CHAPTER 2

LITERATURE REVIEW

The literature review for this research work has been done in the following heads:

2.1 Bioceramics

Bioceramics have gained a formidable impact on human anatomy. It is the prime area of focus in body implants and prostheses. Many kinds of bioceramics are used as implants in human anatomy. Table 2.1 shows the types of bioceramics used as biomaterials [13].

Table 2.1: The types of bioceramics used as biomaterials.

S.N.	Type of Implant	Type of Tissue Attachment	Example
1	Nearly inert	Mechanical interlock (Morphological Fixation)	Al_2O_3, Zirconia
2	Porous	In-growth of tissues into pores (Biological Fixation)	Hydroxyapatite (HA) HA-coated; porous metals
3	Bioactive	Interfacial bonding with tissues (Bioactive Fixation)	Bioactive glasses, Bioactive glass-ceramics, HA
4	Resorbable	Replacement with tissues	Tri-calcium phosphate Bioactive glasses

As shown in Table 2.1, the nearly inert type of implants shows the morphological fixation in which the tissue and implant are only attached mechanically and tissues grow on the surface of implant materials, for example, Al_2O_3, and zirconia. The porous implants show biological fixation which shows the in-growth of tissues into implant pores, for example, hydroxyapatite (HA), HA-coated; porous inert metals. The bioactive implants show bioactive fixation where an interfacial bonding between tissues and implants is developed, for example, bioactive glass, and hydroxyapatite (HA). Whereas, Resorbable implants replace the tissue, for example, tri-calcium phosphate, and bioactive glasses. The bone-forming activity between the implant and tissue is associated with composition, porosity, specific surface area, crystallinity and particle size.

In this research work, bioglass has been selected for its machinability studies, which is a more acceptable material to the human body as compared to stainless steel or zirconia-coated steels [14]. Animal experiments to test the suitability of the new, both machinable and highly bioactive glass-ceramic for artificial bones and bone implants have been concluded successfully [15]. Literature concerning bioactive glass continues to be at the forefront of providing innovative approaches to the medical field [16]. Bioglass and bioactive ceramics are brittle and do not provide sufficient strength for load-bearing applications, thus it has poor machinability [17]. The poor machinability of bioglass is one of the important aspects which restricts the use of it as bulk implants. Therefore, 45S5 Bioglass has been selected for its machinability studies. Its composition consists of SiO_2–CaO–P_2O_5–MO (M= Na, Mg, etc.) [13]. The bone-forming activity of bioglass between the implant and tissue is associated with composition, porosity, specific surface area, crystallinity and particle size. Although, it has limitations that it has a slow induction period for crystalline apatite formation as well as its lack of plasticity limits practical applications. Subsequently, bioglass has some great advantages too. It can be injected and moulded into irregularly shaped defects in bones and teeth as well as it hardens rapidly. It also promotes the rapid formation of biocompatible HA layers that promote cellular processes. Therefore, it becomes a prime aspect to look into the mechanical properties of bioglass, so that a conventional system can be developed to achieve significant machinability. The mechanical properties of bioglass is shown in Table 1.2 [13].

Table 2.2:Mechanical properties of bioglass

Ceramic Phase	**Polymeric Phase**	**Fracture Toughness K_{IC}**	**Young's Modulus (GPa)**	**U.T.S. (MPa)**
Cortical		6.0	15	100
Cancellous		0.1	1	3
HA	/	1.0	85	80
Bioglass	/	0.6	35-55	42
A/W GC	/	2.0	118	215(BS)
BG-C 40%	/	1.0	68	210
BG-C 100%	/	0.8	80	200
HA (0.4 Vf)	PE	3.0	4	23
Bioglass (0.4 Vf)	PE	1.2	3	10
Bioglass (0.4 Vf)	PS	1.2	7	52
Bioglass (0.4 Vf)	PS(Modified)	1.2	5	103

Due to low fracture toughness and young's modulus, the bioglass is very brittle in nature. Therefore, it becomes necessary to look for appropriate machining methods for advanced ceramics.

2.2 Machining methods for advanced ceramics

There are three categories for machining methods for advanced ceramics, abrasive methods, non-abrasive methods and combined methods. Where, abrasive methods are grinding, honing, lapping and polishing, ultrasonic machining, liquid abrasive jet cutting etc., non-abrasive methods are electrical discharge machining, laser beam cutting, electron beam and ion beam cutting, friction cutting and microwave cutting, ductile regime machining etc., and combined methods are electrochemical grinding, thermally assisted turning, mechanical-electrical discharge, chemical-electrical discharge etc.

