CHAPTER 1

INTRODUCTION

This section provides a concise introduction to the fundamentals of ductile regime machining (DRM) of ceramics, the background of the field and motivation towards the present research work to investigate the machinability aspects of 45S5 bioglass. Additionally, it addresses the thesis objectives, structure, and scope.

1.1 Background of the 45S5 bioglass and its machinability aspects

Ceramics have become an irreplaceable part of the current society. They have impacted every area of our society whether it is our household or spacecraft. Ceramics have proven themselves better materials over many metals or nonmetals due to their unmatched properties like hardness, strength, wear resistance, biocompatibility, thermal stability, insulating ability, aesthetically better suitability, etc. There are many kinds of ceramic materials available as per the current requirements of society. They can be classified as glass, whitewares, porcelain enamel, refractories, structural clay, and advanced ceramics. Furthermore, advanced ceramics can be categorized as electronics ceramics, bioceramics, structural ceramics, coating ceramics, ceramic composites, nano-ceramics etc.

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 the literature. The literature on bioactive glass is still at the forefront of developing novel medical treatment methods. 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. Bioglass composition, porosity, specific surface area, crystallinity, and particle size are all related to the bone-forming activity of the material between the implant and tissue. However, it has drawbacks, including a lack of ductility and a long induction period for the creation of crystalline apatite, which restricts practical uses. Consequently, bioglass also provides several fantastic benefits. It can be injected into irregularly shaped flaws in bones and teeth and quickly hardens. Additionally, it encourages the quick development of biocompatible HA layers that support cellular functions. Therefore, it becomes crucial to investigate the mechanical characteristics of bioglass in order to create a traditional system that achieves considerable machinability.

Studies indicate that local thermal heating has been used during scratching or machining processes[1-6]. 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.

The critical depth of cut is defined as the smallest depth of cut at which crack formation initiates on the machined surface. Eventually, this value indicates the ductile to brittle transition during the machining process. The critical depth of cut is usually found very less for ceramic materials in existing machining processes. Therefore, it is necessary to increase the value of the critical depth of cut to an extent to improve the machinability of the hard and brittle materials. More study is still required to fully understand the process by which hard and brittle materials go from the brittle to the ductile regime, even though 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 been examined by numerous researchers utilising a variety of indentation tests using a Vickers hardness tester for hard brittle materials. It has been observed that scratch tests have been used to analyse the zone where brittle materials behave as ductile material and, as a result, to determine the critical 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 the critical depth of cut (DOC) at different temperatures.

There are three categories of 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.

With ductile regime machining (DRM), which is accomplished with a regulated depth of cut, feed, and high cutting velocity, the required machinability aspects of such materials are obtained. A slight increase in the softness of the brittle materials can be used to suppress such carping problems. Therefore, heating such material can improve its softness, hence improving its machinability. However, because of the localized heating, there is a greater temperature difference between heated and unheated zones of the work material, which causes thermal strains that cause both microcracks and macrocracks. The work materials can be heated in large quantities to address such dreadful problems. Apparently, the comparisons of their softness can be examined through the scratch tests performed at different temperatures. In the present time, AE sensors are being used vividly in various applications. Acoustic emission (AE) sensors are being used for in-line monitoring of different machining operations to identify the changes that occurred at the cutting tool and machined surface interface. These changes can occur due to wear of cutting tool, the non-homogenous structure of a material, ramp loading causing ductile-brittle transitions, etc. during the machining process. Since these AE sensors cannot be mounted exactly at the excitation surface of the process but at the nearest place to it. Therefore, these sensors are not able to provide us with the exact quantitative changes in the AE signals. Therefore, the uses of these sensors are limited to qualitative observation of such processes. Apart from this limitation, these sensors are very useful to detect any occurrences on the cutting tool and machined surface interface. These detections are sensed and converted in the form of AE signals. That makes AE sensors a great tool for qualitative analysis of such processes with in-line monitoring. It becomes easy to make decisions on cutting tool replacement or changes in machining parameters for such processes. Therefore, the AE sensors are used in this research work to explore and examine the qualitative changes in AE signals corresponding to the change in temperature and scratch speed.

