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Optimization of wire electrical discharge machining parameters for cutting electrically conductive boron carbide

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ABSTRACT

In this work, Pure boron carbide (B_4C) was consolidated using spark plasma sintering (SPS) at 2050 °C with a dwell of 10 min under 50 MPa uniaxial pressure in Argon atmosphere. The sintered specimen was >99% dense and offered characteristic Vickers hardness and fracture toughness of 31.4 GPa and 4.21 MPa-m$^{0.5}$, respectively, at 4.9 N indentation load. The specimen showed satisfactory wire electrical discharge machining (WEDM) performance because of its good electrical conductivity. The design of experiment (DOE) was arranged by L32 orthogonal array (OA) between the machining input parameters namely pulse on-time, pulse off-time, pulse peak current, dielectric fluid pressure and servo feed rate and the output responses like machining speed and surface roughness (R_a). Regression models were employed to establish the numerical correlation between the machining parameters and output responses. Experimental observations were utilized to formulate the first-order regression models to predict responses of WEDM. The optimized input parameters were 27 μs pulse on time, 48 μs pulse off time, 180 A pulse peak current, 7 kg/cm^2 water pressure and 2200 mm/min servo feed rate for the WEDM performance to produce an optimum machining speed and R_a.

1. Introduction

B_4C has become quite popular for a wide range of engineering applications like refractory, abrasive powder, neutron absorbent cross section (~4000 × 10–28 m^2), body and air-borne vehicular armors against different ballistic threat levels due to its high melting point (>2400 °C), extreme chemical inertness (reacts only with halogens at high temperature), low density (~2.51 g/cc), very high hardness (~30 GPa) and flexural strength (>400 MPa). B_4C also possesses other favorable properties e.g. high thermal conductivity (~40 W/m K at room temperature), low thermal expansion coefficient (~5×10^{-6}/°C) and low electrical resistivity (~0.03 Ω m at room temperature) those make it suitable for multifunctional applications and since, B_4C is electrically conductive, it has a bright prospect toward net-shape manufacturing by WEDM technique [1]. The manufacturing condition is one of the most imperative aspects to take into consideration in the majority of modern manufacturing processes, particularly, in techniques related to WEDM of electrically conductive ceramic materials [2]. Use of conventional machining processes is limited to machine such hard ceramics due to severe tool damage. Some other nontraditional machining processes such as abrasive water jet machining (AWJM) and laser beam machining (LBM) can be used but the machining equipment as well as the machining process both are quite expensive. Furthermore, for AWJM and LBM, work-piece height is a constraint and the surface finish obtained is also not good compared to that obtained in thermo-electrical machining techniques like WEDM [3]. WEDM parameters were studied on hot pressed B_4C sample and machining responses like material removal rate (MRR) and R_a of the material were evaluated [4]. Electrically conductive TiN/Si_3N_4 nano-composite was hot pressed and processed by WEDM and its microstructure was investigated. The dependence of surface texture, R_a and MRR on WEDM conditions such as power transistor numbers and pulse off-time was also analyzed. It was reported that more power transistor numbers resulted in greater MRR and R_a. More pulse off-time resulted in lower MRR [3]. Investigations were also conducted on the effect of WEDM parameters on performance characteristics i.e., MRR, kerf width and R_a. An optimum combination of process parameters was derived for large MRR and small R_a using analysis of variance (ANOVA) [5]. Investigations were carried out on the multiple response characteristics effects like cutting speed, depth of cut and feed rate on R_a using the *Taguchi* technique and Grey relational analysis by optimizing the EDM process parameters [6,7]. The surface roughness prediction model optimized the machining input variables to obtain high surface

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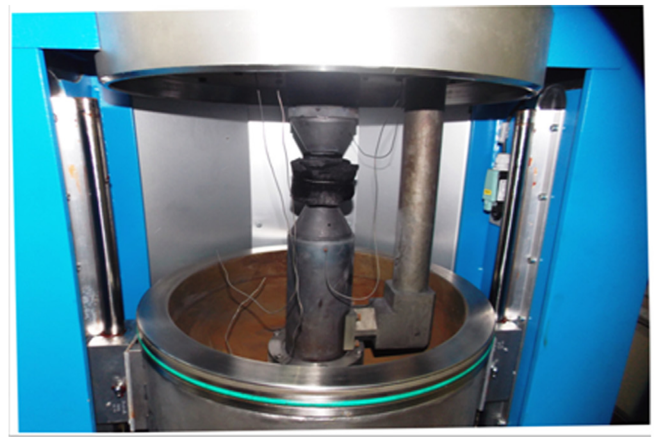
quality of Al_2O_3/SiC/TiC composite [8]. In this work, pure B_4C was fabricated using SPS technique and basic mechanical properties e.g. bulk density (*BD*), apparent porosity (*AP*), *Vickers* hardness (*HV*) and indentation fracture toughness (K_{IC}) were evaluated using standard procedures. Finally, optimization of WEDM parameters for machining of the fabricated specimens were carried out using *Taguchi* method [9,10]. During machining, a detail experimentation was performed to realize the effects of five WEDM input parameters viz. pulse on-time (T_{on}), pulse off-time (T_{off}), pulse peak current (*IP*), water pressure (*WP*) and servo feed rate (*SF*) on output responses i.e., R_a and machining speed. Mathematical models, comprising of the input and output parameters were derived using DOE technique combined with regression analysis for this purpose.

