Removal and Repair Techniques for Thermal Barrier Coatings: A Review

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Abstract

A comprehensive literature review of the existing techniques for removing and repairing of damaged thermal barrier coatings is presented, with the focus of top ceramic coats. The advantages and disadvantages of each technique are compared and assessed. The review shows that there is not a universal method applicable to all coating systems. The selection of the coating removal and repair process must be specific to damaged coating systems, based on their composition, type of damages, and available resources. This review will provide some inside look at various approaches in an effort to meet the different coating repair needs.

Keywords: Thermal barrier coating; Removal; Repair

1. Introduction

The hot sections of turbine engines are covered with thermal barrier coatings (TBCs), which provide thermal insulating protection to the metallic substrates from hot gases. As shown in Figure 1, the TBC is usually comprised of four layers: (1) a ceramic top coat, typically composed of yttria-stabilized zirconia (YSZ); (2) a thin thermally grown oxide (TGO) layer, which acts as a protecting layer to retard oxygen diffusion and oxidation of the superalloy substrate; (3) a metallic bond coat, typically composed of NiCoCrAlY; and (4) a Ni base superalloy substrate.

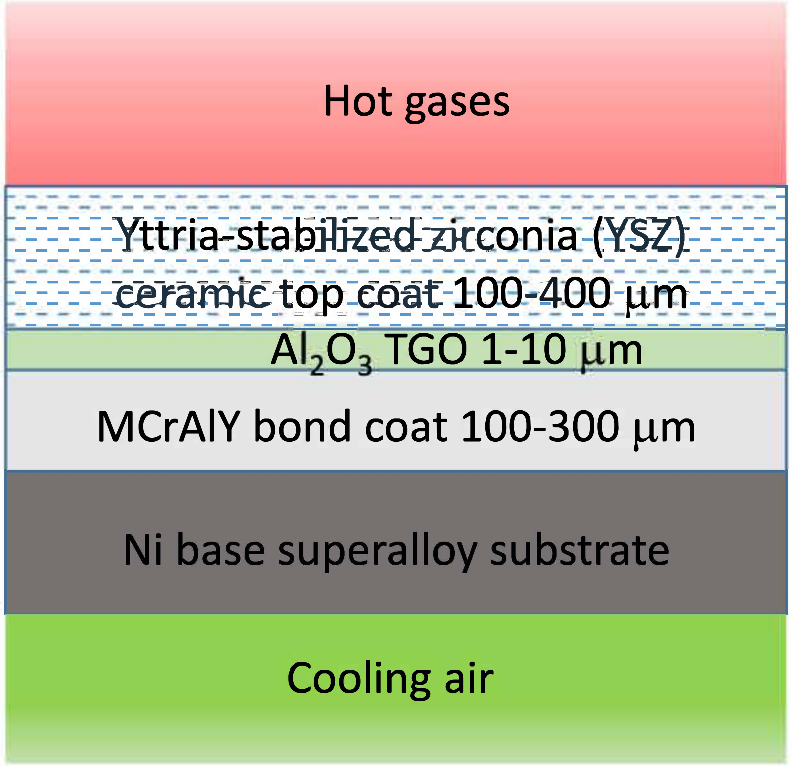


Figure 1: Thermal barrier coating structure and associated layers. The typical thickness of each layer is also given.

Over the period of turbine engine operations, TBC failure may occur. Spallation is a dominant mode of failure. Undesirable elements reduce the life of the coating. TBCs may become spalled, delaminated, chipped or eroded due to debris or environmental degradation. Any component with a damaged TBC must either be repaired locally or globally or replaced during maintenance of the engine. This results in the engines being taken off-line for a period for servicing. Every hour of downtime results in significant revenue loss, particularly in power generation plants.

The objective of this paper is to provide a comprehensive literature review of the existing techniques to remove and repair the damaged thermal barrier coating, with a focus on the top ceramic coat. The various techniques will be assessed and future direction will be given.

2. Removal Methods for Thermal Barrier Coated Components

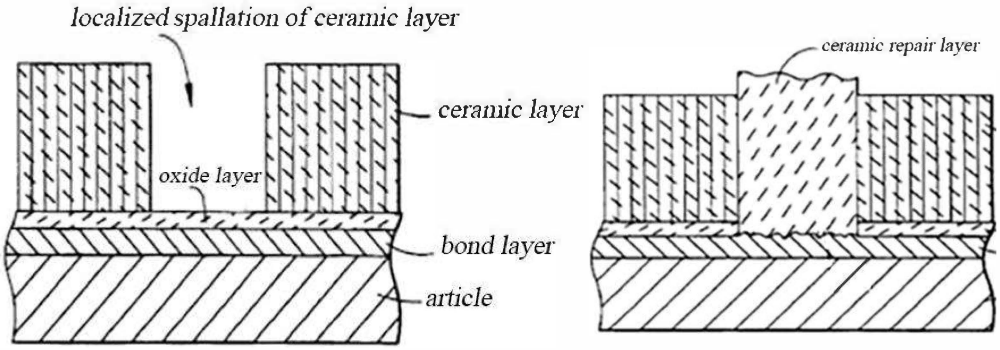
2.1 Blasting methods

2.1.1 Grit blasting with abrasive media

Grit blasting is a mechanical method, in which a stream of abrasive media, *e.g.*, alumina, silicon carbide, or sand, is forcibly propelled against a surface under high air pressure to remove surface contaminants; this process also includes tumble deburring, polishing, and other surface finish procedures [1]. During grit blasting, incident particles have a strong influence on the subsurface microstructures, both the matrix and the precipitates. Measurements revealed a slight increase in hardness of the subsurface layer of grit blasted specimens in comparison with the untreated material[2].