Looking forward to developing a convenient system to achieve better machinability for 45S5 bioglass, the ductile regime machining (DRM) has been chosen for further investigations.

2.3 Ductile regime machining (DRM)

Most machining processes, such as edge grinding, finishing, lapping, and polishing, are based on the grinding or abrasive process, which always generated microcracks and subsurface damage. Therefore, the ductile regime machining method is an alternative method for machining brittle materials to obtain a high-quality crack-free surface finish by a ductile or plastic material removal process [18]. DRM is used for the machining of crack-free high-quality surfaces and the machining of brittle materials regardless of their hardness and brittleness. Subsequently, DRM is a cheaper and higher productivity rate than polishing processes due to higher material removal rate [19].

2.3.1 Mechanism of ductile regime machining

It is known that a brittle material undergoes various mechanisms of deformation during machining. If the resolved shear stress at any point of the material exceeds the critical value of elastic yield stress, the mechanism of deformation transforms from elastic stretching to energy dissipation by means of material removal [20]. It may lead to macroscopic fracture propagation, microcrack formation, phase transformation, dislocations in crystals, and intermolecular sliding in amorphous materials [21]. This energy-dissipated material removal mechanism of brittle materials can be classified into two modes, ductile regime machining due to plastic deformation on the characteristic slip plane and brittle regime machining due to brittle fracture on the characteristic cleavage plane [22].

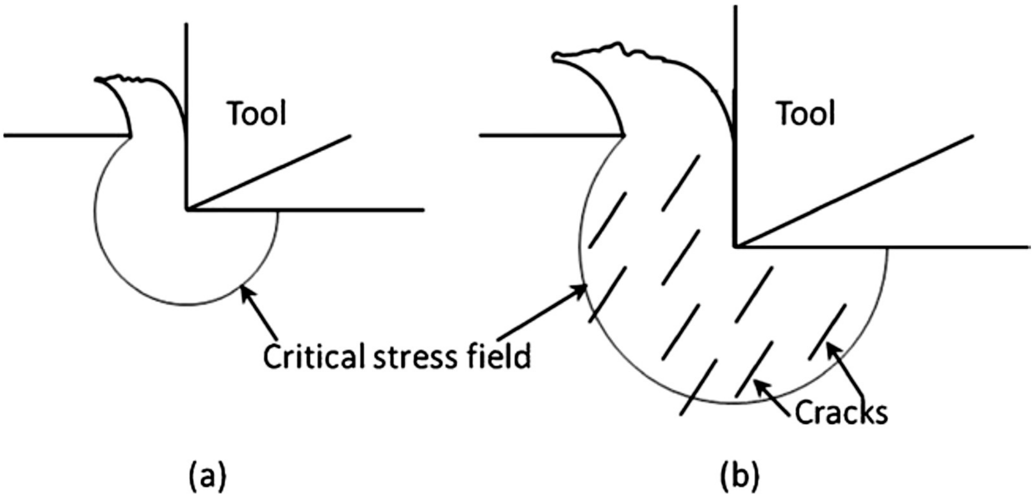

Figure 2.1: Model of chip removal with a size effect. a) Small depth of cut. b) Large depth of cut

The cleavage can be avoided if the size of the critical stress field is small due to the small uncut chip thickness. Hence, the uncut chip thickness greatly affects the chip removal process in the brittle to ductile transition as shown in Figure 2.1 [23]. The ductile regime machining (DRM) mechanism explained in the literature by some researchers are as follows:

- Bifano et al. demonstrated that plastic flow is more energetically favorable material removal process than fracture at lower depths-of-cut [11].
- Nakasuji et al. stated that if the size of the critical stress field is small due to small uncut chip thickness, cleavage can be prevented [23].
- Chip formation takes place in a ductile manner if the depth of cut is small enough. At light indentation loads, region under the indenter behaves like a region of expanding core surrounded by a sphere of the uniform hydrostatic pressure of plastic region. Beyond this plastic region, lies an elastic matrix [24].
- Patten and Gao related the phenomenon of ductile mode behaviour of brittle material removal under low stress to High-Pressure Phase Transformation (HPPT) or possibly direct amorphization of the material [25].

2.3.2 Critical depth of cut

The method used to calculate fracture toughness (K_{IC}) was given as follows[10]:

$$K_{IC} = \alpha \left(\frac{E}{H}\right)^{\frac{1}{2}} \left(\frac{P}{C^{3/2}}\right) \tag{2.1}$$

where α = 0.16, is an empirical constant depending on the geometry of the indenter, E is the elastic modulus, H is the hardness, C is the crack length and P is the peak indentation load.

