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A Short Review on Alternative Cleaning Methods to Remove Scale and Oxide from the Jet Engine Alloys

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***Abstract*—The hot section of the aircraft engine (e.g.: stator casing, turbine blades, etc.,) often gets contaminated with the scale, soil and dirt during its operation. These contaminations adhere strongly to the surface along with oxide build up due to the very high operating temperatures. It severely affects the performance of the gas turbine engine by decreasing its efficiency. As of now, chemical cleaning is the most widely used method by the engine manufacturers and maintenance service providers around the world to restore the material aesthetics and efficiency. Though there are number of cleaning chemistry which could successfully remove these contamination's from the surface, major shortcomings like processing time, disposal (some solvents and chemicals are toxic and not environmental friendly, requires special disposal procedures), user's health & safety and efficiency in cleaning the complex geometries and large parts makes the manufacturers and maintenance service providers to look for alternative cleaning methods. In this paper, some of the commercially available alternative cleaning methods are discussed along with their working principle, capabilities, applications, advantages and disadvantages.**

Keywords—*Scale and oxide removal, jet engine alloys, alternative cleaning methods.*

I. Introduction

The dirt and sand particles ingested into the aircraft engine from the atmosphere forms a glass like deposit on the hot sections like turbine blades, stator and the casing [1]. Other contaminations like carbon deposits or ashes from the combustion chamber also settle on the surface of the turbine blades and critical areas like cooling holes along with the engine oil and coolants during operation. Due to the elevated temperature prevailing inside these hot sections, these contaminations along with the oxide build-up (characteristic of the materials used in the hot sections) strongly adhere to the surface changing the flow field and blocking the cooling holes, thus severely affecting the performance of the engine [1]. These contaminations have been removed from the surface till date by a range of chemicals and solvents.

Despite of the ability of the chemical cleaning methods to remove these contaminations to restore the efficiency, manufacturers and maintenance service providers look for alternative cleaning methods for the following reasons: a) to reduce the processing time, b) the wastes generated after the chemical cleaning process often requires special disposal procedures as the governments around the world follow stringent regulations to protect the environment c) cost reduction and d) personnel's health and safety. Surface finishing is also a critical factor in aerospace component's functionality [2].

Alternative methods which overcome the limitations imposed by the chemicals or solvents are as follows: 1) Shot blasting 2) Water jet cleaning 3) Dry ice blasting 4) Ultrasonic cleaning 5) laser cleaning. These alternative methods are discussed in detail in this paper.

II METALS AND ALLOYS USED IN GAS TURBINE ENGINES

A gas turbine engine is made up of a number of high performance materials. Metals and alloys used for such applications should withstand elevated temperatures and have good thermo-mechanical properties, high strength-to-weight ratio and excellent resistance to fatigue & creep loads [3]. Percentage of different metals and alloys used in an aircraft engine (GE CF6 engine as of the year 2000) is given in the Figure 1.

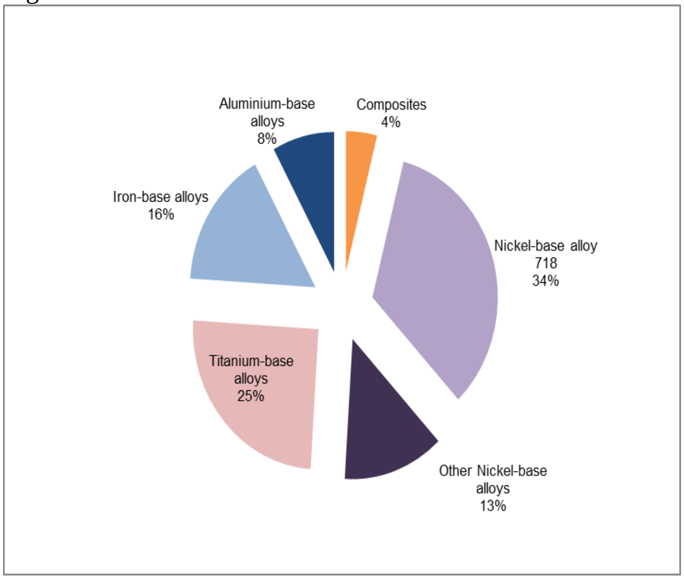

Fig.1 - Types of metals and alloys used in GE CF6 Engine [4]

The materials of interest to this literature review are stainless steel alloys (AMS 5504 & AMS 5524) and titanium alloy (AMS 4911).