1.1 Motivation for the present work

The studies are mostly focused on localized heating of work material, which generates a high temperature gradient between the heated and non-heated zones. This high temperature gradient leads to high thermal stresses. These thermal stresses induce more cracks, which is a carping issue. Such issues can be solved with the bulk heating of the work material during the machining of hard and brittle materials. Figure 1 shows the comparison between localized heating and bulk heating. It is illustrated that the localized heating produces the non-uniform heat affected zone because the heat is transferred to the workpiece through a small area of laser or plasma spot as shown in Figure 1.1 (a). Unlike that, bulk heating produces a uniform heat affected zone because the heat is transferred to the workpiece through a large area of contact as shown in Figure 1.1 (b).

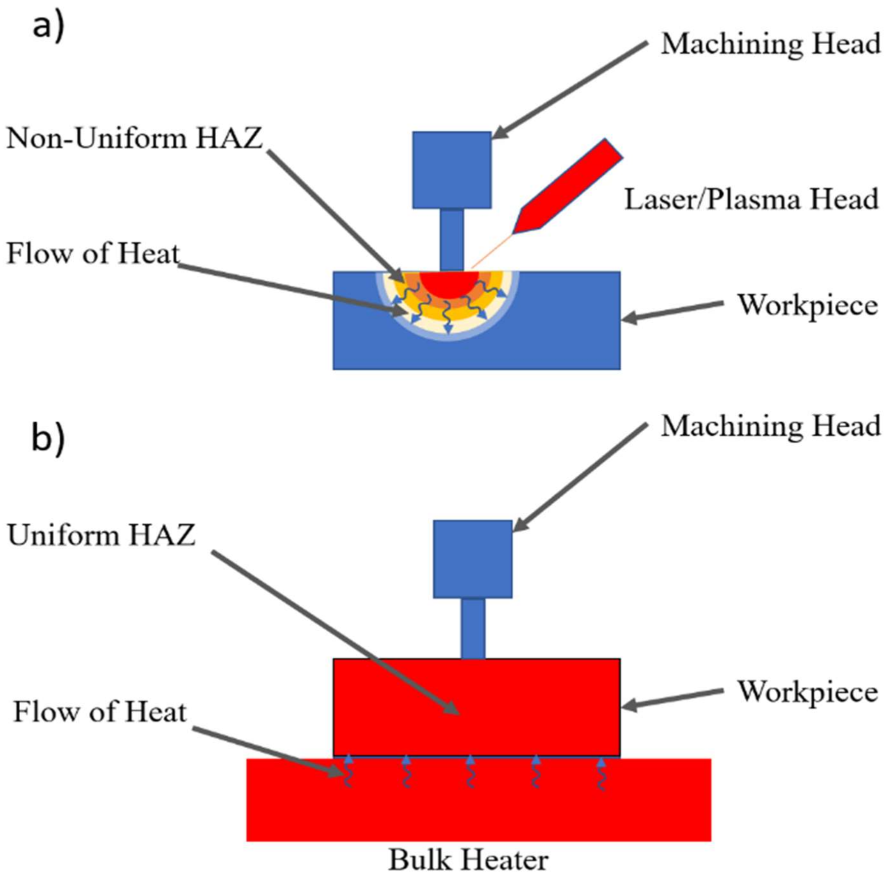

Figure 1.1: (a) Schematic of localized heating, (b) Schematic of bulk heating

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 to the evaluation of the critical depth of cut for such materials [10-12].

These elucidations motivated to develop a portable bulk heating setup for ceramic samples so that elevated temperature scratch and indentation tests are performed. Furthermore, the elevated temperature scratch tests are used to identify the ductile-brittle transition zone during scratch. Additionally, the AE sensor is used to explore monitoring aspects of the ductile-brittle transition process.

1.2 Research objectives

The overall objective of the present research work is to develop an appropriate process to improve machinability for 45S5 bioglass and other ceramic materials. The elevated temperature is used for the thermal softening of the material. Therefore, the present research work also focused to identify the critical depth of cut at different temperatures for better machinability of such materials. The following tasks are set to achieve the elucidated research objectives:

- To design and develop a multipurpose portable heating setup for ceramic samples.
- To study traction forces at elevated temperatures during micro scratch tests on 45S5 bioglass.
- To study the effect of scratch speed at elevated temperatures during micro scratch tests on 45S5 bioglass.
- To study the effect of temperature on brittle-ductile transition and critical depth of cut for 45S5 bioglass.