When machining brittle materials, the change from a brittle to a ductile mode is defined in terms of the energy balance between the surface energy and the strain energy [11]. The critical indentation depth (d_c) for fracture initiation is given as follows [26]:

$$d_c = b\left(\frac{E}{H}\right)\left(\frac{K_{IC}}{H}\right)^2 \tag{2.2}$$

Where b is a constant.

Bifano et al. established a correlation between the calculated critical depth of cut and the measured critical grinding infeed rate. From this correlation, the constant of proportionality for Eq. (2.2) was estimated [11].

$$d_c = 0.15\left(\frac{E}{H}\right)\left(\frac{K_{IC}}{H}\right)^2 \tag{2.3}$$

2.4 Scratch & indentation test of brittle materials

In the present research, the scratch tests can be performed to compare the traction forces and coefficient of friction during scratch tests. A study has shown that strain, strain rate, and temperature are some of the important factors in explaining the material deformation mechanism during scratching [27]. In support of that, the scratch tests were performed and evaluated that the scratch resistance of nickel-nano SiC composite was found to be higher than the nickel-micro SiC composite as indicated by the higher scratch load showing better adhesion of the deposits [28]. Subsequently, elevated temperature scratch experiments were carried out on materials for high-temperature applications, namely an austenite, a ferritic metal matrix composite and a Ni-based metal matrix composite. The influence of load and temperature on the wear behaviour was studied and it is found that due to their inhomogeneous microstructure, multiphase materials have instable scratch behaviour [29]. Apparently, the scratch tests are found to be a great measure to elucidate the machinability aspects of a material. Therefore, it has been often used to run a pilot study about the machinability aspect of different hard to machine materials [30-35].

Many researchers also performed scratch tests to examine the transition zone from brittle to ductile and hence to identify the critical depth of cut [7-9]. Hence it is an established fact that the scratch and indentation tests lead to the evaluation of fracture toughness (K_{IC}) of brittle materials so as to evaluation of critical dept of cut for such materials [10-12]. A combined analytical-numerical characterization of the lateral cracks that develop when a hard item plastically penetrates a ceramic has been provided [36]. Subsequently, many researchers have performed several indentation tests using a vickers hardness tester for hard brittle materials to examine the development and spread of the microcrack and its characteristics [37, 38]. It is shown that single crystal silicon may be machined under the ductile regime using a micromill [39]. An effort was made to evaluate the characteristics of the glass-ceramic rigid substrate using the nanoindentation continuous stiffness measurement technique and to investigate the mechanism of the glass-ceramic rigid substrate's brittle-ductile transition [12]. Additionally, it has been demonstrated that there are two different failure modes for both indentation and rock cutting. When cutting rock, the rock fails in a ductile mode at shallow depths; as the depth of cut grows, the failure mode shifts to brittle [40]. According to research, the edge of the transition zone nearest to the totally ductile region is where the linear crack density steeply decreases from the brittle to the ductile region.[41].

The single-pass scratch test has been often used to characterize the adhesion of coatings to the substrate. An effort was made to show the clear correlation between high-energy AE (Acoustic Emission) pulses and cracking failure and the first attempts to analyse the failure mechanisms, which gave motivation to researchers to look into the possible aspects of the AE technique in the field of scratch testing [42]. The multi-pass scratch test is used to show the mechanisms during the abrasive wear testing of coated materials, but it is not able to make predictions about the wear behaviour of coatings [43]. Many researchers also performed scratch tests to examine the transition zone from brittle to ductile and hence to identify the critical depth of cut [7-9, 12, 40, 41]. Hence it is an established fact that the scratch and indentation tests lead to the evaluation of fracture toughness (K_{IC}) of brittle materials to evaluation of critical dept of cut for such materials [10-12].

2.5 Elevated temperature machining of hard and brittle materials

Machinability of hard and brittle materials remains a big question and poses several challenges, even today. There are many ceramics that are considered less machinable due to their hardness and brittleness and therefore have limited industrial applications. Bioglass and bioactive ceramics are brittle and do not provide sufficient strength for load-bearing applications and therefore have poor machinability [17]. Poor machinability of bioglass is one of the important aspects, which restricts the use of it as bulk implants. Therefore, it becomes essential to lower their hardness and to improve their ductility.

Therefore, the modern age is now focused to manufacture and process ceramic materials in the view of extensive uses of them like electronic parts, semiconductors, insulators, high quality cutting tools, aesthetic items, wear resistant ap-plications, utensils, biological implants, space craft parts, air craft parts, refractories etc. Apart from these alluring uses of ceramics; they involve complex manufacturing processes due to their high hardness and brittleness. Subsequently, they possess poor machinability due to their high hardness and brittleness because of the fact that brittleness leads to poor surface finish while hardness leads to low machinability.