In practice, caution should be exercised to minimize the damage to the bond coat and substrate alloy during grit blasting. The bond coat and substrate alloy are both gray-metallic in color, which make it hard to distinguish the bond coat from the substrate. As a result, grit blasting may result in uneven material removal and thinning of the bond coat and substrate alloy. Additionally, the results of grit blasting can result in uneven removal and distortion of the coating's geometry, plus surface contamination with alumina. Aluminum contamination negatively affects the coating tensile bond integrity.

For localized coating damage, a preferred method is to grit blast the exposed surface of the bond layer, such as a technique known as pencil grit blasting[3], as shown in Figure 2. The first step is selectively performed to remove the damaged ceramic layer while ensuring that the remaining ceramic layer is not subjected to the procedure (Figure 2a). It may be desirable to mask the surrounding ceramic layer with, for example, tape masking, during the grit blasting operation. Finally, a new layer of ceramic coating is deposited on the textured surface to repair the layer (Figure 2b).



(a) (b)

Figure 2: Pencil grit blasting and coating repair [3]. (a) selective coating removal, (b) coating repair.

2.1.2 Blasting with solid CO_2

In this method, solid carbon dioxide (CO_2) is used to grit blast the ceramic coating layer with a spray gun, as shown in Figure 3 [4]. During the process, the solid CO_2 is sublimated into gas. The gas volume grows drastically, which could produce powerful shock waves. The kinetic energy is generated from high speed and thermal energy from the heating and irradiation process. The shock wave removes the coating surface, the existing cracks, and the particles which have been blasted off or which have a poor adhesion to the coating. The shock wave increases with the degree of sublimation. The coating can also be pre-heated with an IR lamp, as shown in Figure 3, to increase the sublimation effect.

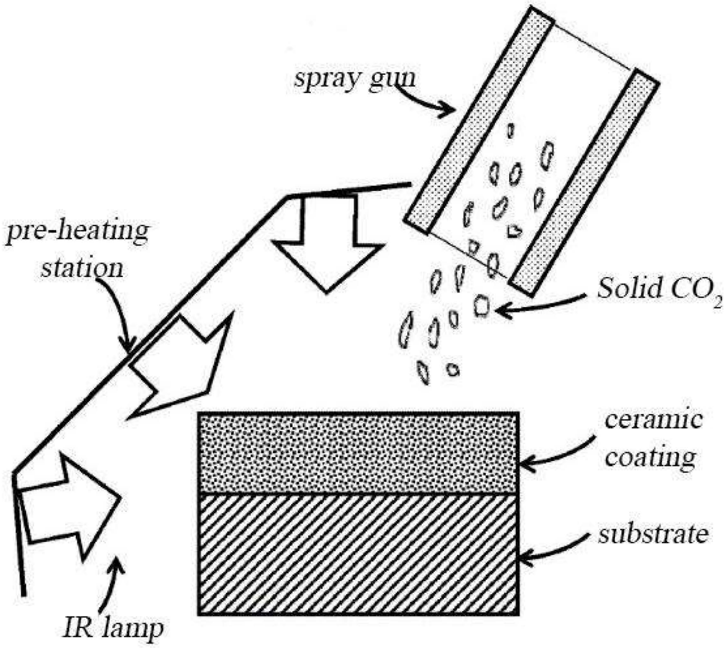


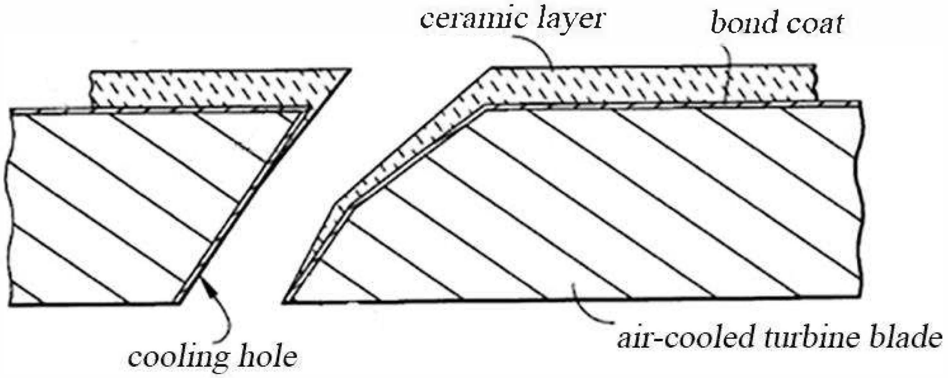
Figure 3: Schematic of coating removal using solid CO_2 [4].

2.2 Chemical stripping

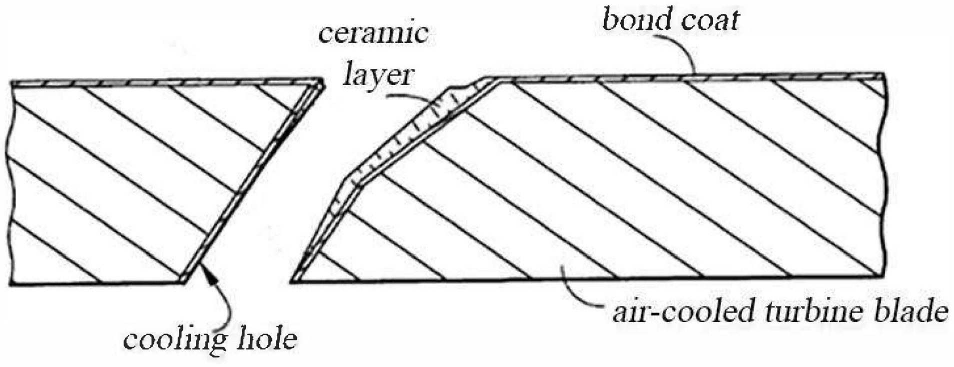
2.2.1 Autoclaving process

One of the disadvantages in the abrasion blasting techniques such a as grit blasting is that it can chip away the substrate, thinning the part's wall over multiple applications. Autoclaving the coating or immersing the part in a caustic solution can better control of the breaking of the bonds [5].

