has led to attrition of staff in the manufacturing, engineering, and technical sectors. Many companies gave senior employees incentives for early retirement. As the market recovers, these voids will need to be filled. Yet replacing those individuals with qualified personnel is difficult as many of the roles have become more demanding and complex (Ref 44). This is particularly critical in the thermal spray industry where skill-based knowledge is acquired through experience and hands-on learning. Furthermore, the complexity of government regulations is on the rise, especially in the aerospace industry where almost all new technology and developments are affected. In order to sustain the workforce and its behavior, three categories need attention.

Tribal Knowledge

Knowledge transfer from experience stakeholders is critical to the success of any company and its employees. It is imperative for individuals to not just understand one aspect of the process, but rather to have an understanding of the overall perspective of the coating solution. In thermal spray, individuals may be experts in one area of development (e.g., materials, equipment, or process) but for an aerospace application to be successful they must understand the synergistic interactions of all related disciplines along with the commercial aspects associated with it. It takes years to gain such a level of experience and the necessary practical learnings. Job rotations within an organization definitely benefit some companies, but when it comes to thermal spray technology, there are many unwritten aspects of the business. Such job rotation programs should be focused only within this area.

Government Regulations

Export control regulations have either slowed down or, in some cases, completely eliminated the information transfer between individuals and companies. It is important to recognize that information, in many cases, can be exchanged but requires licenses which take time to execute. The risks compared to the greater benefit need to be considered. Companies can be proactive by getting involved early on in technical advisory committees which influence export control regulations (Ref 45).

Training and Education—The New Norms

Today’s world is more global and international in nature, with no real physical boundaries. More people are working from home and are being asked to multi-task many items over a given period of time. It is now more imperative that communications are made in such a way as to ensure the same understanding. Education is required to recognize and understand how different regions and cultures of the world may interpret or understand information differently. The training of young professionals on the “soft skills” related to culture and communication is critical. McKinsey Global Institute reported that as workers transition into new roles as a result of evolution in the workforce, they will also need to learn more social and emotional skills. There will be a growing need for skills in advanced IT, programming, engineering, and R&D and these are challenges to employers to develop and provide such training to their workforce (Ref 46).
Cost of Ownership

As new engines and aircraft come online there will be demands for longer life, with reduced maintenance intervals, and quicker turnaround on the repair of components. The value of reduced cost of ownership strongly depends on lower production costs which translate into improved financial returns for the end-user. To achieve these goals, the aerospace supply chain will need more robust and reliable materials, powder manufacturing methods, and equipment, along with new and alternative spray processes. A few examples where the thermal spray industry is seeking to improve the total cost of ownership in aerospace applications are as follows:

Alternative Processes to Electron-Beam Physical Vapor Deposition (EB-PVD)

Many aerospace engine designs utilize a relatively large amount of EB-PVD thermal barrier coatings on its turbine blades. However, the capital cost of equipment is relatively high, and the coating process is labor-intensive. Suspension plasma spray (SPS) has come very close to replacing some of these applications (Ref 47). For larger market acceptance SPS coatings will need to demonstrate reliability, thermal cyclic life, erosion resistance, and CMAS resistance. It will need to be determined whether they can be applied to rotating blades, as opposed to stationary components currently suggested. Many researchers feel that there are great opportunities for MRO applications in the future (Fig. 10).

More Reliable and Robust Air Plasma Equipment

Over the years, plasma torch technology has evolved dramatically. Today, the arc behavior is more stable and the temperature profile in the plasma plume is more uniform. Feedstock powders are processed more uniformly in-flight over relatively long periods of spray operation (Ref 47). This has been achieved primarily by using “low current/high voltage” plasma torch designs that aim to control the arc length and its movement during operation. The main benefits of using such advanced torches are increased coating repeatability and quality, higher throughput and deposit efficiency, and longer hardware life compared to traditional designs (Ref 48).

Alternative Processes to Hard Chrome Plating

Thermal spray technology has already been proven to be a more sustainable and environmentally friendly technology than other processes such as hard chrome plating used on landing gear components for both ID and OD applications. In addition, many studies are currently underway into the potential to reduce chromium in thermal spray powders.

New Gun Technologies: High-Enthalpy Plasma and High Kinetic Energy Processes (High-Velocity Air-Fuel (HVAF) and Cold Spray)

High enthalpy plasma guns are being used to apply ceramics. This will allow for higher feed rates and/or improved deposit efficiency. Guns of this type will allow for greater flexibility of coating microstructures, properties, and performance. The value of HVAF over HVOF (high velocity oxy-fuel) technology may be process economics and the ability to apply improved carbide (thicker, lower stress) and improved MCrAlY (higher density, lower oxides) coatings. Whether HVAF can become an alternative process to LPPS (low-pressure plasma spray) remains a question. The typical cost of an LPPS system is much higher than an HVOF and/or HVAF system. Regarding

![Fig. 10 Comparison between conventional EBPVD TBCs and the recently developed suspension plasma spray (SPS) technologies, presenting opportunities for alternative processing routes to meet the future manufacturing demands (Ref 47)](image)
processes with high kinetic energy, (e.g., cold spray), besides depositing corrosion-resistant coatings on magnesium housings, potential is for the deposition and/or entrainment of new and unique materials that were never before deposited because of the instability of the materials in the flame (borides, silicides). In addition, the ability to deposit corrosion-resistant coatings onto reactive substrates, such as magnesium, cold spray has potential for depositing or entrapping new and unique materials. For example, unstable materials that would otherwise react in a typical high-temperature process might now be considered. Figure 11 shows the temperature and velocity profiles of various thermal and kinetic TS processes (Ref 31).

