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A Critical Review on Effects of Residual Stresses on Machining of Titanium alloys by various Non-Conventional Processes

Abhishek Mishra[1], Mohammad Hassan[2], Monu Pal[3]
[1, 2, 3]Students, Department of Mechanical Engineering, Netaji Subhas University of Technology, New Delhi

Abstract: Titanium alloys possess some excellent properties that make the material of choice in many important industries. However, as titanium alloys undergo various kinds of machining operations in these industries, residual stresses may be generated within them, that can lead to significant reduction in their fatigue performance. Since titanium alloys are best machined by non-conventional processes, it is necessary for industry professionals working with titanium alloys to have accurate knowledge about residual stresses for optimum designing and manufacturing of reliable and safe components. This paper presents a critical review on the studies done by various authors to investigate the effects of residual stresses generated within titanium alloys under different non-conventional machining processes, so as to compile the available literature for the reference of industry professionals who work with titanium alloys.
Keywords: Residual stresses, non-conventional machining, Titanium alloys, fatigue strength, residual stress measurement

I. INTRODUCTION

Titanium alloys are utilized for a wide variety of applications. They are extensively used in aerospace, automobile, biomedical, power generation, chemical processing, and other major industries. Some of the properties which make them usable in such a diverse range of industries are a very high ratio of strength to weight, superior resistance to phenomena like fatigue and creep, exceptional resistance to corrosion, and biocompatibility. However, few characteristics of titanium alloys, like high chemical reactivity or tendency to alloy with most of the tool materials, low thermal conductivity, low elastic modulus, high strength at increased temperatures, resistance to wear, and resistance against chemical degradation are the reason behind the poor machinability of titanium alloys, as they lead to very quick destruction of the cutting tool and significant increase of the temperature at the interface of the tool and workpiece which reduces the tool life substantially. Consequently, attention is turned towards the several non-conventional processes that exist today for effectively machining titanium alloys according to the industry demands. Still, residual stresses may remain trapped inside the machined workpieces, which usually have a detrimental effect and can lead to premature failure of components. Residual stresses of tensile nature have severe effects on the performance of any component. They can lead to unexpected failure in many cases, or cause hidden problems whose effects can only be witnessed during the service life of the component. On the contrary, compressive residual stresses may be beneficial as they enhance the component's service life in some cases. Thus, it becomes very important to have a thorough understanding of the causes and effects of residual stresses during the manufacturing of components. Since titanium alloys are best machined by non-conventional processes, it is necessary for industry professionals working with titanium alloys to have accurate knowledge about residual stresses for optimum designing and manufacturing of reliable and safe components.

II. RESIDUAL STRESSES

Stresses that remain trapped inside a structure or component, even when no external loads, i.e., forces, couples, or applied stresses are acting on it are known as residual stresses. Permanent strains of conflicting nature are the cause of these stresses [1]. Property-altering mechanical, thermal, or metallurgical processes lead to the creation of residual stresses, and even after that process has finished these stresses continue to exist inside the material. In other words, residual stresses are "self-equilibrating" stresses which are present in bodies with no external forces [2]. They are the result of the structural and mechanical changes that occur inside the component while it is being manufactured (i.e., during cutting, forming, casting, heat treatment etc.).

The characteristics of any component can be severely influenced by residual stresses. They generally cause significant harm to the performance of engineering components, as they directly affect the deformation, the static as well as dynamic strength, and the electrical and chemical properties. Residual stresses are especially harmful when their magnitude is in the range of the material's yield strength, thus it is desirable to reduce these stresses.

The effects produced by residual stresses can be determined from their sign, magnitude and distribution inside the component. Residual stresses can be either helpful or harmful to a component's mechanical performance. Tensile Residual stresses come on the harmful side as they degrade the fatigue life and performance of components that are subjected to dynamic loading. In contrast, residual compressive stresses come on the helpful side as they improve these properties. Furthermore, stresses that arise due to loading can be superimposed along with residual stresses and lead to much more severe consequences for structural components [1].
Most of the time, the functioning and structural integrity of components are severely impaired by residual stresses. However, this is not always the case as in some situations, they play the vital function of preventing component failure. Shot peening surface treatment of components is an example of this. Compressive stresses are induced on a component's surface by shot peening, which results in improvement of its fatigue life. The residual compressive stresses produced thus hamper the growth rate of fatigue cracks in the component and improve its fatigue life [3]. While residual compressive stresses inhibit the growth of fatigue cracks, the growth is generally compounded in the presence of residual tensile stresses [4]. Some well-known methods for developing compressive residual stresses are shot peening, laser peening, waterjet peening, abrasive finishing, and cold rolling [5].
Residual stresses have other negative effects also as they can decrease both the static and dynamic strength, decrease the resistance to corrosion, cause dimensional instability (distortion of the component), cause magnetic properties to change, etc. Therefore, their presence must be accounted for while designing and manufacturing components in any industry. Residual stresses of tensile nature are usually unwanted at the surface layers of the component, as they can cause premature fatigue and corrosion failures. Thus, depending upon the kind of application, residual stresses can be helpful or harmful [6].
Most of the mechanical components consist of residual stresses because of the processes and operations performed upon them. The thermal and mechanical processes that occur during the manufacturing stage of a structural component produce local plastic deformation, which is the primary reason for residual stresses. Almost all manufacturing processes, including welding, casting, heat treatment, rolling, forging, and machining, create residual stresses inside components. Residual stresses become a part of almost all machined components. Residual stresses can also be produced during the operational life of a component. If they are not identified and taken into account during the designing process, they can become a critical factor for premature failure, especially for those components that are used in corrosive environments or under fluctuating service loads. Residual stresses can also cause untimely failure of some crucial mechanical components, which can be catastrophic. The primary motive of design engineers is reduction of the tensile residual stresses to the greatest possible extent or their transformation into compressive residual stresses. Most of the time residual stresses are unwanted, but those of compressive nature are required to be necessarily present in certain applications like pre-stressed concrete and toughened glass. Residual stresses play a vital role in all manufacturing industries by being a significant parameter, particularly in aerospace applications, since higher levels of functional performance are expected out of aerospace components. Optimal process parameters are vital during the manufacturing of aerospace components so that the residual stresses can be decreased and a high standard of functional performance can be achieved [4].

A. *Causes of Residual Stresses*

1) *Metallurgically Induced Residual Stresses:* Phase changes are the cause of metallurgically induced residual stresses. When phase transformation of a substance takes place, there may be a difference of volume between the transformed material and the surrounding material which has not yet transformed and is still under transformation. Due to this difference in volumes, there are contractions and expansions in the material which lead to residual stresses in the material [1].
2) *Thermally Induced Residual Stresses:* Temperature-altering processes occurring inside a material give rise to thermally induced residual stresses. When an object at higher temperature is cooled to the ambient temperature (e.g., in welding, heat treatment, hot-rolling, etc.), due to varying temperature gradients along different directions there is a non-uniform rate of cooling throughout the object. As a result, there are localized differences in the thermal contraction. Finally, non-uniform tensile or compressive stresses are induced by these varying thermal contractions [1].
3) *Mechanically Induced Residual Stresses:* Restrained deformations are the reason behind mechanically induced residual stresses. When a material is restricted from coming back to its equilibrium position after it has been deformed by either tensile or compressive loads, restrained forces develop inside the material and result in residual stresses [1].
4) *Machining Induced Residual Stresses:* When the workpiece undergoes machining process, residual stresses are induced. Since the machining process deals with thermal and mechanical changes, these stresses are a combination of both thermal and mechanical residual stresses. When high temperatures are generated while machining at the tool-workpiece interface or its vicinity, thermal residual stresses are formed, and mechanical residual stresses are developed because of the deformation of components by the material removal method [1].

B. Classification of Residual Stresses

Three different types of residual stresses can be observed (shown below in Figure 1):

1) *Type-1 Residual Stress*: Type-1 or macro residual stresses are produced by those processes or treatments that result in non-uniform strain distribution. They are produced across multiple grains. Due to any imbalance in the equilibrium of macro residual stresses, macroscopic dimensions may change.
2) *Type-2 Residual Stress*: Type-2 or micro residual stresses are produced within a single grain. However, their magnitudes may vary among individual grains.
3) *Type-3 Residual Stress*: Type-3 or sub-micro residual stresses are created due to crystalline defects such as dislocations, vacancies, interstitials, etc. and they occupy several atomic distances within the grain.

In actual conditions, all the three types of residual stresses are present simultaneously in a component [7].