Laser sources are widely used now a days to assist the machining processes which is a hybrid method that uses a laser for pre-heating the workpiece prior to material removal with a conventional cutting tool. The yield strength of a brittle material decreases to below the fracture strength reducing the brittleness of the material at the elevated temperature. Also at elevated temperatures, same phenomenon happens for the tough and ductile materials, thus reducing surface roughness and cutting forces as well as tool wear [44]. It is also established that with the softening of glassy phase material, the material removal can be achieved through a combination brittle fracture and plastic deformation [45]. The application orientations of laser sources have also been the other area of research interest. Thus, a double-ramp laser source for LAM on work piece is developed to prelude thermal fracture of the work piece due to low thermal diffusivity, fracture toughness and tensile strength than silicon nitride [46]. Subsequently, Laser assisted machining (LAM) has been identified an important area of research to improvise the benefits of LAM and it becomes necessary to understand the interaction effects of process parameters during LAM on different workpiece materials and to develop the optimum levels of process parameters to achieve lower cutting force, surface finish and low machining cost [4]. In continuation of that, the optimal conditions of machining process parameters are established within the test matrix [45, 47-49]. Laser is an extremely localized thermal process because of the fact that during laser beam and work material interaction, in a small portion of the work material the incident energy beam is absorbed and high temperature is developed in the region of the beam spot, resulting in softening, local yielding, melting, burning, or evaporation [50-52]. It is important to note that the applications of laser sources are limited to localized heating only on the workpieces. Most of the recent researches on LAM have been largely focused on laser assisted turning. However, other machining processes like milling, drilling, and grinding play a vital role in production systems. Due to the brittleness and poor load bearing strength of the bioglass and bioactive ceramics [53], they have poor machinability which restrict the use of it as bulk implants. This draws the attention of research for the machinability aspects of such materials. In the view of this elucidation, the scratch tests can be performed to compare the traction forces and coefficient of friction during scratch tests. A study has shown that strain, strain rate, and temperature are some of the important factors in explaining the material deformation mechanism during scratching [27].

Hardness and brittleness of such materials play the major role for the poor machinability. Thus, application of heat reduces the hardness in brittle materials and induces the thermal softening [1-3]. Apparently, many researchers have worked with local thermal heating during the scratch or machining processes [4]. Amongst them, the LASER assisted machining is found to be a trendy approach [5, 6]. It effectively minimises the amount of cutting force used during production while also enhancing the machining features and geography of hard and brittle ceramic materials [46, 54]. These studies are not limited to ceramic materials, even the process give promising results to hard-to-wear white cast iron and Ti-6Cr-5Mo-5V-4Al beta titanium alloy [55, 56]. For applications in optics, semiconductors, and micro-mold/dies, mechanical micro-cutting is emerging as a competitive alternative to lithography-based micromachining processes. The variety of workpiece materials that can be handled using mechanical micromachining techniques [57]. The rapid rise and development of new high-temperature micro- and nanoscratching/tribology instruments has since been observed [58]. The heat buildup caused by bone cutting during surgery can result in thermal cell necrosis and consequent implant instability. Therefore, it is essential to have a basic understanding of how heat develops and how to control temperature. It has been investigated how cortical bone is machined using the fundamentals of orthogonal cutting [59].

2.6 Application of acoustic emission sensor to machining or scratch process

In order to identify the ductile-brittle transition regime during the machining process, acoustic emission (AE) signals are used. AE responses are found to be an effective tool to identify the different phenomena and to characterize the process aptly [60]. Acoustic emission (AE) is even a great method for online brittle failure detection. However, it is important to validate AE information by offline inspections, which remains the only conclusive method [61]. Apparently, the use of AE sensor technology is found to be a great utility in the monitoring of precision manufacturing processes; grinding, chemical mechanical planarization (CMP), and ultra-precision diamond turning in particular [62]. Subsequently, with regard to its applications and limitations, acoustic emission was found to be a great measure in context with standard ex-situ experimental procedures for crack characterization in micro-electronic structures [63].