In the region with cooling holes, the autoclaving process can be applied to remove the ceramic layer without damaging the bonding layer and cooling holes. During the autoclaving process, the ceramic surface is removed under the caustic solution at an elevated temperature and pressure in the autoclave, as shown in Figure 4 [6]. The caustic solutions are typically mixed potassium hydroxide (KOH), sodium hydroxide (NaOH), ammonium hydroxide (NH_4OH), lithium hydroxide (LiOH), triethylamine ($C_6H_{15}N$, or $(CH_2CH_3)_3N$), and tetramethylammonium hydroxide ($C_4H_{13}NO$). After the autoclaving process, the cooling holes are subject to an ultrasonic cleaning process in a solution of water or glycerol, in which the ceramics are removed from the cooling holes. The autoclaving method can change or repair the ceramic layer without accumulating extra ceramics inside the cooling holes, thereby maintaining the cooling hole size.



(a)



(b)

Figure 4: Schematic of ceramic layer removal using autoclaving process by exposure the coatings to a caustic solution at elevated temperatures and pressures. (a) before the process, (b) after the process [6].

For electron beam–physical vapor deposition (EB-PVD) TBCs, General Electric (GE) Company has developed a proprietary process to remove the ceramic layer while leaving the bond coat fully intact [7]. Figure 5 shows an example of an engine run turbine blade with partial TBC spalling before and after processing through GE's ceramic removal process. As shown in this figure, the GE process removes the ceramic coating from the airfoil surfaces and the cooling holes without impacting the underlying bond coat. The dashed lines on the "after" photograph highlight the region where TBC spallation during engine service resulted in distress of the bond coat. The GE process does not employ traditional stripping methods such as mechanical removal, and as such, there is no risk of thinning of blade walls. Figure 6 shows photomicrographs of a bond coat before and after processing through the ceramic removal process, confirming the bond coat is not damaged during TBC removal [7].

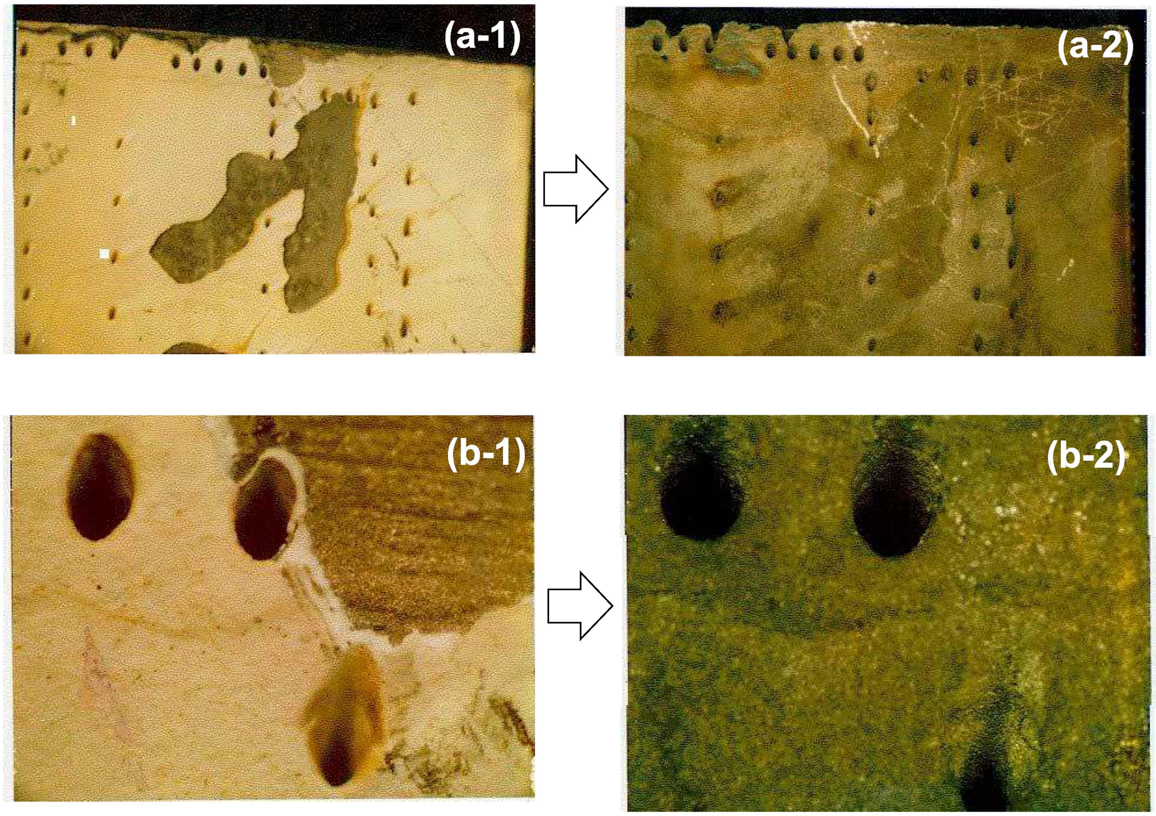


Figure 5: Photographs of an engine run high pressure turbine blade with partial spalling of the PVD thermal barrier coating before (a-1, b-1) and after processing (a-2, b-2) through ceramic removal. The bond coat distress pattern formed in the region of the spall can still be seen after ceramic removal. Note that no residual ceramic in cooling holes in (b-2) [7].