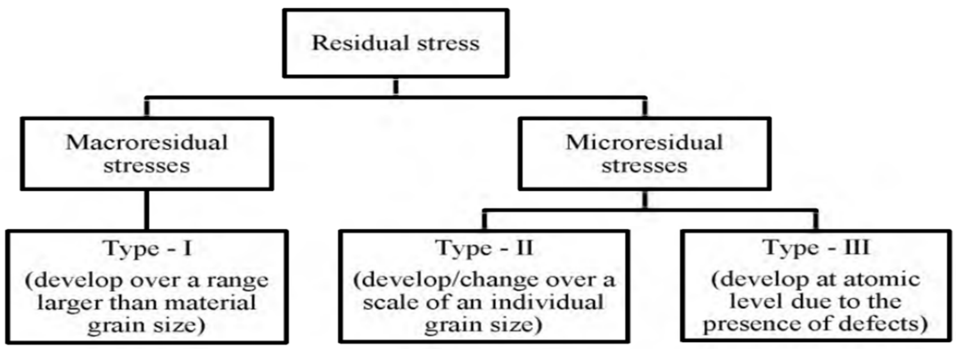

Fig. 1: Types of residual stresses [1]

C. Measurement of Residual Stresses

All manufacturing processes give rise to a certain magnitude of residual stresses. Their effect could be visibly apparent in the form of cracks or they could even be undetectable. Sometimes residual stresses lead to the catastrophic failure of cast and welded components that are subjected to no external loading at room temperatures. Due to this adverse impact on component performance, it becomes necessary to closely examine residual stresses and the effects they may cause on mechanical properties. Residual stress analysis provides a method for failure analysis, and also helps in the design assessment process and quality control.

Several techniques exist to determine the magnitude of residual stresses. They are mainly grouped into three categories: destructive, non-destructive, and semi-destructive. The various techniques to measure residual stresses are shown in Figure 2 below.

The destructive techniques consist of those methods that create disturbance in the equilibrium stress state of the component and thereafter render it unusable. These methods can be mechanical, thermal, or chemical. On the other hand, the non-destructive techniques cause no damage to the components at all. To determine the residual stresses, they make use of the physical or crystalline properties of the material along with its current state of stress. The semi-destructive techniques involve methods that are akin to the destructive ones, but they only create a slight degree of damage on the component [8].

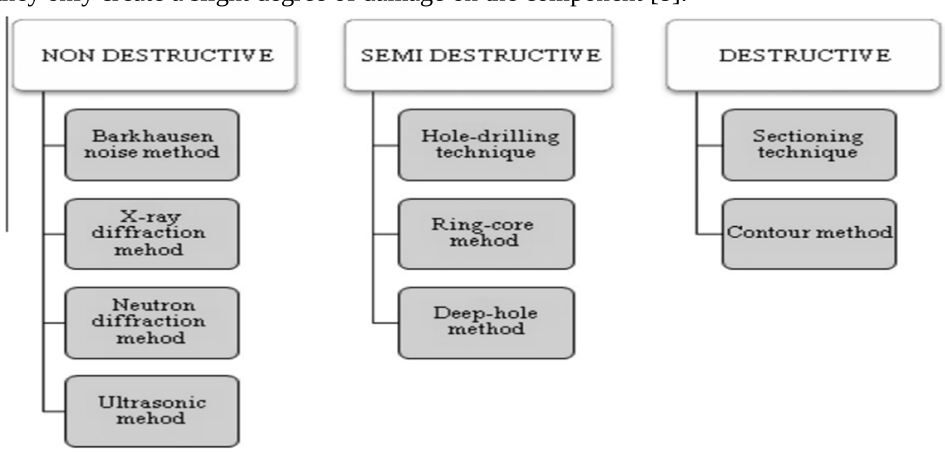

Fig. 2: Residual stress measuring techniques [9]

1) *Destructive*

The destructive method is one of the mechanical methods (semi-destructive being the other one). In this method the initial stress is found using the displacement, which involves the full or partial release of stress by removal of material. Destructive testing is more economically preferable than non-destructive testing. Few methods under the destructive technique are –

a) *Contour Method*: This is used for determining two-dimensional residual stress on a considered plane and is based on Buckner's elastic superposition principle. This technique, which was introduced in 2000, provides higher spatial resolution and has found multiple applications like: aluminum alloy forging, carbon steel Tee-joint welded, cold-expanded hole, and quenched and impacted thick plates. This method is quite easier for measuring residual stresses than the other conventional relaxation methods. Application of this method involves cutting of the specimen, measurement of the contour, reduction of the obtained data, and finally stress analysis [9].
b) *Sectioning technique*: It is a destructive method which works by removing material from the specimen and measuring the deformation to calculate residual stresses. Sectioning technique is mainly employed for analyzing residual stresses in stainless steel, aluminium, and structural carbon steel. It involves forming a cut on a material plate so as to release the residual stresses present on the cutting line. But neither plasticity should not be induced, nor heat should be generated by the cutting process because it can affect the original residual stresses. Either mechanical or electrical strain gauge can be used to measure the strains that are released during cutting.
c) *Slitting*: This method helps determine the residual stresses which are normal to the plane cut through an object. The slitting method uses a long slit which is increased in depth incrementally. The relieved strains are measured using strain gauges that are connected on the front and back surfaces [9].

There are some other destructive methods too which are used less frequently like excision, curvature, layer removal, etc.

In the excision method, strain gauge(s) are attached onto the specimen surface, followed by excision of the fragment of material attached to the gauges. It results in removal of residual stresses from the material fragment, and corresponding strains are measured by the gauge(s). This method is preferred for thin specimens but it can also be used for thick specimens [9].

In the curvature method, material containing residual stresses is removed or added to a thin plate, due to which curvature or deflection takes place in the plate. The deflection or curvature is measured and residual stresses are calculated. It is used in the case of flat or cylindrical specimens [9].

2) *Semi-destructive*

The strain-release principle is applied to evaluate the residual stress in semi-destructive techniques. Only a small amount of material is cut so that the integrity of the structure is better maintained. Examples of semi destructive techniques are -

a) *Deep Hole Drilling*: In this method, first a through-hole is drilled into the specimen and its diameter is measured. Then a core of material is trepanned out around the hole such that the residual stresses in the core are relaxed. The change in hole diameter is calculated, using which the residual stresses can be determined. The hole diameter can be quite small. This method can measure deep interior stresses [9].
b) *Center Hole Drilling*: In this method, a small hole is drilled into the object having residual stresses. The remaining material attains a new equilibrium state after drilling of the hole, and the associated deformations around the hole are measured using optical methods or strain gauges, and further analysis is done. Original residual stresses are calculated using these deformations [9]. Generally, these hole drilling methods are the most common and popularly used semi-destructive techniques as they are comparatively simpler and quicker. The hole drilling method is applicable to mostly all groups of materials, but it should be ensured beforehand that the material is machinable and isentropic with known elastic parameters.
c) *Ring Core Method*: This is another hole drilling method (also known as “inside-out” hole drilling method). A ring-shaped slot is cut off from the material, and deformation is measured in the obtained central area. Ring core method is generally used to determine two-dimensional stresses. The advantage of this method over hole drilling is that larger surface strains are obtained. In spite of that it is used very less as it incurs significant damage and is difficult to bring into operation [9].

3) *Non-destructive*

In non-destructive methods, the changes in material lattice spacing caused by residual stresses are studied. Some of the non-destructive techniques are -

a) *Neutron Diffraction*: Neutron beams are used to measure crystal lattice spacing in an object. The energy difference between the incident neutrons and the exiting neutrons helps to determine the residual stresses from the lattice spacing.

b) *Synchrotron Diffraction*: Electromagnetic radiation is accelerated using a synchrotron, which then passes through the thickness of an object and measures the lattice spacing. Similar to neutron diffraction, the residual stresses are then calculated.
c) *X-ray Diffraction*: X-rays measure the interplanar spacings between atoms. These spacings change if a material is under residual stresses. Using this process only surface residual stresses can be measured because the X-rays penetrate only up to a few hundred micrometers through the surface of an object.

Another technique under non-destructive methods is the Barkhausen Noise Method (MBN) which involves measuring the optical, electromagnetic and few other physical properties in the residual stress regions [9].

III. TITANIUM AND ITS ALLOYS

The alloys based on titanium find application in a vast range of major industries, including aerospace/aeronautical (which consume these alloys more than any other industry), power generation, biomedical, and automotive industries. By virtue of the satisfactory combination of properties like low density (around half of the alloys based on nickel), good resistance to corrosion and creep, and high strength at elevated temperatures, these alloys are the preferable choice for fabricating several airframe and engine components such as blades and discs for compressors, fan blades, inlet and outlet guide vanes, etc. Usage of lightweight materials like the alloys based on titanium results in the reduction in the static and dynamic masses, thereby reducing the fuel consumption and increasing the efficiency of aero-engines [10].

Titanium-based alloys possess an exceptionally high strength-to-weight ratio which makes them the best choice for manufacturing engines and frames for aircrafts. They are able to retain their high strength at elevated operating temperatures (as developed in engines), which again makes them a popular choice for use as engine component materials. Titanium alloys display remarkable corrosion resistance and do not require protective coatings like paints. Thus, they even provide savings over other materials this way [11]. Titanium is used for fabrication of structural frames in aircrafts, since the operating temperatures are normally above 130°C (aluminium alloys cannot be used at such temperatures). Titanium-based alloys perform effectively in low as well as high pressure compressors, and in components that experience centrifugal forces like blades, vanes, etc. Titanium-based alloys can work well even at temperatures touching 600°C.

An idea about the high strength-to-weight ratio of titanium alloys can be obtained from the fact that mild steel and commercially pure titanium have the same strength, but the latter is about 45% lighter. Furthermore, compared to aluminium, commercially pure titanium is 60% heavier but has twice the strength. The density of titanium is about 43% lesser than the density of iron, but the strength of titanium alloys is comparable to the strength of alloy steels [1].