II. MECHANISM OF OXIDE FORMATION

Metals and alloys used in hot section of the aircraft engine react with the oxygen at elevated temperatures and undergo the phase formation as shown in Figure 2 to form an oxide

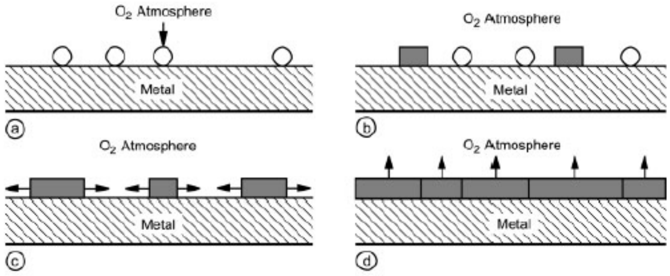

Fig 2 - Phases in the oxide formation on a metal surface a) Oxygen adsorption at the surface, (b) Nuclei formation, (c) Growth of the nuclei in horizontal direction, and (d) Growth of the compact oxide scale in vertical direction [6]

layer over the surface [5, 6]. Oxide film composition of the alloys differs from that of a pure metal and it is influenced by the type, quantity and number of alloying elements [6].

a) Titanium (Ti)

Titanium and its alloys are highly sensitive to oxygen in the atmosphere. A thin layer of oxide is formed on exposure to air at room temperature. The oxide layer grows in thickness as the temperature rises. Beyond 400°C, oxygen diffuses into the already formed oxide/metal interface resulting in further oxidation (referred to as oxygen diffusion zone). At temperatures above 800°C, a very thick and brittle oxide layer is formed which may severely affect the performance of the material [7, 8, 9].

According to Iman and Fraker, oxide film of the titanium and its alloys are composed of three layers: first layer from the top is composed of TiO_2 which forms readily at room temperature; second and third layer is made up of Ti_2O_3 & TiO, with TiO near to the substrate as shown in Figure 3 [10, 11].

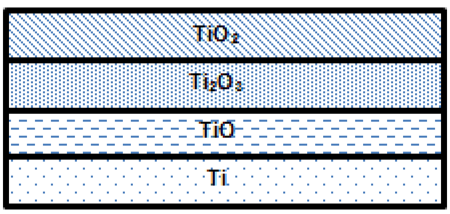

Fig 2 - AMS 4911 oxide film composition

b) Stainless steel

Stainless steel though not as sensitive as titanium, also reacts with oxygen in the air to form a thin oxide layer at room temperature [12]. Generally, the oxide layer exists in two forms (Refer to Figure 4) as iron oxides (outer layer) and chromium oxides (inner layer near to the substrate) [13 - 15].

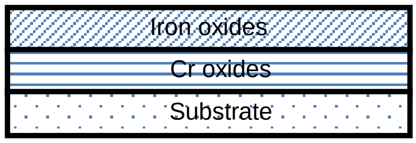

Fig 4 - Oxide composition of a Stainless steel

Table 1 - Scaling temperature for AMS 5504 (AISI 410) & AMS 5524 (AISI 316) [12]

Steel grade	**Composition (%)**						**Scaling temperature**
AISI	C	Cr	Ni	Mo	N	Other	(°C) (aprox.)
410	0.08	13	-	-	-		830
316	0.04	17	12	2.7	0.06		850

Chromium being the main alloying element, forms Cr_2O_3 and offers oxidation resistance at moderately high temperature. Beyond the scaling temperature (See Table 1), the oxide growth is extremely high due to the large rate of diffusion of oxygen, resulting in a thick oxide layer [12, 16]. This thick oxide layer is loosely attached to the substrate.