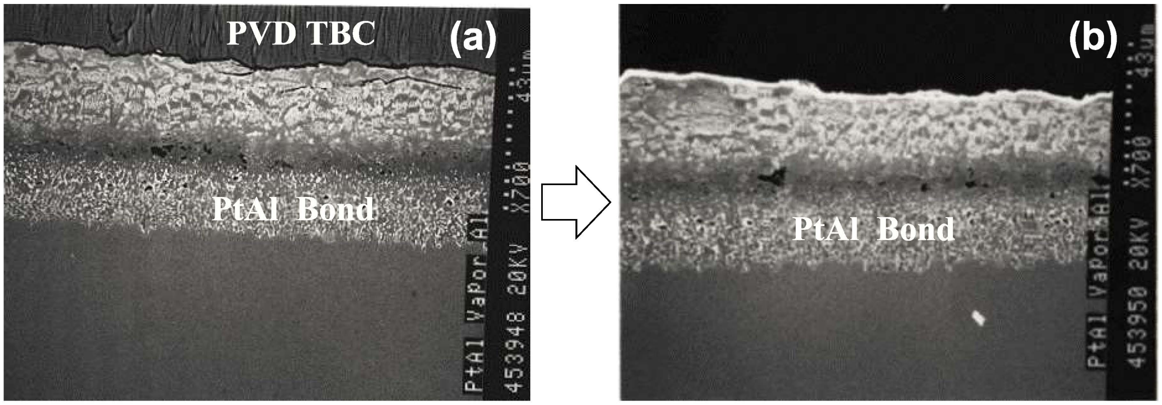


Figure 6: Photomicrographs of a platinum aluminide bond coat before (a) and after (b) ceramic coating removal. Note that the bond coating is not damaged even though a brittle, $PtAl_2$ rich bond coat was used for this trial(magnification 700×) [7].

2.2.2 Aqueous stripping

Aqueous stripping with acid fluoride salt method [8] is used to remove the ceramic layer, such as yttria-stabilized zirconia (YSZ), from substrate without damaging the bond coat. The ceramic layer is removed by exposure to the aqueous stripping solution containing an acid fluoride salt, such as ammonium bifluoride (NH_4HF_2) or sodium bifluoride ($NaHF_2$), and a corrosion inhibitor. The acid fluoride can convert zirconia to zirconium, through a process for treating a zirconia-based material comprises reacting the zirconia-based material with ammonium bifluoride, NH4F·HF. An ammonium fluorozirconic compound is produced [9]. Also, the corrosion inhibitor could protect the metal substrate. The operating temperature is about 60-75 °C, and the stripping time is about 4-5 hours. This process could also be combined with the ultrasonic treatment. The ultrasonic treatment can be continued until the TBC is completely removed or at least sufficiently loosened so that it can be removed by brushing or pressure spray rinsing which could shorten the process time to 2-5 hours.

For corrosion barrier coating, a selective stripping process has been developed [10]. The corrosion barrier coating comprises of a ceramic matrix, e.g., zirconia, containing a phosphate-chromate binder and metallic particles dispersed in the ceramic matrix. The coating system contains a glass composition in at least one of the corrosion barriers and top coatings. The metallic particles are formed of a corrosion-resistant metal alloy. In this method, the process comprises of immersing the component in an aqueous solution containing ferric chloride, nitric acid, and phosphoric acid. The component is immersed in the aqueous solution for a duration sufficient to attack the metallic particles in the corrosion barrier coating. The component is removed from the aqueous solution, and then is rinsed to remove the aqueous solution from the coating system. The immersing and removing steps are sequentially repeated a sufficient number of times to sufficiently attack the metallic particles to render the ceramic matrix as a soft residue that can be mechanically removed from the component.

Chemical stripping is less environmentally friendly than abrasive blasting. The abrasive media are natural, eco-friendly materials that do not emit greenhouse gases during the blasting process. Chemical cleaning often has to be accompanied by a manual procedure using a scrub brush or scraper, but this process is nowhere near as efficient as abrasive blasting. The adhesion profile of a surface can be controlled by using different particle sizes of the blasting medium for the surface preparation process. Chemical stripping does not allow any control over the final surface roughness profile [11].

GE also developed a proprietary corrosion removal process for high pressure turbine blades returned from engine service, which can have a wide range of hot corrosion attack patterns resulting from variation in the operating environment and time on wing [7]. Any process developed for corrosion removal must be able to accommodate this wide variety of incoming conditions and still leave intact coating that is free from corrosion products. Figure 7 shows an example of a blade with corrosion attack before and after processing through the developed corrosion removal process [7].