Another useful quality of titanium is its compatibility with the human body, which enables it to be used in human implants. Titanium alloys are currently utilized for hip replacements, pacemakers, and elbow and hip joints [1]. Titanium alloys are being increasingly used as biomaterials because they have superior biocompatibility, a lower modulus, and improved corrosion resistance than the traditional cobalt-based alloys and stainless steels. However, their poor shear strength and wear resistance are obstacles that have restricted their complete biomedical utilization till now [12].

Other industrially and commercially important applications of titanium alloys include nuclear waste storage, pulp and paper, surgical implantation, petroleum refining, pollution control, food processing, extractive metallurgy, and marine applications [1]. Table 1 presents the applications of some of the common titanium-based alloys.

Table 1
Some Common Titanium-Based Alloys And Their Applications [13]

Material	Alloys	Applications
Titanium and its alloys		
α-alloys/near α-alloys	T-0.3Mo-0.8Ni	Chemical processing, desalination, hydrometallurgical extraction
	Ti-3Al-2.5V	Aircraft ducting, tubing, watches, eye glass frames
	Ti-3Al-2.5V-Pd	Offshore hydrocarbon production
	Ti-3Al-2.5V-Ru	Offshore hydrocarbon production
	Ti-5Al-2.5Sn	Gas turbine engine parts
α–β alloys	Ti-6Al-4V	Aircraft ducting, Airframe parts, Automotive parts, Consumer products (watches, eye glass frames, etc.)
	Ti-6Al-7Nb	Medical implants, surgical instruments
	Ti-6Al-6V-2Sn	Airframe parts
	Ti-6Al-2Sn-4Zr-6Mo	Gas turbine engine parts
	Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.15Si	Airframe parts, Space vehicles/structures
β alloys/near β-alloys	Ti-10V-2Fe-3Al	Airframe parts, Landing gear parts
	Ti-3Al-8V-6Cr-4Zr-4Mo	Geothermal brine energy extraction, navy ship parts, space vehicles
	Ti-3Al-8V-6Cr-4Zr-4Mo-0.05Pd	Navy ship parts, space vehicles

A. *Classification of Titanium Alloys*

On the basis of composition and constituent phases at room temperature, titanium alloys can majorly be categorized into four groups - alpha (α), near α, alpha-beta (α-β) and beta (β). α alloys and commercially pure (cp) titanium are used mostly in very low temperature applications (i.e., cryogenics); while α-β alloys (like Ti-6Al-4V) find the most usage in aerospace industries (in engine components and airframes). β alloys, by virtue of their excellent forgeability, are utilized in applications that demand high strength. On the other hand, the β alloys possess high ductility and low thermal conductivity, leading to lower machinability ratings. The machinability starts to decrease from commercially pure titanium and α alloys till the β alloys [14]. The various phases of titanium alloys with respect to varying amounts of α and β stabilizers are presented in Figure 3.

At ambient temperatures, titanium contains a close-packed hexagonal microstructure that is known as α-phase. The alloying elements aluminum, oxygen, nitrogen, and carbon are known as α-stabilizers and they increase the transformation temperature. α-alloys are generally hard and demonstrate good creep resistance and high affinity towards hardening. Higher strength can be achieved by increasing the oxygen and nitrogen content. On the other hand, a decrease in nitrogen, aluminium, and oxygen leads to superior fracture toughness and ductility. These alloys find major applications in the field of cryogenics. The hcp α-phase changes into the bcc (body-centered cubic) β-phase at a temperature of 882°C. Near α-alloys contain small quantities of β-phase as well, but perform more like α-alloys. Commonly used near α-alloys are Ti-6Al-2Sn-4Zr-2Mo and Ti-8Al-1Mo-1V. Steam turbine blades and autoclaves are manufactured using α and near α-alloys.

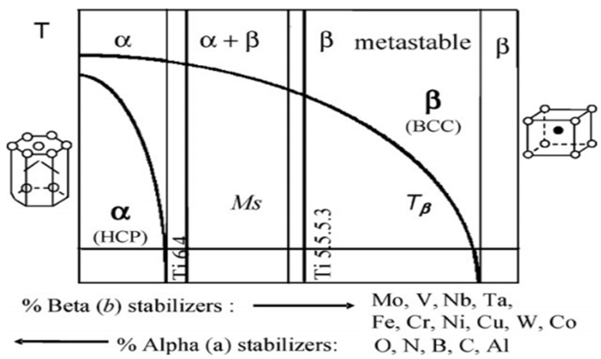

Fig. 3: Phase transformation of titanium alloys [15]

α–β alloys contain both kind of stabilizers in high amounts. In industries, they find usage in high strength applications in the 350–400°C temperature range. The most widely used alloys in this category are Ti-6Al-6V-2Sn and Ti-6Al-4V. β-stabilizers are alloying elements like molybdenum, vanadium, and silicon, and they reduce the transformation temperature. β-alloys are denser and exhibit higher strength at low operating temperatures [14,15].

1) *α-alloys:* The commercially pure titanium alloy grades come under this category. The primary alloying elements are oxygen and iron. The range of their yield strength is from 170 to 480 MPa. This group of alloys is especially useful for applications that require very low temperatures or that include highly corrosive environments. They possess very good weldability as they are not heat-treatable [16,17].
2) *Near-α alloys:* These alloys not only contain α-stabilizers like aluminium and tin, but also trace amounts of β-stabilizers like molybdenum and vanadium. At room temperatures, their microstructure is primarily characterized by the α-phase as well as a little β-phase. Common alloys in this group are Ti-5Al-5Sn-2Zr-2Mo and Ti-6Al-2Sn-4Zr-2Mo. Primary usage of near-α alloys is in the 400 to 520°C temperature range [16].
3) *α-β alloys:* The microstructure of this category of alloys is composed of both α and β phases. Examples are Ti-6Al-4V and Ti-6Al-7Nb alloys. The strength of this class of alloys is more than the near-α alloys. They perform very well in the 315 to 400°C temperature range as they possess a favourable combination of properties. Their corrosion resistance is higher than low alloy steels and aluminium-based alloys, as a result they are generally chosen over steel in majority of the aerospace/aeronautical applications. High proportions of β-stabilizers in these alloys gives rise to high hardenability, and in such cases, they are not preferred for manufacturing components that require welded joints [16,17].
4) *β-alloys:* Due to the presence of β-stabilizers, this group of alloys is characterized by high hardenability. Examples are Ti-13V-11Cr-3Al and Ti-10V-2Fe-3Al. They possess good corrosion resistance. They can be provided high strength using heat treatment, and can also be easily manufactured through cold rolling [16].

Similar to ceramics, nickel alloys, and cobalt-chromium alloys, titanium comes under the category of hard materials. Titanium alloys have poor machinability as a result of their physical properties. They have a strong tendency to form alloys and can also react chemically with a vast majority of tool materials, causing rapid cutting tool damage, smearing, and welding at the interacting surface [1]. High temperatures are created at the tool and workpiece interface because of the low thermal conductivity of titanium alloys, which causes the tool life to decrease significantly [1,18,19].

Other properties like higher strength at elevated temperatures, wear resistance, and lower elastic modulus also play their part in degrading the machinability of titanium-based alloys. Problems like excessively high tool wear, chatter, and deterioration of the surface integrity of the tool material are also induced by these properties [1,20].

A rapid oxidation process also occurs on the machined surface, which explains the severe tendency to react with the cutting tool materials. Simultaneously, the produced chips have a tendency to adhesively stick to the edges of the cutting tool, leading to built-up edges (BUE) [14]. Thus, the majority of the cost for preparation of titanium components is required in machining operations [21].

Although titanium is available in abundance, its production is somewhat expensive because of complexity in the extraction process, the difficulties in isolating and melting it, and also other related problems while fabricating and machining it [1].

Permanent deformation and/or creation of temperature gradients at the interface of tool and workpiece are the modes through which residual stresses are generated within titanium alloys during manufacturing and processing. Machining may also give rise to significant surface residual stresses.

The effects of residual stresses, which may be either beneficial or detrimental, depend on the sign, magnitude, and distribution of these stresses. Detrimental effects are degradation of the fatigue life and performance of the specimen, while beneficial effects are improvement of the same properties via increase of the component's durability [1].

Incidentally, elements like Ti, Ni, Cr, and Co impart high strength and corrosion resistance to the cutting tools, but also cause major problems while machining on the other hand [14].

When alloys of titanium are machined, due to the likelihood of work hardening during machining, lower thermal conductivity, and their tendency to chemically react with most of the tool materials, strong adhesion and higher cutting temperatures develop between the tool and the workpiece, which accelerates wearing of the cutting tool and increases the manufacturing costs. Consequently, titanium alloys are labelled as "difficult-to-machine materials". Hence fracture resistance and resistance to chemical or abrasive wear are expected to the highest degree from the applied cutting tools. Table 2 presents a detailed explanation of those properties of titanium alloys which give rise to difficulties while machining them.

