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Machinability of tool steels machined by electric-discharge machining

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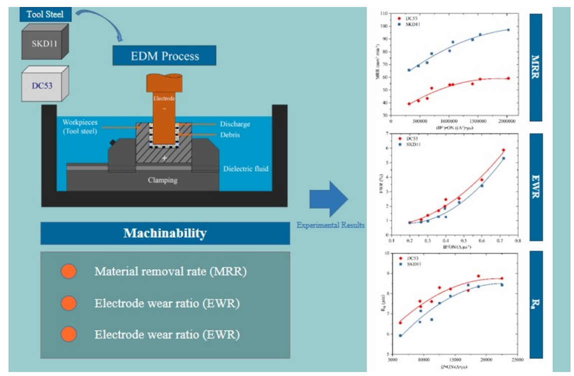
Abstract

SKD11 has been a widely used tool steel for cold works for many years while DC53 tool steel is intently developed to replace SKD11. In this paper, the machinability of these two tool steels was compared in terms of material removal rate (*MRR*), electrode wear ratio (*EWR*), and arithmetic mean of value of roughness (*Ra*) of the specimen machined by electric-discharge machining. The machining variables involved were electric-discharge time and electric-discharge peak current. The machining electrode was made from a copper alloy. Results show that both electric-discharge time and electric-discharge peak current had an influential effect on *MRR*, *EWR*, and Ra of both tool steels. *MRR* of SKD11 was significantly higher than that of DC53 while DC53 caused higher *EWR* than SKD11. It was found that SKD11 provided a better surface finish than DC53. Empirical models for MRR, EWR, and Ra were also presented in this paper.



Keywords: Electric-discharge machining (EDM); Machinability; Tool steel; SKD11; DC53

1. Introduction

Although there are a wide variety of tool steels available for industries, JIS SKD11 is one of the most familiar tool steels for engineers. It has been a widely used tool steel for cold works for many years. With technological progress, many tool steels have been presented to industries, and JIS DC53 is one of them. It is a high alloy tool steel and possesses high hardness and toughness. It is intently improved from the well-known SKD11 cold tool steel. DC53 is developed to remove the weakness of SKD11 in relatively insufficient hardness and toughness when it is high temperature tempered. For example, when they are tempered at 550 °C for 1 h, DC53 provides 62 HRC in hardness whereas SKD11 possesses only 57 HRC and when they have the same hardness at 57 HRC, DC53 has 22 J cm^{-2} in impact values while SKD11 has only 12 J cm^{-2}. Hence, DC53 is suitable to substitute SKD11 in general applications and precision dies [1]. However, no comparative information between SKD11 and DC53 is available in the literature for their machinability.

Materials with high hardness and toughness such as tool steels are typically difficult to be machined by conventional machining processes such as milling, turning, and drilling. Electric-discharge machining (EDM) is a non-traditional machining technique that is generally used to machine tool steels [2, 3]. EDM employs electro-thermal mechanisms to remove electrically conductive material. The material is machined by a series of discrete electric discharges taking place between the electrode and the work surface in a dielectric fluid creating a moving path for each discharge as the fluid turns into ionized in the gap. Consequently, the discharged region was heated to very high temperatures resulting in melting or vaporizing of the discharged surface. The removed particles were then flushed away by the flowing dielectric fluid. The mechanical properties such as strength and hardness of the material did not play an important role in EDM. Only the melting temperature of the material was a significant property [4]. Although the material removal process in EDM is very complex, the use of this machining process in industries is indispensable due to its ability in cutting hard-to-machine materials [5 – 8].

The machinability of materials is important information for cutting materials. For EDM, *MRR*, *EWR*, and surface roughness are three critical machining characteristics determining the manufacturing cost and quality of EDMed components. MRR and EWR are two main variables controlling machining cost while surface roughness involving the fatigue strength, wear and corrosion resistance of the workpiece [9 – 12].

Since EDM is a thermally machining process with complex material removal mechanisms, the machining process could not completely be described. To understand the machining conditions for cutting new materials, experimental investigations are still necessary [13 – 16]. The objective of this paper is to compare the machinability of SKD11 and DC53 tool steels when they are machined by EDM. *MRR*, *EWR*, and Ra (arithmetic mean of value of surface roughness) were three machining characteristics studied in this paper. Machining variables were changed to observe the variation in the machining characteristics. In this study, electric-discharge time (ON) and electric-discharge peak current (IP) are two machining variables involved during the machining process because they are two main variables controlling the discharge energy of EDM processes. An empirical model for each machining characteristic was developed to relate the relationships among the machining variables and the response.