The uses of AE signals in the machining field are increasing day by day because of the fact that AE sensors are easy to install, and they provide inline monitoring of the processes. Therefore, it becomes convenient to track acoustic emission changes induced due to physical changes in machine tool conditions. Hence, AE techniques have diversified capabilities in process monitoring and improvement. In continuation of that, AE spectra were recorded during micro grinding of brittle materials, and it was found that the specific AE energy was lower for fracture-dominated grinding than for plastic flow dominated grinding. Also, AE energy measured during micro grinding is sensitive to changes in the mechanism of material removal [64]. Later, a study is made to explore the applicability of the AE sensor for monitoring the machining processes such as turning, milling, and grinding. The AE sensor was found quite effective in monitoring such machining processes and detecting some malfunctioning. However, it was also concluded that the AE sensors are too sensitive to the process state and therefore, further improvements must be incorporated in order to utilize the AE sensors appropriately and reliably [65].

The single-pass scratch test has been often used to characterize the adhesion of coatings to the substrate. An effort was made to show the clear correlation between high-energy AE pulses and cracking failure and the first attempts to analyze the failure mechanisms, which gave motivation to researchers to look into the possible aspects of the AE technique in the field of scratch testing [42]. The multi-pass scratch test is used to show the mechanisms during the abrasive wear testing of coated materials, but it is not able to make predictions about the wear behavior of coatings [43]. The AE technique is found as a well complementary method of observation for scratch tests. Among the various physical measurement techniques such as microscopy, acoustic emission, and normal, tangential and lateral forces, acoustic emission detection is the most straightforward method to determine critical load during the scratch test [66, 67]. Furthermore, an analysis was done on the AE intensity of TiN coatings that are deposited under various conditions leading to the conclusion that intrinsic cohesion properties of coatings, the critical load and the toughness of PVD coatings were learned from analysis of AE behavior [68]. Subsequently, the AE technique appears a great tool for investigations of scratch deformation mechanisms [69]. Also, the use of the AE technique in the scratch tests was reportedly found as a useful tool for adhesion measurements in a performance study during the cyclic fatigue performance of motor valve springs [70].

Subsequently, the AE profiles have also been generated during scratch testing of a range of metallurgical coke-like samples which were recorded and linked to the concurrent energy release, dispersal or absorption on it [71]. Since the AE sensors are too sensitive to the scratch testing process and subsequently it provides a large data set of AE signals, it becomes necessary to use a proper tool to analyze the AE signals. The wavelet analysis found to be an appropriate tool to analyze the AE signals. Researchers have used wavelet analysis to analyze the flank wear and Coating–substrate adherence in galvanized steel [72, 73].

The scratch test are found to be helpful for the characterization of materials as well as coatings [67]. The present research tends to develop new strategies in AE acquisition and processing during scratch testing of material to develop a better understanding of the elementary processes of local plastic deformation under the scratch. In this research work, 45S5 bioglass samples are used for elevated temperature scratch tests to determine ductile regime in terms of acoustic emissions.

2.7 Research gaps

The machining of hard and brittle materials presents several difficulties. Due to their hardness and brittleness, many ceramics are thought to be less machinable and so have fewer industrial uses. Simultaneously, there has been a lot of recent progress in the search for materials that are appropriate for applications involving human anatomy. In comparison to stainless or zirconia coated steels, bioglass, for example, is thought to be a better alternative for human body implants. In fact, successful animal tests to determine if the novel, machinable, and highly bioactive glass-ceramic may be used to create artificial bones and bone implants have been reported in literature. The literature on bioactive glass is still at the forefront of developing novel medical treatment methods.

Numerous studies indicate that local thermal heating has been used during scratching or machining processes. However, most of these studies concentrate on localised heating of the work material, which results in a significant temperature difference between heated and unheated areas and consequently, high thermal stresses. More cracks are caused by these thermal stresses, which is a concern. During the machining of hard and brittle materials, such problems can be resolved by bulk heating the work material. These studies motivated to develop a lab purpose portable heating setup which can hold as well as heat the ceramic samples in order to perform pilot studies about elevated temperature machinability of 45S5 bioglass and other ceramic samples.

More study is still required to fully understand the process by which hard and brittle materials go from the brittle to the ductile regime, despite the fact that many researchers have worked hard in recent years to improve quality by machining brittle materials in the ductile regime. The genesis and propagation of the microcrack as well as its properties have since been examined by numerous researchers utilising a variety of indentation tests using a Vickers hardness tester for hard brittle materials. Numerous researchers also used scratch tests to analyse the zone where brittle materials become ductile and, as a result, to determine the crucial depth of cut. Therefore, it is a known fact that scratch and indentation tests help determine the critical depth of cut and fracture toughness (K_{IC}) of brittle materials. Hence the effect of thermal softening and elevated temperature scratch tests on 45S5 bioglass and other ceramic materials are yet to be explored for determination of critical depth of cut (DOC) at different temperatures. Apparently, the uses of AE sensors are to explored in order to support appropriate machining of such materials.