XRD spectra results on the oxide layer of AMS 5524 by Guillamet et al. shows that the oxide film consists of Fe_2O_3, Cr_2O_3 and a spinel oxide (oxide formed by the combination of alloying elements like Mn, Ni, Cr & Fe) [17]. According to Montemor, increasing the oxidation temperature in a furnace from 250°C to 450°C, thickens only the external iron oxide while thickness of the internal Cr oxide remains the same for AMS 5524 [15].

Cheng et al found that oxide film composition of AMS 5504 varies depending on the oxidation atmosphere. For dry and moist air at 850°C in a furnace, a duplex structure copmosed of Fe_2O_3 and Cr oxides were identified, whereas for N_2, a multi layered oxide structure with Fe_3O_4, $(Fe,Cr)_3O_4$ & little Fe_2O_3 were detected. Metallic Fe and $(Fe,Cr)_3O_4$ were the main composition of the oxide layer exposed to 10% $H_2 + N_2$ [18].

IV. ALTERNATIVE CLEANING METHODS

A. Shot blasting

Shot blasting also known as abrasive blasting is a technique in which selected grades of abrasive particles are used to remove the material from the surface by erosion at high speeds (65 – 110 m/s) [20, 21]. Acceleration medium can be either air or water. This process is highly useful in surface preparation like roughening a smooth surface and vice-versa. It can also be used to strip paint and remove surface contaminants like rust, scale, etc., from the metal surface.

A shot blasting system is made up of the following sub-systems namely abrasive acceleration system (compressed air or centrifugal turbines), abrasive recovery and cleaning, blast cabinet, dust collector, part movement and support system, controls and instrumentation [21].

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Different types of abrasives have been in use, since the invention of this method. It is classified into various categories as shown in the Table 2 [21]:

Table 2 – Various types of abrasives used in shot blasting [22]

Type	Abrasive Materials
Metallic	Steel shot, copper shot, aluminum shot, zinc shot, steel grit, stainless steel shot and cut wire.
Mineral	Silica and garnet
Synthetic	Corn starch, sodium bicarbonate, wheat starch, dry ice, engineered abrasives, recycled products
Agriculture	Crushed nut shells, fruit nut shells

Based on the application and level of surface finish needed, abrasive grit sizes can be selected (See Table 3).

Table 3 – Abrasive sizes and their properties [22]

Relative Grid size	Property
8-24	Coarse
30-60	Medium
70-180	Fine
220-1200	Very fine

Shot blasting is beneficial in removing strongly adhering oxide from the substrate. It was employed to remove scale from the stainless steel [24]. Similarly, micro-abrasive blasters were used to dislodge the oxide layer formed inside the turbine blade passages and cooling holes [25].

The major disadvantage of this process is that it does not lead to uniform cleaning and ensures only partial removal [24]. The main challenge however lies in controlling the material removal to avoid damage to the substrate material.

B. Water jet cleaning

Water Jet cleaning also known as hydro blasting involves the use of high pressure streams of water to remove the coatings and deposits from the substrate (See Figure 5). The cleaning effect is achieved by means of an erosion process; the continuous flow of water jet from the nozzle becomes a stream of water droplets and these droplets upon impinging the surface, creates impact force recurrently to remove the contamination [26, 27, 28].

Water jet cleaning system has the following subsystems [29,30]: a pump, nozzle (usually with multiple orifices and attached to robotic arm in case of automation), enclosure, base to which the component is attached (movable and rotates on its own in case of automation), draining and filtering system, process control devices like flow meter, pressure indicator etc.

Water jets used for cleaning operations have the velocity range of 80-200 m/s [26]. Water pressure, nozzle radii, number of orifices in the nozzle and stand-off distance between the nozzle and the surface are some of the important parameters to be optimized for obtaining a surface free from contamination [27]. The impact pressure force generated by the water jet striking the surface decreases with the increase in stand-off distance [31].