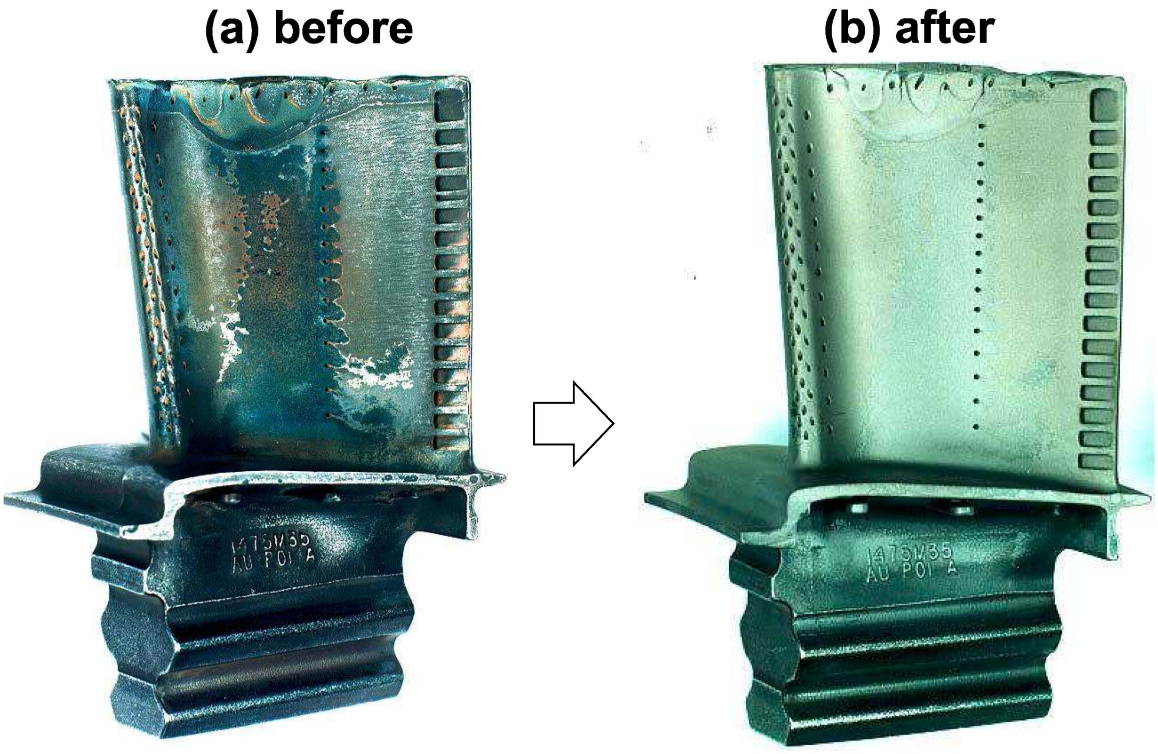


Figure 7: Photographs of an engine run CFM56-3 high pressure turbine blade with hot corrosion before (a) and after (b) processing through GE's proprietary corrosion removal process [7].

2.3 Water jet

2.3.1 Non-abrasive water jet

The non-abrasive method uses a high pressure water jet to remove the ceramic layer from both the inner and outer surfaces [12, 13] (see Figure 8). The water jet is at normal angle to the surface of the TBC layer and the surface of the substrate. Therefore, the non-abrasive water jet can remove the ceramic coating layer without destroying the underlayer part. Besides, the jet also has the influence on the surface roughness, which could promote the adhesion of new ceramic coating layers.

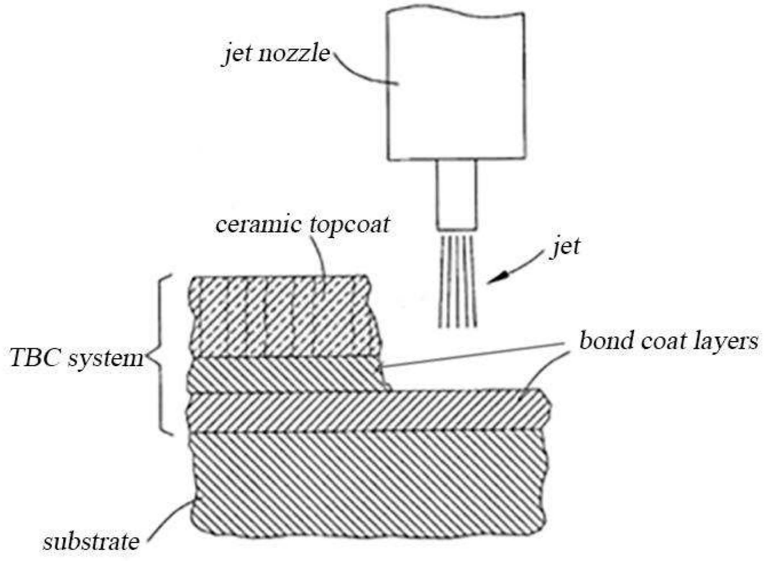


Figure 8: Schematic of water jet process [12].

2.3.2 Precision abrasive waterjet process

Precision abrasive waterjet process (AWJ) is an environmentally friendly process that removes coatings without damaging the turbine component, which can lower the costs [14]. In this process, a five-axis computer numerically controlled (CNC) AWJ [14] removes the coating in iterative steps. The CNC process offers certain advantages. It is a controlled mechanical removal process, like a surface milling process with tight tolerance control. The waterjet stream is controlled to a specific distance from the surface, with feed and speed controlled by computer software that, for example, keeps the offset angle normal over the entire form of a blade. The damaged coating thickness is measured before and after the AWJ to insure full removal of the bond coating and diffusion layer, as well as any contamination or corrosion under the ceramic top coat. Many companies use this method then bag the part and send it directly to coating.

2.4 Laser ablation

Lasers can be used to selectively remove the coating instead of stripping away all the ceramic coating. In this process, less of the ceramic is wasted than the water jet process [5]. Carbon dioxide CO_2 lasers emit radiation of wavelengths around 9.6 µm and 10.6 µm which are absorbed quite well by ceramics. CO_2 lasers do not interact much with metals, which means the metallic bond coat and substrate underneath will be preserved [5]. Figure 9 shows the working principle of the laser ablation system [15]. The work head receives the laser signal and the laser signal passes through the focusing lens to the samples. After a section is ablated, the work head is moved to another region and the process is repeated.

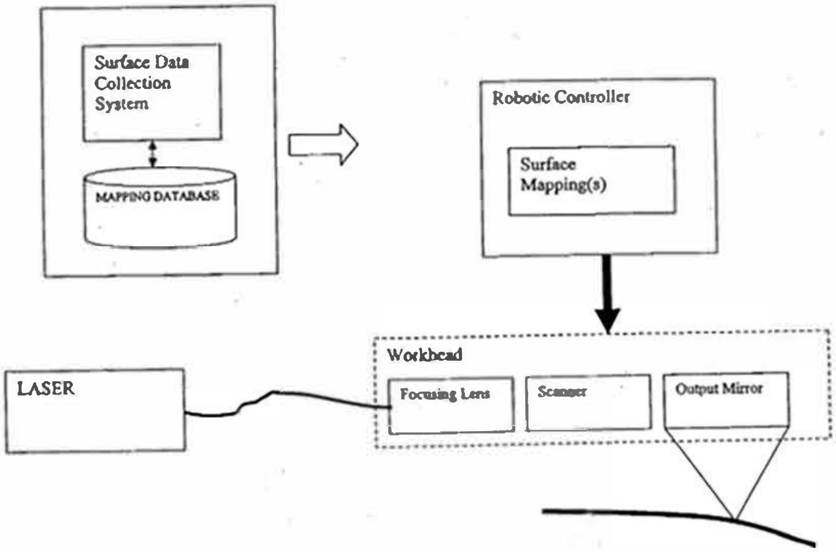


Figure 9: The working principle of a laser ablation system [15].