Some attempts to overcome the challenges of machining titanium-based alloys include specially designed tools, like polycrystalline diamond (PCD), cubic boron nitride (CBN), and high-speed machining (HSM), but they all have had limited success till now. As a result, there has been a worldwide interest for research among various industries and academic researchers to achieve effective machining of titanium alloys economically [23].

Table 2
Some Problems Related To Machining Of Titanium Alloys [22]

Property	Description
Thermal conductivity	Low thermal conductivity causes the concentration of heat on the tool cutting edge and face, influencing the tool life negatively.
Chemical reactivity	Reactivity with common gases such as oxygen, hydrogen, and nitrogen lead to the formation of oxides, hydrides, and nitrides, respectively. These cause embrittlement and decrease the fatigue strength of the alloy.
Elastic modulus	Low elastic modulus allows deflection of the slender workpiece under tool pressure, inducing chatter and tolerance problems.
Hardness and strength	The high-temperature strength and hardness of titanium alloys requires high cutting forces.
Work Hardening	The peculiar work hardening of titanium alloys causes the absence of a built-up edge in front of the cutting tool and an increase of the shearing angle which in turn induces a thin chip to contact a relatively small area in the cutting face, resulting in high bearing loads per unit area. However, the formation of built-up edges is referred to as detrimental for tool coating.

Titanium alloys have some outstanding properties like great resistance to creep and fatigue, high ratio of strength-to-weight, superior resistance to corrosion, and biocompatibility. As a result, usage of titanium alloys (in particular the α-β two-phase Ti-6Al-4V alloys) is increasing continuously in automotive, aerospace, biomedical, power generation, marine, chemical processing, and other prominent industries.

The most abundantly used alloy of titanium is Ti-6Al-4V. It is heavily used in aircrafts (commercial as well as military) by virtue of its mechanical properties that are well-suited to those applications which are related to load-carrying. It is also known as Grade 5 titanium, and performs fairly well in those applications where good thermal and mechanical properties in addition to a good strength-to-weight ratio are the essential requirements. Being corrosion resistant, it gives good results in strong environments, and is thus preferred for turbine blades, medical implants, nuclear reactors, and marine applications [21]. Figure 4 shows the machining difficulties encountered in case of Ti-6Al-4V in comparison with other important industrial materials.

Another type of titanium alloys are the gamma titanium aluminides, which are inter-metallic materials. Being light-weight and resistant to heat and oxide formation makes them useful in aircrafts, jet engines, sporting instruments and automobiles. However, they have less ductility. The density of γ-TiAl is typically around half of that of materials such as Inconel 718 [24].

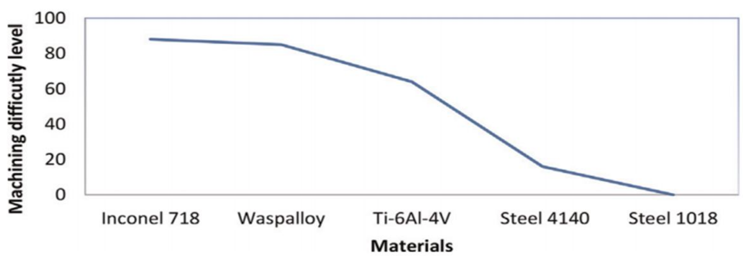

Fig. 4: Difficulty in machining Ti-6Al-4V (relative to other alloys) [21]

IV. NON-CONVENTIONAL MACHINING PROCESSES

Titanium and its alloys play a crucial role for many technologically advanced industries like nuclear energy, aeronautics, automobiles, etc. that demand materials having high strength-to-weight ratios and high strengths at higher temperatures. As the demand for materials having superior strength, toughness, hardness, and other diverse characteristics is increasing, material science researchers have been consistently developing titanium-based alloys. This further necessitates the development of better machining tool materials so that there is no compromise with productivity [25].

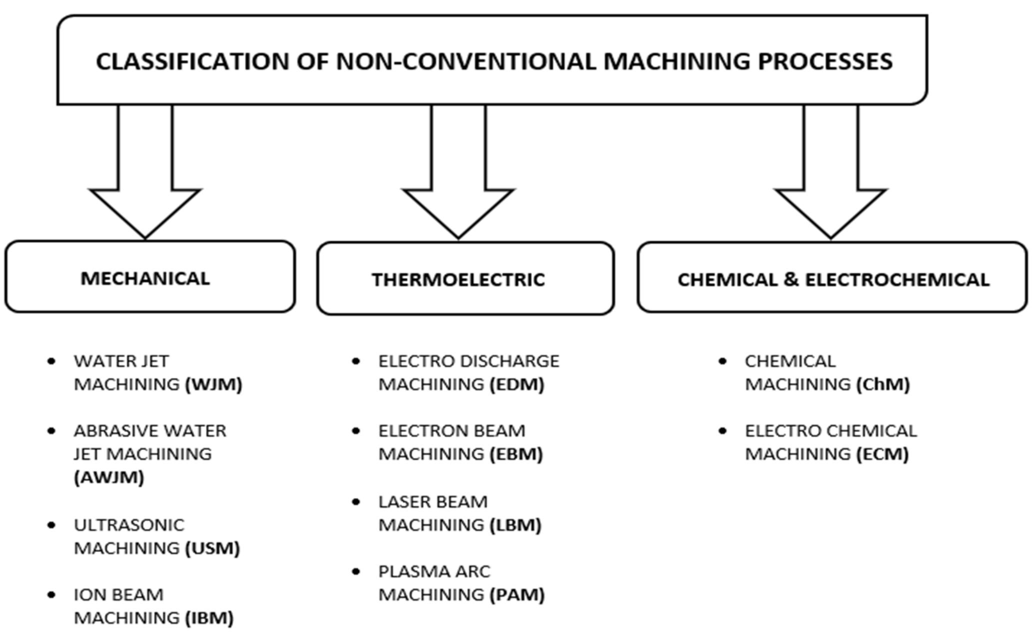

Fig. 5: Classification of non-conventional machining processes [25]

For conventional machining processes, as the hardness of the workpiece increases, the economic cutting speed for the tool decreases. It is very difficult to find tool materials that are hard and strong enough to work on the difficult-to-machine titanium alloys at economic cutting speeds. Development of complex shapes over such materials by conventional methods is still more difficult. Some other frequently important requirements are good surface finish, miniaturization, lower values of tolerances, higher production rates, etc. Another challenge that demands attention is making holes in difficult-to-machine materials. The above-mentioned requirements are essential for products like missiles, nuclear reactors, aerospace equipment, automobiles, turbines, etc. To fulfill these demands, an advanced class of machining processes, i.e., non-conventional (or non-traditional) machining processes has been developed for commercial demands. A classification of these processes has been shown in Figure 5. Further, Table 3 presents the suitability of the several non-conventional machining processes for titanium alloys. It can be seen that EDM, EBM, and LBM work best on them.

The range of applications for these non-conventional processes of machining is ascertained by the properties of the work material like thermal and electrical conductivity, melting point, electrochemical equivalent, etc.

TABLE 3
DIFFERENT PROCESSES ON TITANIUM ALLOYS [26]

PROCESS	SUITABILITY WITH Ti ALLOYS
USM	Fair
AJM	Fair
WJM	Poor
IBM	Good
ECM	Fair

PROCESS	SUITABILITY WITH Ti ALLOYS
ChM	Fair
EDM	Excellent
EBM	Excellent
LBM	Excellent
PAM	Fair

The biggest advantage of these "advanced" machining processes is that some of them can remove material from the workpiece from areas which are beyond the reach of conventional tools. The commercial application of these processes has become increasingly popular and unavoidable in industries over the past many years. When precision and ultraprecision machining are considered, these processes become even more important, since it is not possible to achieve such high degrees of accuracy by conventional methods. In the non-conventional machining techniques, material removal occurs in the form of atoms or molecules (that too either individually or in groups), whereas in the conventional methods of machining, removal of material happens in the form of chips [25].

There are three basic categories of non-conventional machining processes, namely electrochemical and chemical, thermoelectric, and mechanical machining processes. It should be borne in mind that none of these processes can be termed as the best under all machining conditions. Some of them can only be used when the workpiece material is electrically conducting, while other processes can be used for both electrically conducting as well as non-conducting materials. It is essential to select the most suitable process according to the requirement as each non-conventional machining process has some distinctive features [25].

A. Waterjet Machining (WJM)

Water jet machining utilizes a jet of water (without any abrasives) at a high speed to shear off material from the given workpiece. A high-pressure jet of water attains a large kinetic energy when it emerges from a nozzle.

The kinetic energy of the very high-speed jet of water starts converting into pressure energy as soon as it hits the workpiece, giving rise to large stresses in the workpiece.

As soon as the stress induced exceeds the ultimate shear stress, material removal starts taking place. Thus, erosion is the process of material removal. Figure 6 shows a typical WJM system.

The WJM process is commonly used for cutting materials like asbestos, rocks, wood textiles, leather, concrete, rubber, etc. which are difficult to cut by conventional means.

The advantage of WJM is that it can cut materials without interfering with their original structure, and no heat-affected zone is formed.