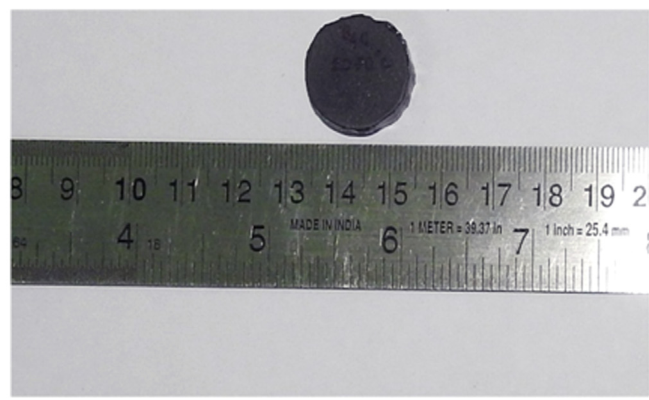
2. Expeimental

2.1. Raw materials and specimen fabrication

B_4C powder (*H. C. Starck*, Germany, *HD-15A*) was procured from having B:C ratio of 3.7–3.8 and surface area of 15–21 m^2/g was used. The d_{50} of as-received powder was found to be ~0.6 µm when analyzed using a laser diffraction particle size analyzer (*LS-13–320-MW, Beckman Coulter, USA*). The as-received powder was directly poured into a graphite die-plunger assembly having 20 mm internal diameter and sintered at 2050 °C in a SPS furnace (*HP-D-25, FCT Systems GmbH, Germany*) with a dwell of 10 min under 50 MPa uniaxial pressure in Argon atmosphere to produce a ~5 mm thick pellet (Fig. 1(a-b)). During the sintering cycle, furnace was heated up to the peak temperature at a heating rate of 400 °C/min and after completion of the dwell time, cooling was done at the rate of 200 °C/min.



(a) Spark plasma sintering furnace inside view with sample loaded in graphite mould (*HP D-25, M/s FCT System GmbH, Germany*)



(b) B_4C sample of diameter 20 mm

Fig. 1. (a) The SPS furnace holding the graphite die/plunger assembly within the graphite top and bottom rams, (b) The sintered pure B_4C after the SPS cycle.

Table 1
Wire EDM parameters and their levels.

Level	T_{on} (µs)	T_{off} (µs)	IP (A)	WP (kg/cm^2)	SF (mm/min)
1	27	48	180	7	2100
2	30	52	200	8	2200

2.2. Physicomechanical characterizations

Bulk density of the sintered B_4C specimen was measured using *Archimedes* water immersion principle in distilled water. Grinding-polishing of the sintered specimens was performed in a *Spectrum System 1000* instrument of LECO *Corporation*, USA. H_V of the sintered specimens was measured using a micro-*Vickers* hardness tester (*402 MVD, Wolpert-Wilson, Germany*) at 4.9 N with 10 s dwell. K_{IC} of the specimen was evaluated using direct crack measurement (DCM) technique and the well-known equations proposed by Niihara et al. [12,13] which were individually suitable for median ($c/a >$ 2.5, where, '*c*' is length of the crack emanating from corners of *Vickers* impression and '*a*' is half of the indentation diagonal) and *Palmqvist* crack ($c/a < 2.5$) systems. *HV* and K_{IC} data were further analyzed using the 2-parameter*Weibull* statistics to obtain the much dependable characteristic hardness (HV_{CH}) and toughness ($K_{IC,\ CH}$) values and corresponding *Weibull* modulus (*m*) [14–18].

2.3. Machining of sintered B_4C

The machining operations were conducted in a CNC WEDM (*EUROCUT Mark-I, 734, India*). Range of machining input data sets at two levels are shown in Table 1. To study the effects of machining parameters on performance characteristics and to trace out the optimal machining condition, a specifically designed experimental procedure was required [19–22]. WEDM input data was prepared by DOE. Process characterization was made using ANOVA to identify the key input variables that affected R_a and machining speed [22]. R_a values of the machined sample under different machining conditions were examined using an optical surface profilometer (*Contour GT-K, Bruker Corp., USA*) with a cut-off length of 6 mm. A typical outcome of roughness measurement is shown in Fig. 2. Since, thickness of the sample was kept constant (5 mm) during this work, the MRR (mm^3/min) was equivalent to the machining speed (mm/min). The machining speed (mm/min) was determined by noting the time taken in minutes for a particular length of cut (say, 4 mm) with the observation that variation in kerf width is negligible for this set of experiments.

2.4. Mathematical modeling

Mathematical models of machining responses were developed by regression analysis from the experimental observations. Each of the response function can be expressed [10] as:

$$Y = C_O + \sum_{i=1}^{n} C_i{*}X_i + \sum_{i=1}^{n} C_j{*}X_j + \sum_{i=1}^{n-1}\sum_{j=2}^{n} C_{ij}{*}X_{ij} \quad (1)$$

where, *Y* is the response characteristic. Regression models were utilized to correlate the x_i (1, 2,…., n) are coded levels of n quantitative input process variables i.e. machining parameters, the