Figure 10 shows the experiment in which the laser ablates the YSZ ceramics. This method is superior to the current grit blasting and chemical processes. Increased precision of coating removal leaves a high level of cleanliness, eliminates chemical waste, reduces labor input, and improves worker safety. The process also leads to large savings from the enhanced life of engine parts, and minimization of down time during engine overhaul or repair process [16].

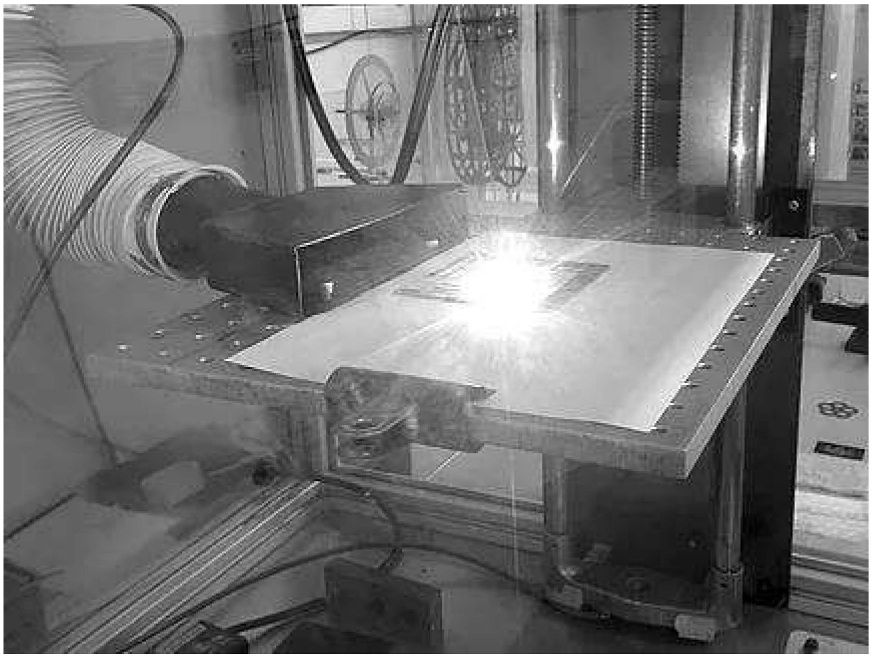


Figure 10: Experiment showing laser is capable of melting YSZ ceramics [5].

3. Repair Techniques for Thermal Barrier Coatings

3.1 Plasma spraying

3.1.1 Air plasma spray

The plasma spray technique is often used to repair the less complicated surface [3]. When a cooling hole exists, fibers or flowing gas are used to prevent the closure. The repaired layers have good thermal cycle resistance. The repaired layer is usually thicker than the original coated substrate, and the repaired surface is polished until it is substantially flushed with the original ceramic layer.

3.1.2 Suspension plasma spray

Compared with traditional plasma spraying, suspension plasma spraying (SPS) allows smaller particles to produce the fine columns to repair the vertical cracks or defined gaps , as shown in Figure 11 [17]. Therefore, it can provide strain tolerance to the coating layer. Besides, the repaired layer of SPS is polycrystalline and has no obvious lamellar features, which can be used to repair the gas turbine engines. Although the ceramic microstructure of the SPS repaired layer is different from the EB-PVD produced coating layer, the microstructure of the SPS repaired layer can provide a long lifetime.