The thermal damage to the workpiece is almost negligible as there is no heat generation. It has the capability to produce complex and intricate cuts in materials. The working area during WJM also remains clean and dust-free.

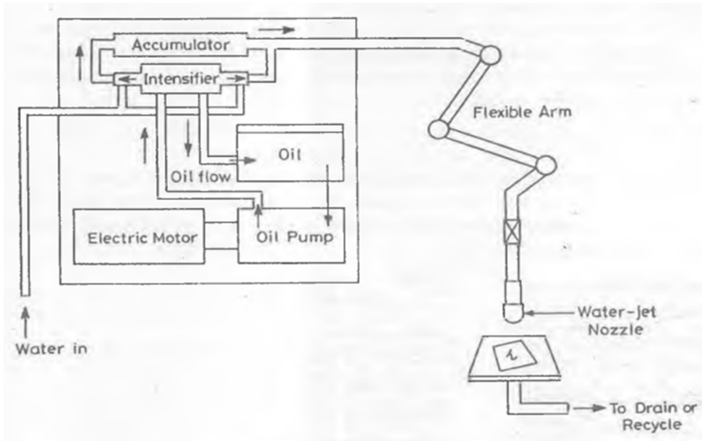

Fig. 6: Water Jet Machining System [25]

The operating and maintenance costs of this process are lower because there are no moving parts. However, the initial cost of WJM is high. It is environment-friendly as it does not cause any pollution or form any toxic products. One limitation is that very thick materials cannot be machined by this process.

An investigation by Arola et al. [27] illustrated the effects of operational variables like jet pressure and abrasive size on residual stresses resulting from AWJ and WJ peening of cpTi and Ti-6Al-4V with the help of XRD method. The residual stresses for both materials were compressive for WJ as well as AWJ peening. They ranged from 60 to 200 MPa for cpTi, and from 30 to 400 MPa for Ti-6Al-4V. The residual stresses generated during the two processes principally depended on the treatment conditions. Figure 7 represents the effect of abrasive mesh number and jet pressure on residual stresses within the cpTi and Ti-6Al-4V specimen. For both materials, compressive residual stresses increased in magnitude due to a decrease in jet pressure and abrasive size. The authors commented that increasing the jet pressure and using larger abrasives led to more hydrodynamic erosion. For the WJ peening of both metals, residual stresses increased with jet pressure. At the same jet pressure, residual stresses corresponding to AWJ peening were larger than those corresponding to WJ peening for both materials. The authors also noted that for AWJ peening under the same conditions, residual stresses within cpTi were lower than those within Ti-6Al-4V, whereas for WJ peening under the same conditions, residual stresses within cpTi were greater than those within Ti-6Al-4V.

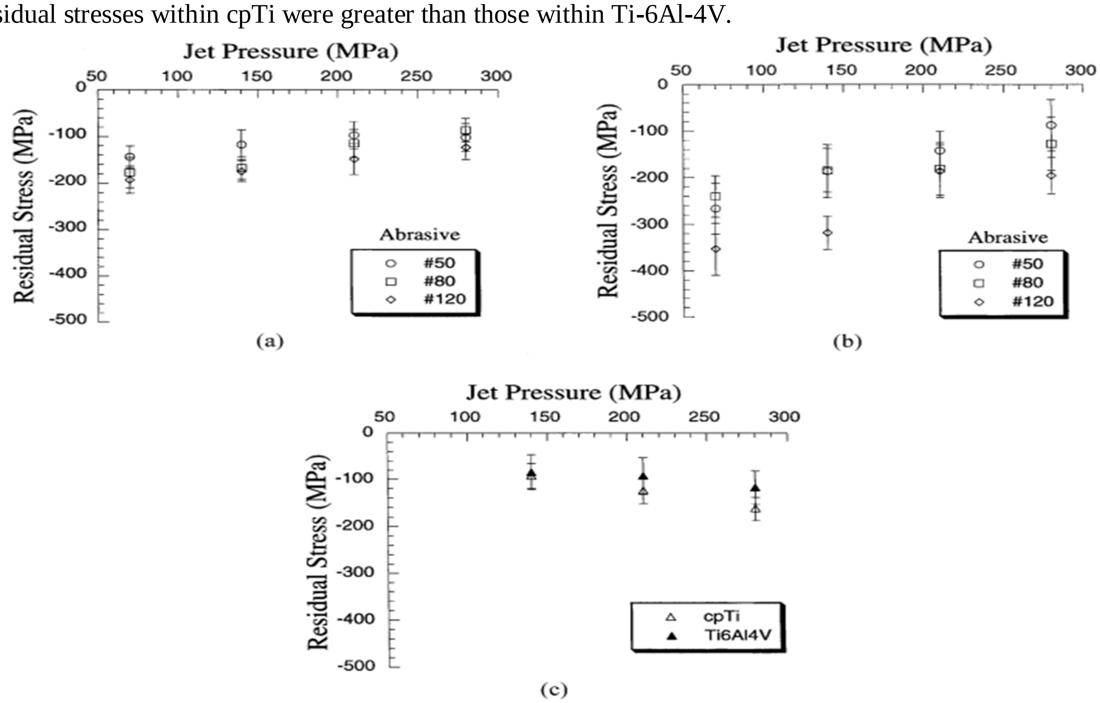

Fig. 7: Impact of treatment parameters on residual stress (a) AWJ peening of the cpTi (b) AWJ peening of the Ti-6Al-4V (c) WJ peening of the cpTi and Ti-6Al-4V [27]

In a study by Huang et al. [28], the authors subjected Ti-6Al-4V alloy with a brittle, hard and oxygen-enriched surface layer to a plain jet of water over a range of parametric conditions. The magnitude of the residual stress of PWJ-machined surfaces was measured using X-ray diffraction. The advantage of material removal through a waterjet is that the consistent impacts of droplets may develop compressive residual stress in the subsurface and machined surface layers. It was found that compressive residual stresses ranged from 18 MPa to 563 MPa within all PWJ-machined surfaces. The largest compressive residual stress was obtained when the applied water pressure was minimum and the standoff distance and exposure time were intermediate.
Many authors have reported a decrease in cutting forces and residual stresses as the pressure goes high in water jet-assisted machining of Ti-6Al-4V alloy. In a study by Vosough et al. [29] on Ti-6Al-4V bar, high pressure jet-assisted machining resulted in a compressive residual stress of about 300 MPa. The compressive stress decreased as the cutting time was increased. The authors also reported that whenever a compressive residual stress is superimposed over the stress that results from the service loading, there is a possibility that the load spectrum will remain entirely in the compressive region.

B. Abrasive Water Jet Machining (AWJM)

In abrasive water jet machining, abrasive particles like silicon carbide or aluminium oxide are added to the jet of water, which increases the MRR. The AWJM process can be used to cut metals, non-metals, and advanced composite materials.
This process is especially suited for materials that are sensitive to heat and are difficult to machine by heat-producing processes. The cutting speed for reinforced plastics can reach as high as 7.5 m/min, but for metals it is much smaller. As a result, this process is unsuitable for higher rates of production. An AWJM system is shown in Figure 8.

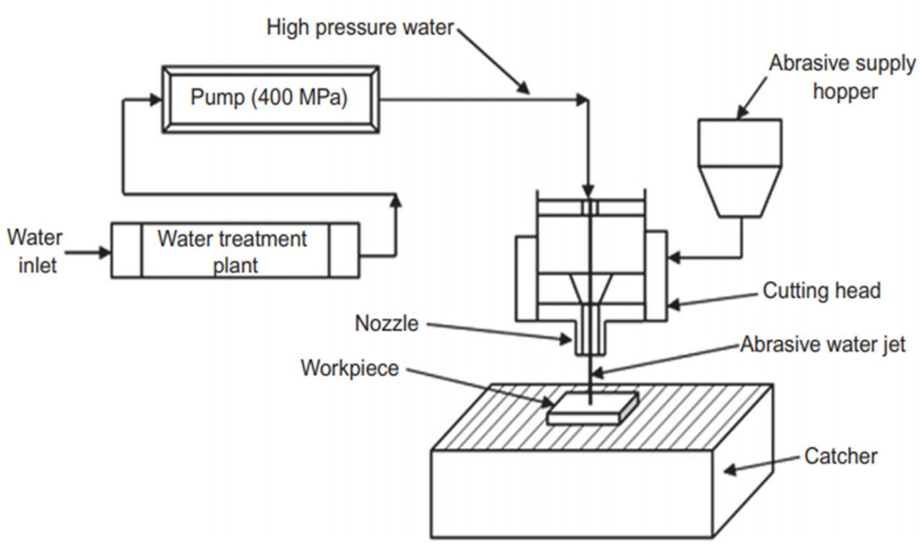

Fig. 8: Abrasive Water Jet Machining System [30]

The optimal quantity of abrasives in the jet stream can be regulated by the modern auto-control AWJM systems. Reasonable nozzle life is a big issue due to continuous wear and tear by the abrasive particles, but by producing nozzles using sapphires, rubies, and carbide-based composite materials, this issue has been overcome. The main advantages of AWJM are that the heat-affected zone on the workpiece is kept to a minimum, and there is versatility to cut very soft to very hard materials.
Arola et al. [31] determined the residual stress fields created from AWJ machining of hot-rolled Ti-6Al-4V alloy using X-ray diffraction under different conditions of the depth of cut and jet energy. The authors drew the following conclusions:

1) Residual stress measured by $\sin^2\Psi$ and RIM techniques showed that considerable compressive residual stresses, ranging from 400 to 800 MPa, resulted from the AWJ treatment of the Ti-6Al-4V workpiece.
2) The free surface of the AWJ machined Ti-6Al-4V was the location for the maximum compressive residual stress.
3) Compressive residual stress fields superpose with the tensile service loads to decrease the resultant stress at the free surface and enhance the fatigue life.
4) The magnitude of the residual stress fields increased with abrasive size, although changes in the cutting pressure caused no difference in the residual stress fields.