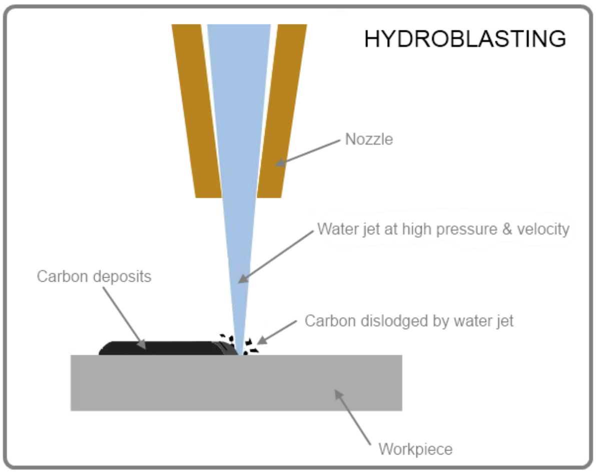

Fig 5 – Schematic of water jet cleaning method

Industrial applications of water jet cleaning and the parameters influencing the cleaning process have been discussed in detail by Ping Meng in his dissertation work [28].

Denjet has recommended pressure settings according to the industries and type of material to be removed [32].Other than cleaning, applications of high pressure wate rjet includes surface texturing, surface preparation and peening of the metals [33].

Pure water jet by itself has the capability to remove a wide range of contaminations. However, use of abrasives and ultrasound along with the water jet further enhances its ability to remove the material from its surface [34, 22]. The main drawbacks of this cleaning method are complexity of the system and very high capital costs [35].

C. Dry ice blasting

In dry ice blasting, the non-abrasive media (Solid CO_2 particles in the form of pellets) is accelerated along with the pressurized air stream or inert gas at supersonic speed through the nozzle over the surface with contamination. Solid CO_2/dry ice undergoes sublimation at atmospheric pressure and gets converted into gas due to the combined impact-energy dissipation and rapid heat transfer between the dry ice pellet and the surface. The gas on striking the surface expands approximately to 800 times the volume of the dry ice pellet, causing a micro-explosion capable of dislodging the contamination or debris from the surface as shown in Figure 2 [36].

The cleaning equipment consists of mainly a hopper to store the pre-manufactured CO2 pellets, compressed air connection hose through which compressed air is supplied, feeder system where the dry ice is mixed with compressed air and nozzle to accelerate the mixture. Dry ice blasting service providers around the world use 3mm diameter pellets for their blasting machines as it is the standard size available commercially in the markets. Other pellet sizes have to be manufactured specifically according to the user's requirement [37].

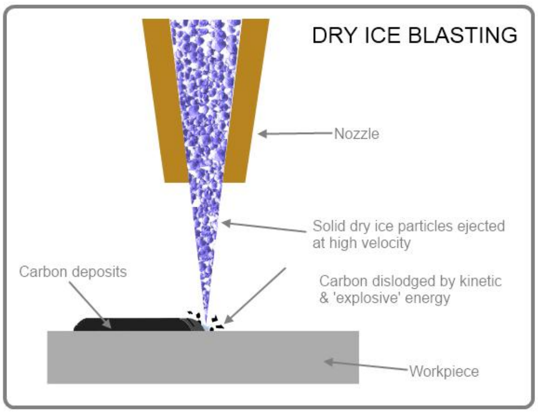

Fig 6 Schematic of dry ice blasting

Over the years, dry ice blast machines were developed with options for varying parameters like dry ice feed rate, blast pressure etc., according to the user's requirement and application. The parameters influencing the cleaning process and the relation between them has been well documented by Spur et al (Refer to Table 4) [38].