Alternative Process Gases and Longer Life Consumables

Helium is an expensive gas and is difficult to obtain in various regions of the world. With regards to plasma processes, cost-out can be achieved by using nitrogen or argon as primary gases and hydrogen and/or nitrogen as secondary gases. Additional development should be made investigating the elimination of helium as a process gas along with the use of powders that exhibit wider and more controlled particle size distributions.

Supply Chain Vitality

Supply chain vitality is an important challenge and growth opportunity for the aerospace industry; however, it is clearly dependent on a number of other pillars such as technology, people, and cost/process improvement programs. As the industry grows, there will be increased demands on the supply chain in terms of speed, efficiency, automation, and reliability.

The vitality of the supply chain requires serious attention, and the industry must embrace Industry 4.0. This can be seen through harvesting Big Data, digital twin models, as well as improved quality control management systems. Big Data analysis can not only be used to increase the speed of development for new material systems, but there is also the possibility of lowering the cost, ease of supply, and ease of manufacturing of alternative products. One such example could be the elimination of high-cost materials by investigating alternative chemistries. Furthermore, digital twin models enable engine manufacturers to accurately predict when replacement parts would be needed so they can better control supply chain management.

The following represent a few examples of supply chain vitality.

(a) Sensor Technology and Quality Management Future manufacturing sites will implement systems and processes that will have a higher level of control and digital “smartness” in order to achieve the requirements of aero-engine coatings. For example, the growth of sensor technology in the thermal spray field, for the spray process as well as for coating characterization, will lead to improved documentation and management of the processes needed for OEM approvals and for developing quality control standards. This should mitigate or remove human error from the process. The impact will be shortened fabrication lead times and improved component reliability. The “spray and pray” approach will eventually become outdated as more technology is implemented, and model-based engineering concepts become digitalized.

(b) Digital Twin Technology and Big Data Today engine manufacturers are also developing “digital twin” models to better understand and predict the life of engine components in order to extend service cycles and to increase maintenance intervals. Empirical data collected can be fed into sophisticated digital models that will refine the predictability of the performance of engine components under various environments. The use of digital twins along with harvesting Big-Data can reduce the time needed to design and commercialize new alloys. Historically, approximately 15-20 years was needed for next-generation super-alloys and TBC coatings. Digital twins are also being developed to mimic thermal spray systems. Integrating the models of the thermal spray machine with the components to be coated can...
greatly reduce the time needed to develop robot programming for complex geometries and to predict resulting coating characteristics (Ref 49, 50).

(c) People and Tribal Knowledge Finally, one area where the human element is still needed is in specification design and development. A common-sense approach to specification design is critical for the supply chain. In many cases, the designers of specifications lack experience and do not realize the broad implications of overly designed and unrealistic specifications. This relates back to tribal knowledge and experience, both of which are essential for developing sound and robust cost-efficient applications for the aerospace industry. The consequences of engine designers and material suppliers not communicating can be severe. A key question to ask is what coatings work in the field and on which components. Designers of specifications should work backward to develop acceptable design requirements and collaborate with their suppliers to ensure viable solutions in the end.

Conclusions

Despite the recent challenges of the past couple of years, the aerospace industry will continue to expand and follow the world population growth.Aligned with this growth, existing and new environmental concerns will lead to technical challenges which, in turn, will create new opportunities for the thermal spray industry. The growth of the thermal spray industry will be both evolutionary as well as radical in nature. Evolutionary growth will continue to address jet engine efficiency through new thermal spray materials and processes, such as thermal barrier and clearance coating systems for the turbine and combustor sections. Radical approaches might be needed to meet the industry targets to address environmental issues, such as hard chrome plating replacement for landing gears and some mainframe applications. Manufacturing and process engineering will play a critical role in many areas both in the fabrication of new lightweight ceramic matrix composites and environmental barrier coatings, as well as the integration of thermal spray technology with additive manufacturing requirements in the years ahead. There are other in-direct technologies, such as nondestructive evaluation (NDE), integrated computational materials engineering (ICME), and in-situ inspection of thermal spray process, that are enablers and critical for sustainable TS industry growth. New material concepts and designs can only be implemented successfully if manufacturing costs are controlled and new thermal spray equipment and processes are robust and reliable. Industry 4.0 implementation is now more critical and will help the supply chain to reduce internal costs and improve overall cost of ownership. To meet these challenges and sustain the growth of the thermal spray industry, investment in the development of people will be key. Development of “soft skills” and technical “hands-on” skill sets will be critical for collaborations to continue in the global world in which we are living.

Where we go in the future remains to be seen. However, researchers are exploring and starting to implement alternative fuels with the long-term potential use of hydrogen-based fuels and battery/hybrid jet engine propulsion technology in the years ahead. The use of hydrogen-containing fuels that operate at higher temperatures will present new challenges for our thermal spray coating systems and may open up the need for entirely new solutions by the year 2050 and beyond.

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