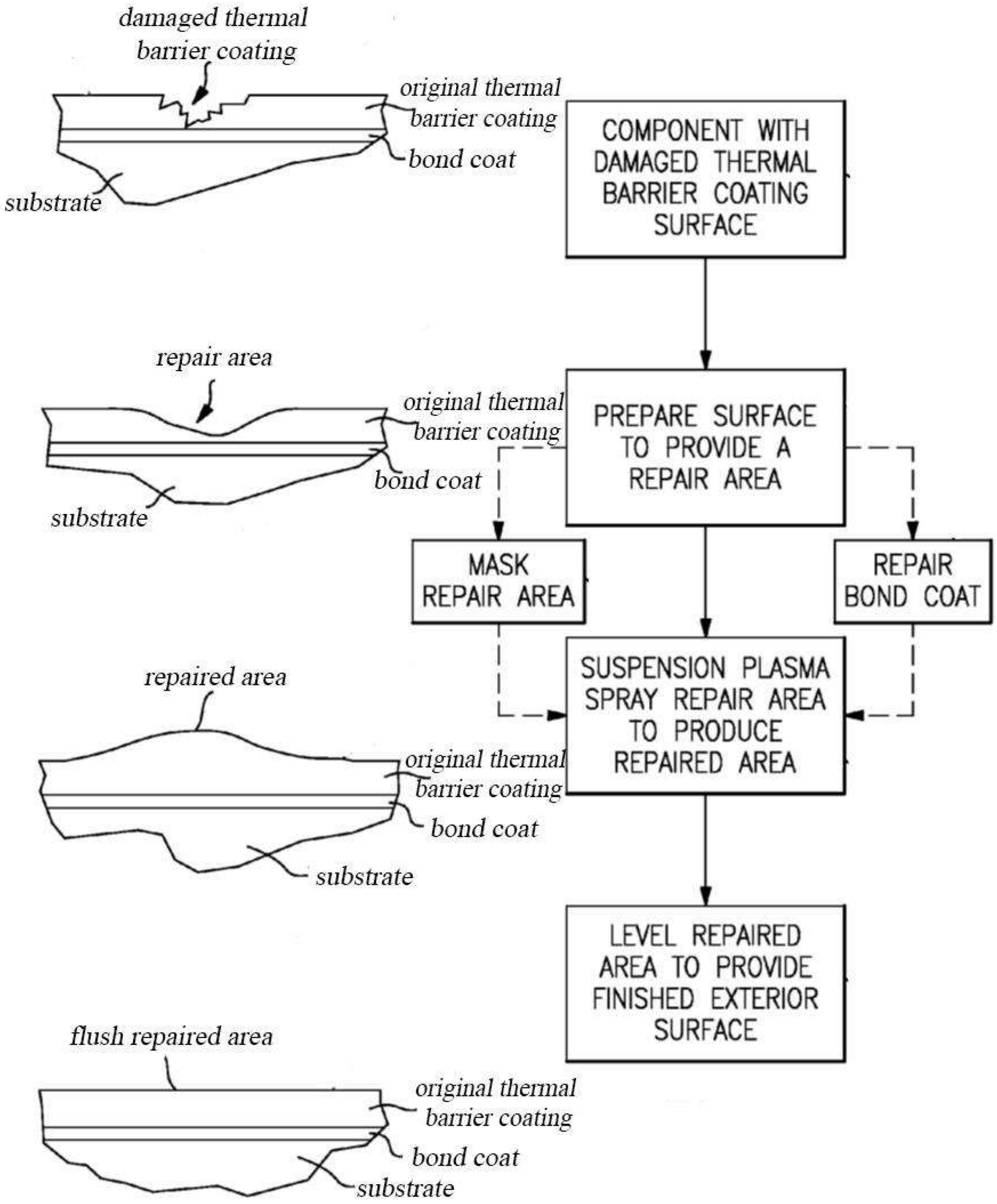


Figure 11: Schematic and flow chart of using SPS technique to repair a damaged TBC [17].

3.2 Chemical paste

3.2.1 Ceramic paste

Figure 12 [18] is a cross-sectional side view of a typical thermal barrier coating (TBC) system associated with a component of a gas turbine engine or the like, in which the TBC system has suffered localized spallation. Figure 12 shows the localized spallation in a TBC system, which is filled with a ceramic paste with TBC patch composition. The ceramic paste contains scandia yttria stabilized zirconia (SYSZ) and an organic binder. During the repairing process, the ceramic paste with a TBC patch is dried under 65 °C to prevent violent volatilization and bubbling, then dried under 300 °C so that the silicone resin is transformed to silicone resin with a high strength.

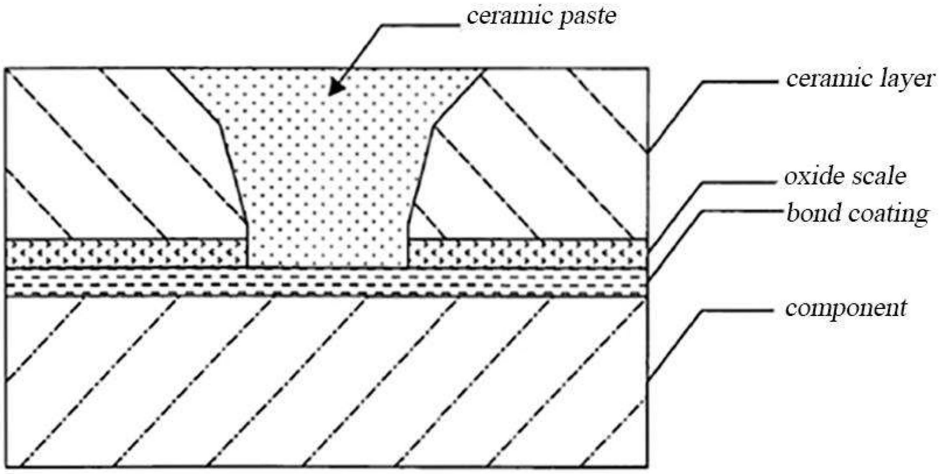


Figure 12: The localized spallation in a TBC system is repaired filling in a ceramic paste [18].

3.2.2 Ceramic gel

A gel is applied on the thermal barrier coating surface and then heated [19]. The heating process occurs in two steps. The first step is heating to remove impurities and volatile material from the gel. The second step involves curing the actual gel coating to the thermal barrier protective layer. The coating of the slurry contains zirconia filler. The curing of the slurry component transforms precursors into the oxide matrix. Depending on the intended application, the gel can also be applied in layers with different percentages of zirconia filler.

Partially yttria stabilized zirconia (YSZ) [20] sol-gel can be used to fill the crack of the damaged TBC layer. The solution is evaporated to leave the partially stabilized zirconia precursor. The solvent is evaporated until a suitable thickness of repair layer is produced. Then the partially stabilized zirconia is heated under 900°C to produce the thermal barrier coating layer.

3.2.3 Composite preform

The composite preform method repairs a metal component especially for damaged coatings [21]. By sintering mixed particles of the coating layer and brazing alloy, a composite preform is produced. Then the preform is deposited on the surface of the metal component that the damaged coating layer has removed. The composite preform and metal surface are bonded by a brazed joint through heating under appropriate temperatures. As shown in Figure 13, once the composite prefab is prepared, additional coatings may be optionally placed on the surface of the composite prefab. For example, also as seen in Figure 13, a TBC layer can be deposited on the composite prefabricated piece. In addition, an oxide layer of the same composition as well as the oxide layer of the metal turbine components can be deposited on the composite prefabricated piece to facilitate bonding between the TBC layer and the composite preform piece.

