Preface

The development of high-tech materials aims at meeting the specific technological requirements of the modern society. In the context of advances in aerospace, aeronautical, nuclear, and chemical industries new types of metallic, ceramic and plastic materials have been developed. Among them, carbon-carbon composites are one of the most promising and advanced high temperature engineering materials. Carbon-Carbon composites consist of a carbon fibre reinforced in carbon matrix system with high strength to weight ratio, high stiffness to weight ratio, excellent fatigue resistance, good wear resistance (self lubricating) and low coefficient of friction, mechanical damping ability better than metals, excellent creep resistance and low density. These properties though, good for high-tech applications other properties like hardness, intrinsic brittleness, anisotropy and non-homogeneity make this material a difficult to machine by conventional machining methods and hence drastically reduces its use. Although composite parts and structures are process moulded to the near finished state, machining, drilling, and trimming are often required as final steps. Therefore, the assembly and finishing of the fabricated part are important in the creation of a final product. There is always a possibility of damaging the composite material in these finishing post-treatments.

Conventional machining methods damage the carbon-carbon composite through chipping, cracking, delamination and high tool wear. These results generated interest in various researchers to look for non-conventional machining methods like electro-discharge machining, ultrasonic machining, laser beam machining, etc. Among these machining methods, electro-discharge machining (EDM) emerged as one of the most successful and widely accepted processes for production of complicated and miniature shapes on conducting difficult to process materials with high accuracy. Researchers have investigated the individual effects of pulse current, pulse duration, electrode materials and polarity in the electrical discharge machining of carbon fibre composite materials using conventional and wire cut EDM. They analysed the individual effect of these parameters on (a) material removal rate (MRR) (b) recast layer (c) the surface topology (d) edge damage on top surface and (e) the chemical composition of the machined surface using copper electrodes. The effect of pulse current and pulse-on-time on de-
lamination, thickness of the recast layer, material removal rate and surface roughness is investigated to find that the extent of de-lamination, thickness of the recast layer and surface roughness. However no comprehensive work, modelling the machinability parameters like material removal rate, overcut, and electrode wear rate considering more relevant variables like gap voltage, pulse current and pulse-on-time, is reported. Moreover the effect of density on machinability, the influence of electrode materials on machinability and comparison of machinability of carbonised and graphitised carbon-carbon composite is not investigated.

Estimation of machinability responses like the electrode wear rate (EWR), overcut (OC) and material removal rate (MRR) as a function of the process variables while machining carbon-carbon composites using EDM, with copper and graphite electrodes, are of considerable interest for the planners of production. In may cases the required response function values may act as a constraint on the machine setting for carbon-carbon composites machining. This work is an attempt to develop predictive empirical models for various machinability parameters, relevant to the process planners, as a function of the process variables.

The thesis is divided in to eleven chapters. Chapter 1 introduces carbon-carbon composite in terms of its applications and depicts an overall picture about the problems faced during conventional machining, and suitability of unconventional machining methods apart from the scope, objectives and strategy adopted in the present investigation. It also cover the literature review comprising details of fabrication, properties, applications and conventional and non-conventional machining of carbon-carbon composites and the details of electro-discharge machining process.

Chapter 2 explains the basic principles of design of experiments and its suitability for multi variable experimentation, strategy of efficient experimentation, fundamental concepts of factorial experimentation, two level factorial design of experiments, fractional factorial design and methods of reducing experimental error. This approach forms the background for the data analysis.
Chapter 3 illustrates response surface methodology (RSM), which is an extension of design of experiments. It is a very useful tool for analysing problems where several independent variables influence a response or dependent variable and the goal is to optimise the response. Moreover it enables the development of empirical relations between the variables of electro-discharge machining and various machinability parameters. This methodology is selected to develop the machinability models.

Taguchi method is explained in Chapter 4. This method also has its roots in the design of experiments. The parameter design approach of this method enables most efficient identification of significant process parameters and their values to get optimum response. The preliminary experimentation is carried out according to this method.