Table 4 – Parameters influencing the dry ice blasting process [38]

Influencing parameters		
Machine parameters	*Pellet parameters*	*Process parameters*
Process principle	Density	Air pressure
Hose diameter	Shape	Flow rate
Hose length	Hardness	Humidity and temperature of compressed air
Type of nozzle	Dimensions	Pellet mass flow
Dimensions of nozzle	Surface finish	Jet angle
Pellet storage	CO_2 content	Working distance
Pellet feed		Feed speed
Hose laying		Dynamics of flow
Roughness of hose		

Nozzles used were of single hose and two hose type. In single hose type, dry ice and compressed air is mixed in the feeder and then supplied to the nozzle whereas for the two hose type, compressed air and dry ice are supplied through a separate hose and mixed within the mixing tube in the nozzle before acceleration [39]. A number of high performance nozzles (round, conical, flat, angled and custom made based on the applications) have been developed in the recent years. These nozzles can also be turned in any desired position during the operation [40, 41].

Dry ice blasting is ideal for use in many industries as it does not leave secondary waste and residue behind. In addition to that, dry ice pellets have a low hardness (2 – 3 Mohs) and do not cause damage to the base material [38]. They are highly reliable and efficient to remove adhesive, oil, grease, soot, rust, paint etc. from the surface of the metal, molds, electrical & electronic components, production tools and so on [39]. Apart from the cleaning applications, investigations by researchers served to prove the feasibility of dry ice blasting in the surface preparation [42, 43].

Table 5 shows the advantages of using dry ice as a blasting media in comparison to their counterparts [37, 44]:

Table 5 - Advantages of using dry ice as a blasting media [37, 44]

Waste disposal	Toxic	Abrasive	Electrically conductive	Performance
No	No	No	No	Excellent

Limitations in using this method include clogging of dry ice within the hopper during cleaning operation which tends to affect the efficiency of the contamination removal.

D. Ultrasonic cleaning

An ultrasonic cleaning device uses ultrasound waves and a cleaning medium to remove the contamination. The setup mainly consists of a bath (or tank), generator, transducer (to generate ultrasound waves, mounted at the bottom of the tank) and cleaning medium (appropriate liquid according to the contaminants to be removed). The frequency utilized for cleaning ranges from 20 KHz – 500 KHz [45, 46].

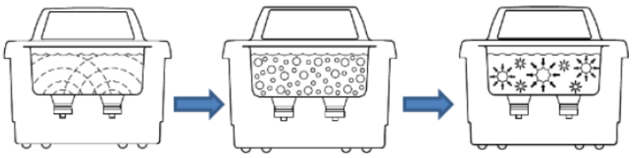

Fig 7 Schematic of ultrasonic cleaning [47]

The cleaning action is achieved by the cavitation effect. The ultrasound waves on passing through the cleaning medium lead to the generation of number of tiny bubbles [See Fig 7]. These tiny bubbles break down and produce force to displace the contamination from the surface as shown in Figure 7 [46, 48 - 51].

Rinsing is necessary to remove the residues from the ultrasonically cleaned part. Ultrasonic waves can also be employed to quicken the removal of residues from the substrate [48].

The selection of ultrasonic frequency, processing time, temperature and viscosity of the cleaning fluid and number of rinses plays a vital part in attaining the desired cleaning results. Bubble size and number of bubbles produced depends on the ultrasonic frequency (See Figure 8) [48]. The bubble size gets larger at low frequencies and has more energy, but only fewer numbers of bubbles are released. At high frequencies, large number of bubbles, smaller in size with less energy is released (See Figure 8). Thus high frequencies are suitable for cleaning materials with complex geometry and delicate parts [48, 50].

Cleaning medium can be a solvent, degreaser or aqueous cleaning solutions containing surfactants, detergents etc. based on the type of contaminant to be removed. Aqueous cleaning liquid comprises of water, surfactants and other additives. Surfactants added to the cleaning fluid encapsulate the dislodged contamination and helps in preventing its re-adherence to the substrate [45].