C. Ultrasonic Machining (USM)

In ultrasonic machining, a vibrating tool, kept normal to the work surface, hammers a slurry of abrasive grains onto the work surface, and the size of removed material, i.e., chips is extremely small. A feed mechanism gradually feeds the tool towards the work surface. The slurry is formed by suspension of abrasives into the fluid medium. The most commonly used fluid is water, but others like benzene, oils, etc. can also be used. An ultrasonic machining system is shown in Figure 9.

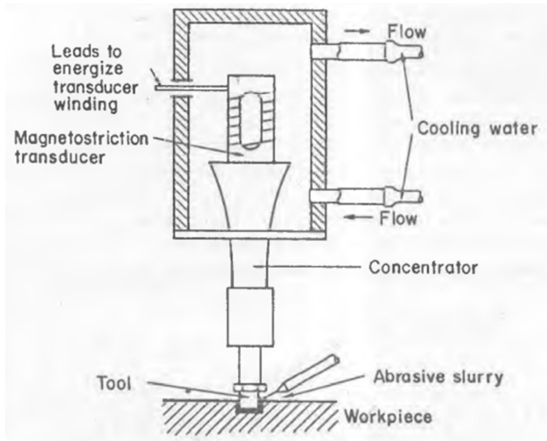

Fig. 9: Ultrasonic machining system [25]

The contact time between the surface of the workpiece and the abrasive particles is quite small and the area of contact too is very less. As a result, high magnitude stresses are generated as the abrasive particles strike on the workpiece. These stresses are large enough to trigger erosion and microchipping of brittle work surfaces. Thus, USM is most suitable for brittle materials that are to be holed, such as carbides, ceramics, hardened steels, and precious stones.

USM operates with very little or almost no noise. Both skilled and unskilled labour can easily operate on the USM equipment. The heat generated in this process is negligible, and it also provides a great surface finish along with high accuracy. The biggest advantage of USM is that every material irrespective of its conductivity can be machined, although softer materials are a bit difficult to machine. Further, MRR is very low while the requirement of energy for the cutting operation is very high.

Since USM does no thermal damage to the workpiece, it does not introduce any significant level of residual stresses [32]. Further, the machining time reduces in case of USM-assisted turning, and the residual stresses and strain hardening in the workpiece also reduce with it, while it improves surface quality of the workpiece and life of the tool in contrast to conventional turning [32]. Since it is a non-chemical as well as non-thermal process, it does not lead to any metallurgical changes or residual stresses inside the workpiece [33].

D. Ion Beam Machining (IBM)

Ion beam machining operation takes place at the atomic level, and it is employed to machine products with high resolutions (close to 0.1 mm). Inert gas ions, possessing large kinetic energies of around 10 KeV, bombard into the workpiece and the elastic collisions cause ejection of atoms from its surface. Figure 10 shows an ion beam machining arrangement.

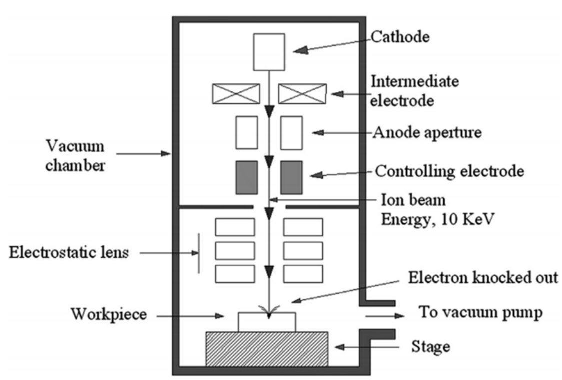

Fig. 10: Ion Beam Machining System [34]

IBM process works on the "sputtering-off" phenomenon, which is the ejection of atoms from the surface of the workpiece through kinetic energy transfer from the incident ions to the target atoms. Ejection of an atom occurs when the energy it receives from collisions exceeds the binding energy with its neighboring atoms.

IBM does not give rise to any heat-affected zone as the removal of material does not involve any fusion and vaporization of material. IBM can also be utilized for micromachining. The biggest disadvantage is that an IBM setup is quite expensive, due to which the cost of machining rises. The IBM process is thus uneconomical. We have found no studies about residual stresses in the ion beam machining process.

E. Electric Discharge Machining (EDM)

In this machining process, a discharge occurs between the workpiece and the tool rapidly and causes erosion, due to which metal is removed. Material removal occurs by the fusion and vaporization mechanism. The basic principle is that when a discharge takes place in between the workpiece and tool, intense thermal energy is produced near the sparking zone. A typical EDM arrangement is shown in Figure 11. The workpiece is made the anode because the positive terminal erodes out faster.

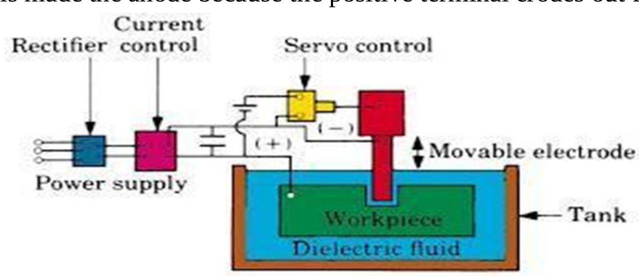

Fig. 11: EDM System [25]

It can also be said that material is eroded by a spark erosion method in the EDM process. It is a low current and high voltage process. The capacitors charge during a major portion of the cycle, and as soon as the voltage attains a threshold value, all the capacitors discharge simultaneously, producing a spark at the tooltip. Wherever the spark strikes the workpiece, a crater is produced. A lot of heat is generated during EDM, due to which the tool material may also melt out, and hence graphite is mostly used as the tool material due to its high melting point. Some copper may also be added to graphite to increase the tool conductivity. Tool wear rate is generally very high in EDM which limits the accuracy. It can be seen that the MRR is low if the thermal conductivity of the workpiece is high, and tool wear will be high if the specific heat of the tool is low. A flushing arrangement is also required to flush out the removed material that starts accumulating in the tool-workpiece gap as the EDM process goes on. A constant value of the inter-electrode gap voltage is maintained.

EDM has a higher material removal rate when compared with other non-traditional machining methods. The surface finish is also very good. Complex cavities can also be created by this process.

Nowadays, EDM is being used more and more prominently as direct contact between the tool and workpiece is not required, and hence the tool has a longer life. It can also eliminate mechanical vibrations and chattering problems that occur during conventional processes. The biggest drawback of EDM is that only good conductors of electricity can be machined. But hard materials which conduct electricity (like titanium) can be easily machined with this process.

Locally accumulated thermal energy is responsible for crack formation (when exceeded beyond ultimate tensile strength) and residual stresses in Ti-6Al-4V [35]. In the research performed by Trail and Bowen [36], the effects of residual stresses were evaluated on the fatigue life of Ti-48Al-2Mn-2Nb(at.%)+2TiB_2(wt.%) alloy. They analyzed the residual stresses by blind hold drilling process for three different surface conditions - one pass of the EDM wire; three passes of the EDM wire; and conventional grinding and polishing. The EDM process causes high residual tensile stresses at the surface. Small residual stresses of tensile nature were discovered at near-surface positions in the ground and polished specimens, whilst the EDM specimens were having relatively higher residual tensile stresses. They concluded that the reduced fatigue strength in EDM was due to a rough surface with a high residual tensile stress. The stresses arose mainly from the large thermal contraction of the liquid surface on the relatively cool base metal and rapid solidification that induced plastic deformation and biaxial tensile stresses. The residual tensile stresses arising from the EDM process, when superimposed on the applied fatigue stresses, effectively increase the mean stress of the fatigue cycle and possibly decrease the fatigue life for crack initiation in some circumstances. One effect of using EDM was that the induced stresses reached such high levels at the surface that widespread cracking occurred.

In a study carried out by Pramanik et al. [37], it was found that a large density of micro-cracks and tensile residual stresses within the surface layers degraded the fatigue strength of titanium alloys. Improvement in the fatigue strength took place due to the presence of compressive residual stresses whereas fatigue strength was degraded by tensile residual stresses as they cause crack growth. Consequently, titanium alloys experience reduction in fatigue strength during the EDM process due to presence of microcracks and tensile residual stresses in recast layers. However, experiments performed by the authors showed that fatigue life can be improved by reducing the recast layers through electro-polishing.