Chapter 5 gives the preliminary experimental work on carbonised carbon-carbon composite specimen based on the parameter design approach of Taguchi technique. The range of values of the process variables used in this set of experiments is: pulse-current = 1 to 9A, gap-voltage = 20 to 100V, and pulse-on-time = 100 to 750μs. This investigation identifies that the order significance of the process variables on the machinability parameters like material removal rate, overcut and electrode wear rate is gap-voltage followed by pulse-current and pulse-on-time, respectively. It also demonstrates that the right combination of the values of the process variables can enhance the machinability of the composite.

Based on the investigation explained in chapter 5 further experiments are conducted on carbonized carbon-carbon composite specimen according to RSM and predictive first order empirical models of various machinability parameters like material removal rate, overcut and electrode wear rate are established as a function of the variables of the process. The range of experimentation of process variables is pulse-current = 1 to 9A, gap-voltage = 20 to 100V, and pulse-on-time 100 to 500μs, respectively. The adequacy of the established models is tested using analysis of variance (ANOVA). It has been observed that the fitted models are adequate and the first order terms are significant. Moreover, it identifies pulse-current as the most significant parameter followed by gap-voltage and pulse-on-time. The method of steepest ascent/descent is used to identify the optimum region of various responses and found that the
selected ranges of values of the process variables are optimum. These details are explained in Chapter 6.

Chapter 7 describes the effect of electrode materials on the machinability of carbonised carbon-carbon composite through empirical relationships established for both copper and graphite electrodes as a function of the process variables. It has been found that there is only marginal influence of the electrode material on the machinability parameters though the order of significance of the process variables is same for both copper and graphite electrodes.

Empirical models are used to compare machinability of carbonised and graphitised carbon-carbon composites machined by EDM using copper electrodes, and the same is discussed in chapter 8. It is found that the carbonised carbon-carbon composite is relatively more machinable compared to graphitised carbon-carbon composite and the most significant variable of machining is pulse-current. The other variables, according to their significance is gap-voltage and pulse-on-time.

Chapter 9 analyses the machinability of carbonised and graphitised carbon-carbon composites compared to conventional synthetic electrode grade graphite through appropriate empirical models developed as a function of the process variables. It is found that compared to carbon-carbon composites graphite is more machinable. The difference in machinability between composites and graphite could be attributed to de-lamination, which produces pseudo-machined surfaces in composites.

Empirical models are also developed to compare the influence of density on the machinability of graphitised carbon-carbon composite specimens machined by EDM using copper electrodes and is discussed in chapter 10. This analysis shows that density influences the machinability of the composites. It has been found that graphitised carbon-carbon composite with lower density is more machinable and the most important machining variable is pulse-current followed by gap-voltage and pulse-on-time.
Chapter 11 summarises, co-relates the results of various experimental investigations, and also presents future scope of work.

Empirical models are established for the machinability parameters overcut, material removal rate and the electrode wear rate as a function of the process variables and the order of significance of the process variables is pulse-current, gap-voltage and pulse-on-time, respectively and the optimum range of experimentation for these variables is identified as pulse-current = 1 to 9A, gap-voltage = 20 to 100V, and pulse-on-time 100 to 500μs. In this optimum range of process variables it is found that, there is marginal influence of the electrode material on machinability parameters, whereas the density of the carbon-carbon composites has significant influence on the machinability parameters. Graphite is used as a benchmark for comparison of machinability of carbon-carbon composites because it is free from de-lamination, which occurs during machining of carbon-carbon composites using EDM. It has been found that both carbonised and graphitised carbon-carbon composites are relatively less machinable, relative to graphite, within the range of experimentation.

The major problem encountered during machining of carbon-carbon composite is its inherent characteristics of de-lamination of its layers during machining by electrodischarge machining, which produces pseudo-machined surfaces and hence affects machining time and hence machinability.

The carbon-carbon composites may be analysed, as future work, to understand the effect of the spark erosion on its properties and various flushing techniques.