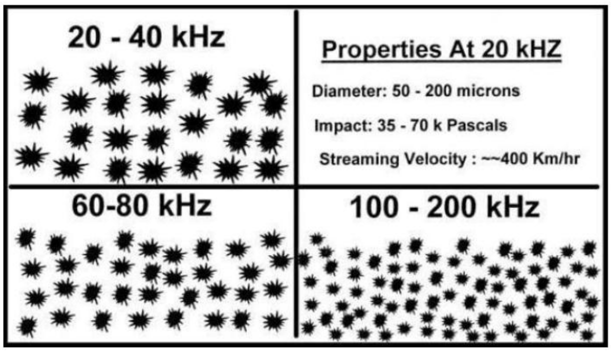

Fig 8 - Cavitation and population size according to the frequency [45]

Very little research work has been carried out on the ultrasonic cleaning of aerospace components. There are a lot of commercial service providers around the world with proven technologies for metal cleaning. Applications in aerospace include the removal of contaminations like carbon, lubricating oil stain etc. from the hydraulic systems, filters, gearbox, manifolds and turbine blades/vanes of the gas turbine engine during maintenance and overhauling [52, 53]. Alkali based solution is capable of cleaning oil, grease, coke and carbon deposits from metals to non-metals, while acid cleaners are employed for removing lime scales, rust etc from the metal surface [54]. For unpolished surfaces as in the engines, lower frequency could be used to remove grease, oil and other deposits. Significant removal of contamination from the porous and polished surfaces can be achieved at frequencies above 40 KHz [51].

Recent advancements include sweeping the frequency and use of multiple frequencies (produced by the same ultrasonic generator) in the same cleaning bath to improve the cleaning efficiency and ensure the removal of broad range of particle sizes [50, 55].

Though ultrasonic cleaning mainly relies on the cleaning medium and ultrasonic frequency, following are some of the advantages [55]: 1) Particulate contaminants of micron and sub-micron size can be removed efficiently without affecting the bulk material. 2) Parts with blind holes and difficult-to-access areas can be cleaned with high frequencies

For hardly strongly adhering metal oxide, scrubbing action provided by the ultrasonic waves may not be able to dislodge it from the substrate surface. Another disadvantage is the large amount of space it occupies for the tank and peripheral equipment.

E. Laser cleaning

In Laser cleaning, the material is subjected to high energy laser beam to remove the contaminations adhering to the substrate. Some of the commonly used laser sources were Nd:YAG laser, CO_2 laser (pulsed and continuous wave) and KrF excimer laser.

Contaminations that can be removed through laser cleaning are silica, tungsten and other deposits like carbon, grease, synthetic oil, paint, oxide, rust etc. from various types of the metal substrate.

Pulsed lasers were found to be frequently employed for cleaning than the continuous wave laser. For Nd:YAG, both the normal and Q-switched mode were utilized to clean the surface.

Different types of mechanisms responsible for the cleaning action were found in the literature. Those include spallation, ablation, laser shock cleaning, angular laser cleaning and steam laser cleaning.

Spallation: It is believed that oxide layer is peeled off from the metal surface either due to this phenomenon or due to ablation. Incident high energy and short pulsed laser beam (typically in ns) produces high pressure acoustic pulses. It propagates into the oxide/substrate interface leading to the creation of stress fields strong enough to free the oxide layer from the surface [57, 64, 65].

Ablation: The undesired layer undergoes vaporisation from the bulk material on very quick heating of the pulsed laser beam [63, 70]. It can also be done with high intensity continuous wave irradiation laser [71].

Angular laser cleaning: In this technique, the laser beam is focused at an angle to the substrate (as shown in Figure 9) in comparison to the conventional laser cleaning where the beam incidence angle is 90°.

Lee et al used this method to remove encrustation from the marble and has achieved better cleaning efficiency at lower laser fluences than the conventional laser cleaning, thus substrate damage could be reduced. It is because, at the glancing angle, the laser beam interacts directly with the interface between the contamination and substrate (Refer to Figure 10).