Residual tensile stresses are generally produced during EDM because the workpiece material contracts during cooling while being restricted by the relatively cooler interior material. The lower thermal conductivity of titanium alloys adds on to this effect. They finally concluded that non-conventional machining processes like EDM and LBM produce tensile residual stresses near the surface along with a network of cracks. Propagation of these cracks leads to premature failure of specimen as compared to those produced by conventional machining processes [37].

Tang and Yang [38] conducted simulation studies on residual stresses in single-pulse EDM of Ti–6Al–4V. According to them, EDM gives rise to residual stresses primarily due to the high temperature gradients, phase transformation and non-homogeneous plastic deformation near the discharge spot. During the electric discharge and crater formation, rapid heating and quenching cause non-homogeneous thermal phase transformations and plastic deformations in recast layer and heat-affected zone (HAZ). Consequently, residual stresses are generated and remain inside the material around the discharge crater. They noted that once the residual stresses exceed the tensile strength of the material they lead to micro-cracks and reduce the fatigue life of the component, thereby resulting in an overall degradation of the component's mechanical properties.

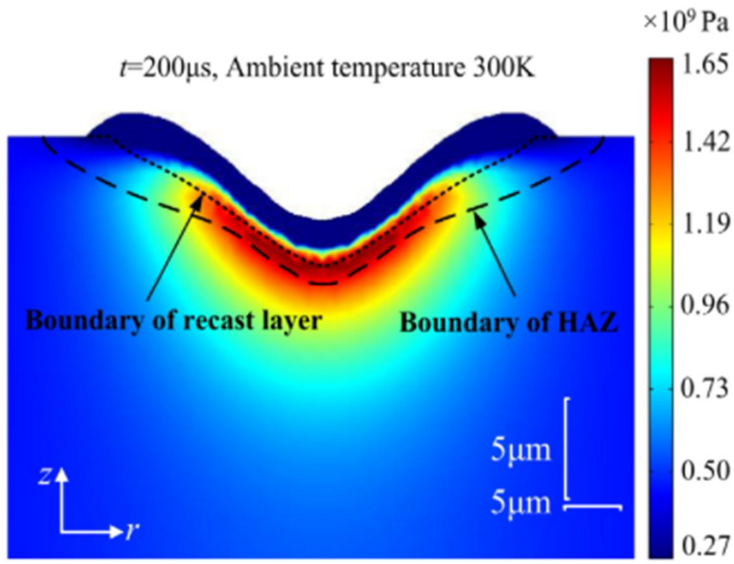

Fig. 12: Distribution of residual stresses around the discharge crater [38]

As can be seen from Figure 12, a region of stress concentration appears at the center of discharge crater, with the peak stress value being as large as 1650MPa - far greater than the yield strength of Ti–6Al–4V (828MPa) [38]. From the crater surface, the residual stresses first increase and then decrease along the depth, reaching their peak value near the interface of HAZ and recast layer. The region near the HAZ and recast layer interface is the most vulnerable due to large plastic deformations. A great compressive stress component as well as a tensile stress component exist simultaneously in the recast layer.

Murali and Yeo [39], developed a mathematical model for the simulation of single-spark machining during μEDM of Ti–6Al–4V alloy. They compared the simulated residual stress values with the experimentally obtained values by nanoindentation technique. The simulated stresses exceeded the material's ultimate tensile strength (860 MPa) near the spark center and gradually diminished as the distance from the spark center increased. However, the stress values of the spark-eroded surface measured using nanoindentation technique were within 300 MPa. According to them, during the electric discharge, the workpiece is heated locally and subjected to severe temperature gradients. Local thermal expansion of the workpiece occurs because of the non-uniform temperature distribution. Along with this, metallurgical transformations due to melting and solidification give rise to residual stresses in the workpiece.

F. Laser Beam Machining (LBM)

This machining process uses a powerful radiation (coherent, high-energy beam of light) to remove material from both metallic and non-metallic specimen through fusion and vaporization mechanism. There are two laser heat sources which are extensively utilized for LBM process: solid-state lasers and gas lasers. Among solid-state lasers, ruby lasers are popularly used, and among gas lasers, carbon dioxide lasers are preferred. Solid-state lasers have very low efficiency compared to gas lasers. However, in modern laser machining methods, fiber lasers are gaining popularity because of their even higher efficiencies.

LBM should not be used for materials having high reflectivity, and low thermal conductivity. The workpiece material should possess low specific heat, low heat of vaporization, and high capacity to absorb light energy. Laser beams can be maneuvered in various directions and in intricate positions to machine complex shapes. This process can be used to machine materials possessing high strength and hardness.

Yilbas et al. [40] performed laser cutting to create holes of small diameter in Ti-6Al-4V sheets, and recorded the residual stresses in the neighbourhood of the cut section using XRD. The residual stress calculations were carried out for the α-Ti (101) plane of the titanium alloy.

Predicted residual stress: 300 MPa

Measured residual stress: 330 ± 10 MPa

In previous study by the authors [41], it was found that residual stresses have a higher magnitude around the hole periphery, where they are tensile in nature, but they convert into compressive stresses as one goes towards the bulk of the workpiece.

G. Electron Beam Machining (EBM)

An electron beam gun source is used in the electron beam machining process. Electrons are accelerated due to attraction of anode and converged by electromagnetic lens. A focused beam strikes the workpiece. When high-speed electrons bombard the material, their kinetic energy converts to thermal energy, thereby increasing the temperature. Fusion and vaporization of the material follow. EBM is carried out in vacuum so that electrons remain undisturbed from atmospheric gases. Hence this process has higher accuracy.

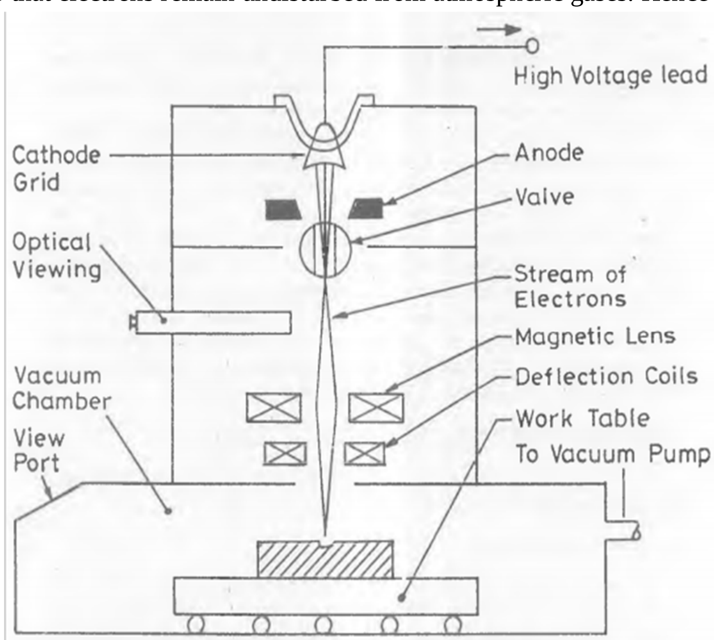

Fig. 13: Electron Beam Machining system [25]

EBM is used for producing fine holes on thin sheets. It is used for machining injector nozzles in diesel engines. However, it cannot be used to machine large workpieces because maintaining vacuum in such cases is difficult. EBM cannot be used for materials having high reflectivity and thermal conductivity. Material removal rate is less in EBM. A general EBM arrangement is presented in Figure 13. We have found no studies about residual stresses in the electron beam machining process.

H. Plasma Arc Machining (PAM)

Very high temperature ionized gas is known as plasma. In this machining operation, a high-speed discharge of plasma is used. The high temperature ionized discharge of gas heats and melts the specimen in desired regions. An electric arc is established between the anodic nozzle and the electrode, and a diatomic gas is made to flow through the arc, so as to subject it to electronic bombardment. High energy electrons from the arc collide with the molecules of the gas, leading to dissociation of the diatomic molecules into ions and electrons. The gas is now in the plasma state and its conductivity has increased considerably. More heating and ionization are caused by the accelerated free electrons. Afterwards, an additional increase in temperature occurs when the ions and free electrons recombine, via an exothermic process, into atoms or molecules. Thus, high-temperature plasma is produced that is forced in the form of a jet through the nozzle.

All materials which are electrically conducting can be machined by using plasma arc machining (even the materials which offer resistance to other gas cutting techniques). PAM is used heavily for profile cutting plates of stainless steel. The major disadvantage of PAM is that it offers very low accuracy. A plasma arc machining system is given in Figure 14.

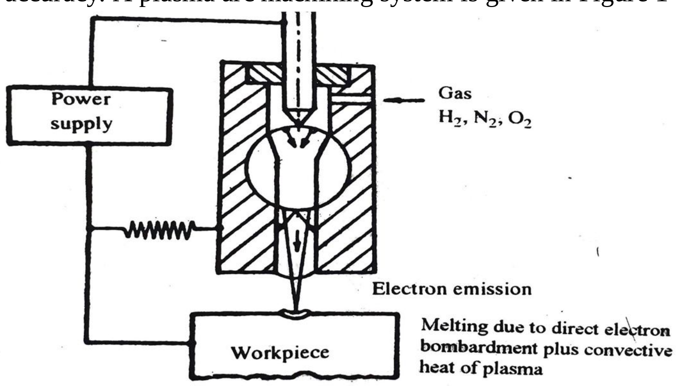

Fig. 14: Plasma Arc Machining system [42]

The process of machining involves (i) heating due to the exothermic process and melting of the specimen, (ii) ejection of the molten material due to the blasting mechanism of the plasma discharge. We have found no studies about residual stresses in the plasma arc machining process.