2. Materials and Methods

Materials employed in this experiment were JIS SKD11 and JIS DC53 tool steels. Their chemical compositions are shown in Table 1. As received SKD11 and DC53 bars were machined into a cubic block of 30 mm. The EDM operation in this study was performed on AQ35L Sodick die-sinking EDM machine, and Sodick Vitol-2 was employed as the dielectric fluid. The electrode used in this experiment was ASTM C18150 copper alloy. It is composed of about 0.70 – 0.91 wt% Cr, 0.031 – 0.041 wt% Zr, and the remaining is Cu. The diameter of the electrode was 15 mm and the machining depth was 15 mm as well. The melting point of SKD11 was 1421 °C while that of DC53 was reported in the range of 1450 – 1510 °C [17].

In this experiment, three levels of each machining variable were selected as follows: electric-discharge time at 125, 190 and 250 µs; electric-discharge peak currents at 50, 75 and 90 A. The machining ranges of variables were identified from the manufacturer manual. Each machining condition had three replications to obtain a more precise estimate of the effect of the machining condition. During machining, other machining parameters were set at a constant. For example, the electrode polarity was set to be negative while the gap voltage was 55 V and the off time was 40 µs. After machining, the specimen and the electrode were dried and measured the loss weights, and then the specimen was measured for surface roughness of the EDMed surface. To measure the weight, an electronic balance with 0.01 g. accuracy was employed. The electronic balance was manufactured by Oertling, UK. The surface profiler used in this study was Tokyo Seimitsu model Surfcom 480 A. To minimize the measurement error, the surface roughness was measured three times at three different locations on each machined surface to obtain the average value of the surface roughness of the specimen. The cut-off length and evaluation length of the measurement were 2.50 and 12.50 mm, respectively. *MRR* and *EWR* are calculated as expressed in Eq. (1) and (2), respectively. Fig. 1 represents schematic of the experiment and the machined surface of the workpiece.

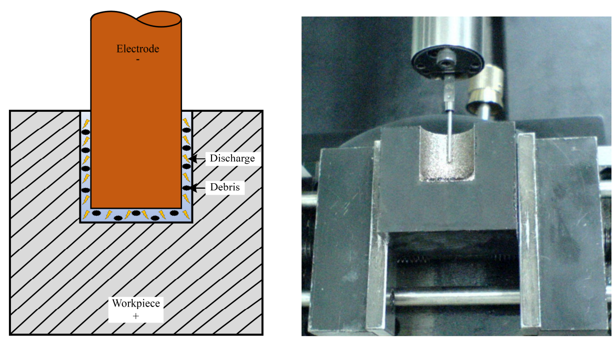


Fig. 1 Schematic of the experiment (left) and the machined surface (right).

$$MRR = \frac{V_W}{T_M} \tag{1}$$

$$EWR = \frac{V_E}{V_W} \times 100\% \tag{2}$$

where V_W is the volume of the workpiece machined during time T_M. V_E is the volume of electrode worn due to machining volume V_W of the workpiece.

Table 1 Chemical compositions of JIS SKD11 and JIS DC53 tool steels.

Tool Steel	**Composition (wt%)**								
	C	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**V**	**Fe**
JIS SKD 11	1.49	0.28	0.39	0.017	0.009	12.05	0.80	0.21	Balance
JIS DC 53	1	1	0.40	0.017	0.002	8	2	0.30	Balance

3. Results and Discussion

Since the electric-discharge time (ON), and electric-discharge peak current (IP) were two main factors controlling the machinability in EDM [4], they were used to formulate the *MRR*, *EWR*, and Ra of the two materials. The best-fitted model of each machining characteristic was determined by the least-squares method. Using the experimental results shown in Table 2, the relationships among *MRR*, ON, and IP are plotted in Fig. 2.

A statistical t-test was performed and confirmed that both *MRR*'s are significantly different with 95% confidence level. It is noticed that at the same machining condition, *MRR* of SKD11 was higher than that of DC53, and *MRR* of both materials was increased as electric-discharge time and electric-discharge peak current increased. This is due to the increase of discharge energy when these two machining variables increase.