Faster cleaning is possible as the laser imprint covers large area. However highest cleaning rate was obtained at angles less than 30° [67, 69].

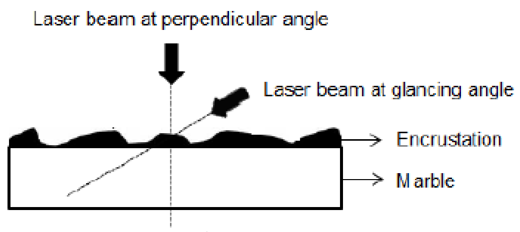

Fig 9 Schematic of the angular laser cleaning [72]

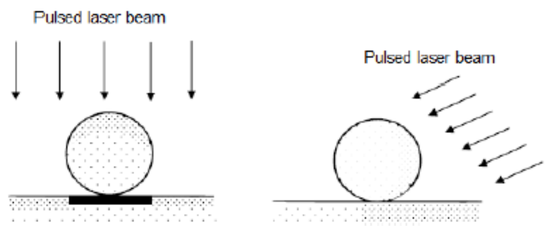

Fig 10 Principle of Angular laser cleaning [72]

Laser shock cleaning: In this method, the laser beam does not interact with the surface directly. Instead it is applied parallel to the surface (as shown in Figure 11). Air surrounding the laser beam becomes ionized due to rapid heating and produces shock waves. These airborne shock waves were used by Lee et al to remove 1μm sized tungsten particles from the silicon wafer surface without any damage to the substrate [67, 68]. Distance between the tested sample and laser beam defines the cleanliness level [68]

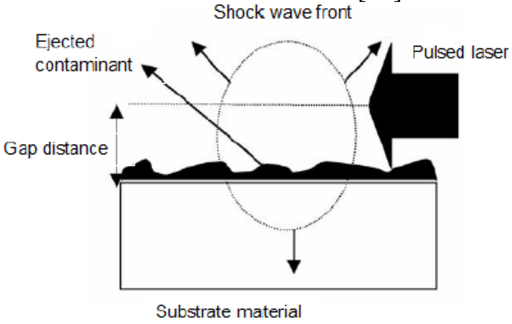

Fig 11 Schematic of Laser shock cleaning [67]

Steam laser cleaning: A thin film of liquid which is applied to the substrate before irradiation gets superheated to vapour generating an acoustic pressure force greater than the bonding force between the undesired material and substrate to dislodge it from the surface [63, 72, 73, 74]. Material deduction was augmented on using liquid film which is usually water (can be mixed with 20% alcohol to enrich the adhesion to the surface) [63]. This method has proven to be effective in cleaning the particulate contaminants [73, 74].

Lasers have the capability to remove strongly adhering oxide layers; welds without damage were attained by removing the oxide layer using fibre laser from the Titanium alloy tubes [70]. Guo et al. has shown that removal of oxide layer from the stainless steel increases with the decreasing wavelength and scanning speed, while it can also be achieved by concentrating more number of pulses on the same spot at the expense of substrate damage [65]. Similar results have been obtained by Kearns et al on copper [56]. Successful cleaning of rust from the steel has been reported by Zemin et al using pulsed Nd:YAG laser. In addition to that, it has also helped in improving the corrosion resistance and roughness of the surface [58].

Experimental investigations were confined to a closed chamber filled in with inert gas to avoid re-oxidation during the cleaning process [61, 62, 66, 70]. Despite these measures, the formation of fresh oxide still cannot be eliminated for Titanium alloys [70]. Another method of preventing re-oxidation involves the use of electrochemical cell in which the sample (serves as the working electrode) is immersed in an electrolyte solution along with the counter electrode; cathodic electric potential is applied by the potentiostat and then subjected to laser irradiation (as shown in Figure 12) [64].