I. Electro-Chemical Machining (ECM)

In electro-chemical machining, a metallic workpiece, which is positioned at the anode, is shaped through electrochemical dissolution that occurs due to the application of electrostatic potential between the workpiece and a tool, which is positioned at the cathode. ECM is a high voltage and low current process. As the electric current flows across the inter-electrode gap through an electrolyte solution, metal removal occurs at the surface of the anode at a rate proportional to the current density. A little gap is maintained between electrodes, and anode is dissolved electrochemically into a shape complementary to the cathode.

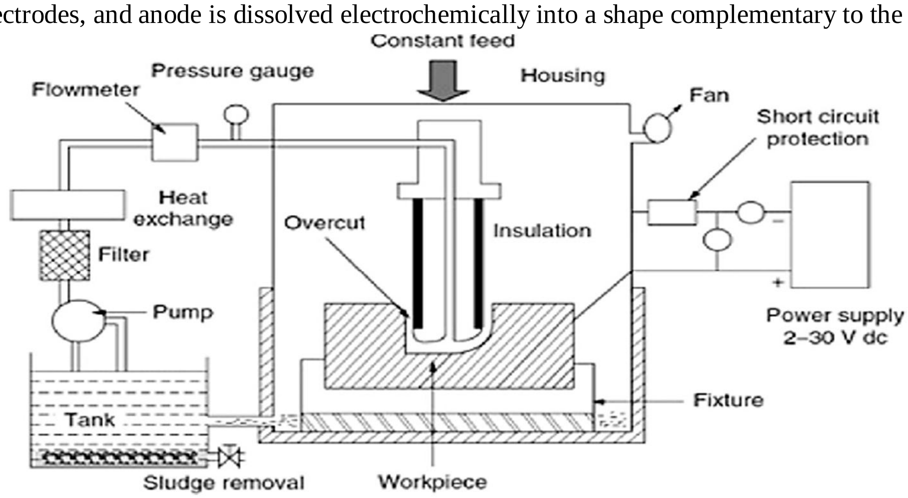

Fig. 15: Electrochemical Machining system [25]

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Figure 15 is the general arrangement of an ECM system. To remove the gas, debris, and heat that accumulates in the gap between the electrodes, the electrolyte is pumped at a moderate velocity. Since it is a no contact machining process, it is suitable for materials that are hard-to-machine irrespective of their strength and hardness. During this process, wear and tear does not take place at the cathode (tool) as only H_2 is released at the cathode. Along with high accuracy and better surface finish, high MRR are obtained without any deformation, surface residual stress, microcracks and heat-affected regions. During ECM, mechanical load does not occur; there is only a moderate amount of fluid forces. Furthermore, the increase of temperature within the electrolyte (which occurs due to the Joule heating effect) is limited by the boiling point of the electrolyte. This leads to the conclusion that thermal loads do not occur during this process. As a result, no residual stresses are generated during ECM. Despite this, there is uncertainty as to how the material removal mechanism in ECM interacts with the already present residual stresses that have been induced by earlier processes in the manufacturing chain. Thus, the biggest advantage of ECM is that no residual stresses are created inside the workpiece during the process. It is one of the last steps in manufacturing chains very often as a result [43].

In the study conducted by Sharman et al. [44], a grain-refined γ-TiAl alloy workpiece was used. Four machining procedures were used – turning, electro-chemical machining (ECM), and electro-discharge texturing (EDT) with high and low energy parameters. Figure 16 shows the SN curves for all the specimens, which are relatively flat with large variation in the number of cycles to failure at similar stress levels. The fatigue test results indicated a higher fatigue strength (475 MPa) on turned specimens, probably the reason being that the turning operation resulted in high compressive residual stresses.

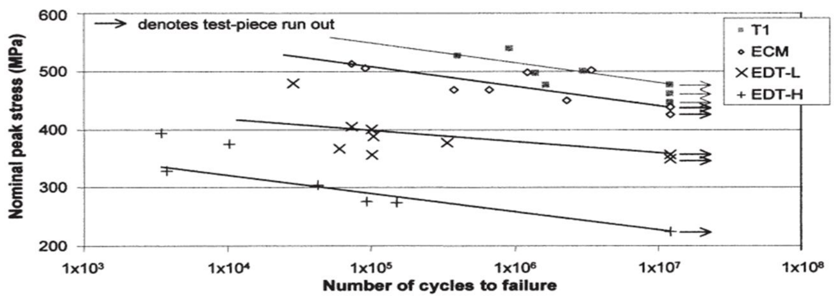

Fig. 16: S-N plots for EDT, ECM, and turned workpieces [44]

The ECM processed workpiece showed a lower strength of 440 MPa, while considerably lower values of 225 and 357 MPa were shown by the EDT-H and EDT-L specimens, respectively. Cracks that run into the bulk of the EDT specimen are responsible for their very low fatigue strength. Temperatures of the order of 10,000°C are produced during EDT, and then the rapid cooling results in tensile residual stresses and microcracks. ECM gave rise to no residual stresses. No damage or harmful effects such as cracking of the surface were observed on the workpiece using ECM.

J. Chemical Machining (ChM)

The material removal technique in chemical machining operation is the chemical dissolution of specimens in the controlled manner in the availability of strong chemicals like strong alkaline and solid solutions. The energy of chemicals is the main source for the process of material removal. A chemical machining system is shown in Figure 17.

Maskants are used to protect the regions where the removal of material is not required. Chemical machining involves many for example photochemical machining, electropolishing and chemical machining according to the type of application. There are many masking materials that consist of polyvinyl chloride, neoprene, polyethylene, and a few other polymers.

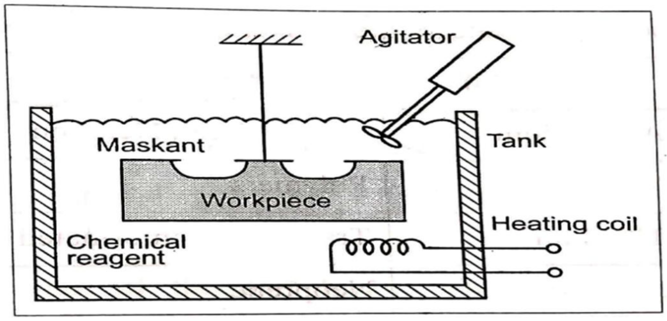

Fig. 17: The Chemical Machining Setup [25]

Chemical machining consists of the following four steps:

1) *Cleaning*: The workpiece surface is cleaned from dirt, sand and grease before chemically machining the workpiece.
2) *Masking*: A protective coating is applied to the workpiece surface on those parts which are not to be machined. The material of masking should be such that it should not react with chemicals.
3) *Etching*: After masking, the specimen is submerged into the etchant tank, the etchant reacts with the surface that is unmasked, a chemical reaction occurs, and material removal starts. When the required quantity of material is removed, the specimen is pulled out from the etchant tank.
4) *Demasking*: This is the last step in which the protective layer of maskant is separated from the workpiece surface.

The advantages of chemical machining operation involve easy machining of complex contours with reduction in weight, less scrap formation, negligible residual stresses and many more. Its disadvantages involve difficulty in handling the reagent and it requires a surface which is metallurgically homogeneous to get a good finish etc. We have found no studies about residual stresses in the chemical machining process.

V. GAPS IN THE LITERATURE

There was no literature available regarding the residual stresses induced in titanium alloys due to ion beam machining, electron beam machining, chemical machining, and plasma arc machining. Studies can be performed in the future for the same. Moreover, experiments can be designed to determine the optimum process parameters that minimize tensile residual stresses or maximize compressive residual stresses in various non-conventional machining processes.

VI. CONCLUSIONS

A. Abrasive water jet machining induced compressive residual stresses so that whenever a titanium-made component will undergo tensile stresses while in service its failure strength would be good.

B. It has been found that the ECM process induces no residual stresses in the specimen because there is no thermal load occurring in ECM.

C. The USM process can also be used for titanium alloys since no residual stresses are generated because it is a non-chemical and non-thermal process.

D. But we can speculate that IBM and EBM will induce zero or negligible residual stresses because there is no heat-affected zone (HAZ).

E. EDM produces high tensile residual stresses in the bulk part and residual compressive stresses on the surface layers.

F. In LBM, near the hole circumference, residual stresses are tensile in nature but they convert into compressive nature on going towards the bulk.

G. For EBM, IBM, ChM, and PAM, we have found no available literature.

H. However, it is widely accepted that in chemical machining, there are negligible residual stresses.

I. More work is required to be done to ascertain the effects of residual stresses on titanium alloys in case of ion beam machining, electron beam machining, chemical machining, laser beam machining, and plasma arc machining, and to determine the optimum process parameters so as to maximize the beneficial effects of residual stresses.

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