1.3 Approach taken to meet the objectives

To meet the research objectives of the thesis, thermal softening is taken as the key step to reduce the hardness of 45S5 bioglass. Hence, a portable heating setup has been developed to heat the samples. Heated samples underwent scratch tests and indentation tests at different temperatures. Subsequently, the scratch tests provided the normal load, traction force, coefficient of friction, and scratch images on different scratch conditions. The indentation tests provided the change in fracture toughness concerning the changes in temperature. The reduction in traction forces on elevated temperature during the scratch tests is the direct implication of less cutting force required for machining operations. In addition to that, the scratch images are analysed to find the ductile-brittle transition zone and the scratch depth at the transition zone was measured which is referred to as the critical depth of cut for better machinability. Thereafter, a mathematical model has been proposed to find the critical depth of cut at different temperatures for 45S5 bioglass. Furthermore, the AE sensors are used to record the AE signals during the scratch process. Since these signals have very less visible variations during the process, these signals have been processed using wavelet analysis and then correlated with the scratch process. These experimentations led to an understanding of the scratch behaviour of the 45S5 bioglass at different temperatures.

1.4 Scope of the thesis

The scope of the thesis is to develop an effective process to increase the machinability of hard and brittle materials. Since it is not possible to conduct experiments on all types of hard and brittle materials, this research work is focused on machinability studies of 45S5 bioglass. This study is focused on elevated temperature scratch/indentation tests. This study provides insight of the critical depth of cut for machining of 45S5 bioglass as well as the effect of thermal softening on the process.

1.5 Thesis outline

This thesis comprises 8 chapters as followings:

Chapter 1: This chapter discusses a concise introduction to the fundamentals of ductile regime machining (DRM) of ceramics, the background of the field, and the motivation for the present research work to investigate the machinability aspects of 45S5 bioglass. Additionally, it addresses the thesis's scope, structure, and objectives.

Chapter 2: This chapter presents the literature review about bioceramics, 45S5 bioglass, machining methods for advanced ceramics, ductile regime machining (DRM), the mechanism of ductile regime machining, critical depth of cut, scratch and indentation tests of brittle materials, elevated temperature machining of hard and brittle materials, and the application of an acoustic emission sensor to the machining or scratch process. This chapter also discusses research gaps that led to the motivation for the present research work.

Chapter 3: This chapter describes the details of the 45S5 bioglass used in the present study. The details of sample preparation have been discussed, along with the specimen geometry. It includes casting, heat treatment, cutting, and polishing. Efforts are made to develop a sophisticated lab-made portable multipurpose heating setup for achieving various operations such as machining, elevated temperature scratch and indentation tests, grinding, etc. on hard and brittle materials by softening the material by preheating of the samples. This chapter also describes the equipment utilized, such as the portable heating setup, the elevated temperature scratch testing setup, the use of the AE setup with scratch testing, and the elevated temperature hardness test setup.

Chapter 4: In this chapter, this setup has been evaluated at different temperatures of the sample surface up to 426 °C. The heating characteristics of the portable heating setup have been plotted. Furthermore, this setup is modified to work up to 1000 °C. This setup is capable of holding and heating the samples.

Chapter 5: In this chapter, 45S5 bioglass samples have been used for micro scratch tests, as well as the portable heating setup used to heat those samples. The temperature values were kept between room temperature (27 °C) and 420 °C during the tests. Subsequently, traction force, coefficient of friction during the scratch tests, and scratch images are compared to elucidate the softness of the material. It is found that there is a significant reduction in traction forces and coefficients of friction during tests with a rise in the sample temperature.

Chapter 6: In this chapter, scratch tests are conducted to determine the ductile-brittle transition load and the related depth of cut. In order to accomplish this goal, samples of 45S5 bioglass are scratched at various sample temperature ranging from 27 °C to 700 °C, ramp loads, and fixed scratch speeds.

Chapter 7: Furthermore, in this chapter, different scratch speeds and sample temperatures ranging from 0.5 mm/sec to 2.0 mm/sec and 27 °C to 420 °C have been used in the enhanced temperature scratch testing. The objective of this chapter is to support the previous studies done in this thesis. It is not a stand-alone study. This provides a qualitative study in support of the previous study. In this chapter, the effect of temperature on AE signals has been studied and the scratch depth on different AE signals has been studied.

Chapter 8: This chapter represents the conclusions of the present research work along with suggestions for future work.