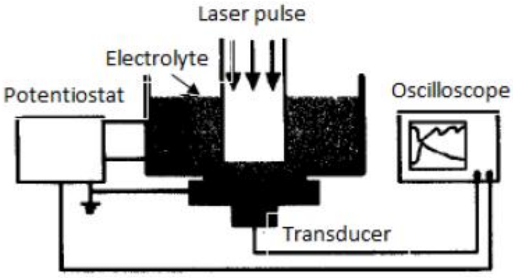

Fig 12 Laser induced oxide removal in a liquid confinement at controlled electrochemical potential [64]

For effective cleaning, the selected laser wavelength should be absorbed by the substrate than the contaminant and liquid film (in case of the steam laser cleaning) [63, 64, 73]. There exists an upper and lower limit in the fluence values for all the laser wavelengths employed [56, 58, 68, 69, 70]. Fluence is defined as the laser energy per unit area on the tested material (SI unit: J/cm2) [75]. Below the lower limit, no cleaning occurs and beyond the upper limit, damages to the bulk material could be seen in the form of melt patterns, craters and heat affected zones [56, 58, 70]. Generally, qualitative evaluation of the damages on the laser cleaned surface was done through optical microscope and SEM. Quantitative assessments were performed by EDS, XPS, AES, FTIR and SSIMS [57, 58, 60 - 62, 64 - 66, 70, 74]. Profilometer [57, 58] and mass loss analysis [57] were utilized to determine the thickness of the material removed from the surface.

Laser cleaning is an emerging process and it offers a promising solution to the traditional solvent cleaning due to the following reasons: 1) Selective material removal by choosing the appropriate laser wavelength [65, 70]. 2) Environment-friendly and does not generate wastes that require special disposal procedures [65, 76]. 3) Process can be automated using robots [77]. 4) Optimization of the parameters could overcome the problem of overexposure and under exposure.

Though this method has the capability to remove a wide range of contaminations from delicate parts to hard metal surface, the main challenge is to avoid the substrate damage as sometimes the distribution of contamination may not be even [57, 59, 60]. However, this drawback could be eliminated to some extent by using in-situ process monitoring techniques like laser induced breakdown spectroscopy (LIBS), probe beam reflection system, laser plume emission spectroscopy and laser induced fluorescence spectroscopy [76, 78].

V. CONCLUSION

The hot section of the gas turbine or jet engine is made up of stainless steel, titanium and nickel alloys. These alloys have the ability react with oxygen and form an oxide layer along with dirt sand and scale even in the room temperature. At elevated temperatures, the oxide along with dirt, sand and scale gets adhered to the surface severely affecting the performance of the jet engine. Scale and oxide is traditionally removed by the use of chemical solvents. Factors like environmental impact, health and safety hazards, processing time, etc. makes the researchers to look for alternative cleaning methods.

Some of the cleaning methods alternative to the traditional chemical cleaning which are currently in use was discussed in detail. The summary of all the cleaning methods discussed above is given in Table 5.

Table 5 – Summary of the alternative cleaning methods

Technique	Cleaning medium	Cleaning mechanism
Shot blasting	Abrasive media	Erosion process
Water jet cleaning	Water (micro abrasives and ultrasound to enhance cleaning)	Erosion process
Dry ice blasting	Dry ice pellets	Impact energy of dry ice and thermal shock due to rapid heat transfer between dry ice pellets and the surface
Ultrasonic cleaning	Ultrasound waves and cleaning fluid (solvents, degreaser based on the application)	Cavitation effect
Laser cleaning	Different types of laser namely CO_2 laser, Nd:YAG laser, KrF excimer laser, etc.	Spallation, ablation, laser shock cleaning, angular laser cleaning and steam laser cleaning.

Of all the alternative cleaning methods, Laser cleaning is considered to be a potential technique for removing scale and oxides from the metal alloys, as it has the capability to remove strongly adhering contaminants and does not leave any secondary residue to dispose other than the contaminants. Researchers have also demonstrated the ability of laser to clean the oxide layer from stainless steel and titanium alloys. However laser cleaning will be beneficial only under closed conditions with the use of inert atmosphere.

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