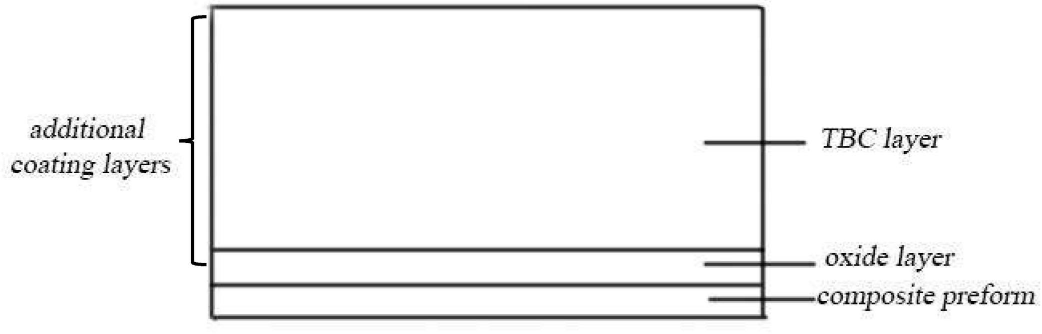


Figure 13: Schematic of repaired coating which the TBC layer is deposited above the composite preform [21].

3.3 New repairing techniques

In addition to the traditional coating removal and repair processes discussed above, new processes are being developed thanks to advanced technologies. For example, in 2018, Rolls-Royce demonstrated a future technology of engine maintenance with robots that can crawl inside engines [22]. The Rolls-Royce technology is named FLARE, which is the world first prototype snake robot for *in-situ* coating repair in jet engines. FLARE is a pair of ‘snake’ robots which are flexible enough to travel through an engine, like an endoscope, to carrying out patch repairs to damaged thermal barrier coatings [22].

4. Assessment of Different Coating Removal and Repair Techniques

This report summarizes a review of the different methods used for repairing damaged thermal barrier coatings in the literature. Table 1 and Table 2 summarize and compare the different removal and repair methods for damaged coatings. It is clear that based on the literature survey data, there is not a universal method applicable to all coating systems. The selection of the removal and repair process must be specific for damaged coatings, given its composition, process, type of damages, and available resources.

Table 1: Removal Methods for Thermal Barrier Coatings

Grit Blasting	Grit blasting	Advantages 1) Relatively inexpensive to operate and maintain 2) No harmful chemicals are needed 3) Creates a cleaner surface finish Disadvantages 1) Can result in uneven surfaces caused by uneven material removal. 2) It's usually a non-controlled process which leads to varying results. 3) Can potentially distort part geometry.
	Grit blasting with solid CO_2	Advantages 1) Unlike other blast media, the CO_2 particles have a very low temperature of -109° F, giving a unique thermodynamically induced surface mechanism.
		Disadvantages 1) State of the art blasting machines for dry ice can use only a discontinuous (pulsed) solid CO_2 blasting flow. 2) Removal rate decreases if a pulsed flow is used.
Chemical Stripping	Autoclaving	Advantages 1) This process enables the ceramic layer of an air-cooled component to be completely replaced without accumulating additional ceramic in the cooling holes. [3] 2) Because the present process can remove ceramic from a cooling hole, the performance of an air-cooled component treated with this process is

		promoted by the restored uniform film cooling of the component surfaces. 3) This process is less costly and time-consuming than if a waterjet were used to remove the ceramic layer from the substrate
		Disadvantages 1) Requires the use of an autoclave operating at high temperatures and pressures. 2) Equipment is expensive.
	Aqueous stripping	Advantages 1) Reduced labor, equipment and processing cost. 2) Can be used to treat a variety of issues such as removing impurities including stains, rust, and contaminants. 3) Removes TBC from the cooling holes of air-cooled components. 4) Since all the TBC is removed from the holes, the performance of the component is increased.
		Disadvantages 1) It requires the use of corrosion inhibitors. 2) The process is toxic. 3) Acid can result in cracking, corrosion, and other destructive effects on the material. 4) High cost for waste stream control.
Water Jet	Precision Abrasive Water Jet	Advantages 1) Environmentally friendly 2) Removes coatings without damaging components. 3) Surface produced is free of contamination. 4) CNC process to promote consistency.

		Disadvantages 1) Could be slightly higher in cost due to required equipment and maintenance.
	Non-abrasive Water Jet	Advantages 1) Could remove the TBC layer without damaging the substrate. 2) High level of cleanliness 3) The jet has the influence on the surface roughness, which could promote the adhesion of new ceramic coating layers.
		Disadvantages 1) limited to use on thin or soft materials
Laser Ablation		Advantages 1) The laser ablation process can be used as a cleaning system and for removing damaged TBC. 2) The level of accuracy and cleanliness is high. 3) The position of the laser work head can be adjusted. 4) It can be used as a laser-based analysis system. 5) It can clean the turbine in its housing.
		Disadvantages 1) Power requirement is high. 2) Skilled workers are required for operation. 3) It is expensive to set up.

Table 2: Repair Methods for Thermal Barrier Coating Components

Plasma Spraying	Advantages 1) Coatings are strongly bonded to the substrate.

	2) They have higher integrity. 3) The repair method enables faster repairs as full coating removal is not necessary.
	Disadvantages 1) The high temperatures associated with the plasma jet can result in excessive oxidation when spraying in air, giving carbide coatings with lower hardness or metallic coatings with higher oxide levels compared with HVOF sprayed coatings.
Chemical Paste	Advantages 1) The gelation time can be manipulated by varying amount of water added. 2) It takes comparatively less time. 3) A simple repair process
	Disadvantages 1) Polishing is needed to even out the surface. 2) It cannot be used for complex spot repairs. 3) The quality of repair is mediocre.

5. Concluding Remarks

In summary, the type of method used for repairing the damaged TBC depends on multiple factors. There is not a universal method applicable to all coating systems. The selection of the coating removal and repair process must be specific to damaged coating systems, based on their composition, type of damages, and available resources.

Acknowledgments

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