When considering the slopes of the graphs in Fig. 2, it is found that the electric-discharge peak current had a more powerful effect on *MRR* than electric-discharge time. It can be explained that the absolute value of the energy density strongly depends on the plasma channel radius, which increases with time. If the plasma channel radius exceeds a critical value, a decrease in the melted metal volume occurs. Although the discharge energy increases with the discharge time, the discharge time also has a negative effect on the strength of the density of discharge energy while a high electric-discharge peak current provides high discharge energy without any negative effect [13]. Therefore, as shown in Fig. 2, when the electric-discharge time increases, it does not strongly increase *MRR* as occurring with the rise of the electric-discharge peak current. The finding in this experiment was in agreement with the result of Rebelo *et al.* [18, 19].

As mentioned earlier, the IP had a stronger effect on *MRR* than ON, it, therefore, hinted a rough relation among the three parameters. Fig. 3 shows *MRR* plotted against parameter (IP^2*ON), and this plot suggests an empirical *MRR* model for each type of steel. The empirical model found from this plot is in the formula expressed in Eq. (3) and providing the best fit in this form. The values of the constants k and α were obtained by fitting the curves by the least-squares method.

Table 2 *MRR* of JIS SKD11 and JIS DC53 tool steels.

ON (μs)	IP (A)	Material removal rate (mm^3 min^{-1})					
		SKD11			DC53		
125	50	64.69	65.98	66.41	41.35	38.46	37.82
125	75	80.12	75.84	79.69	50.64	51.61	52.24
125	90	78.83	82.69	80.55	56.41	51.28	54.49
190	50	69.41	67.70	69.41	41.35	39.74	43.27
190	75	86.98	87.83	87.83	55.44	54.81	52.57
190	90	93.41	97.26	89.97	61.54	63.14	50.96
250	50	71.56	71.56	71.12	44.55	41.66	44.23
250	75	89.97	89.11	89.11	54.49	55.45	54.49
250	90	95.12	98.11	98.11	59.30	58.34	59.93

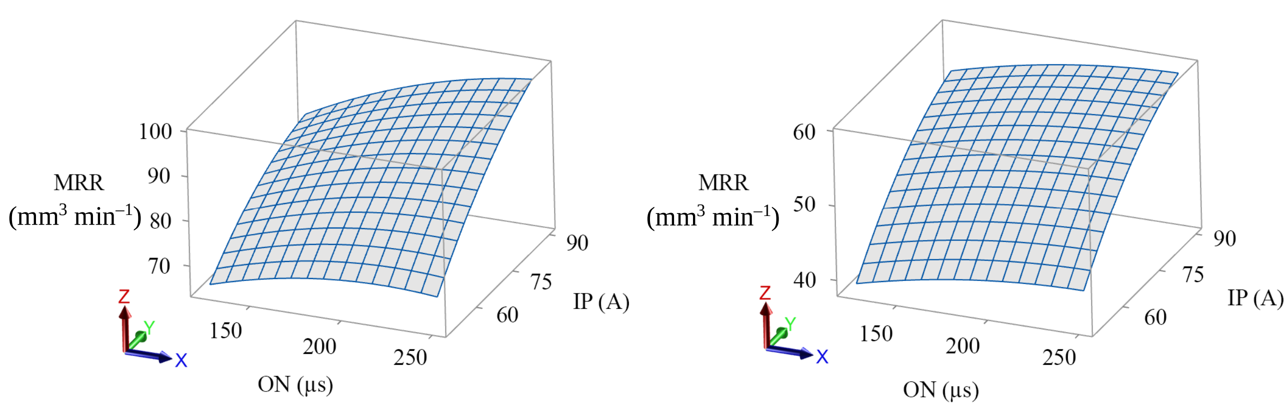


Fig. 2 *MRR* of SKD11 (left) and DC53 (right).

$$MRR = k\left(IP^2 * ON\right)^{\alpha} \quad (3)$$

As illustrated in Fig. 3, the experimental results for *MRR* of SKD11 obeyed the equation *MRR* = 3.6047 $x^{0.2272}$ with the coefficient of correlation R^2 = 0.9575. This means that this empirical model can explain 95.75% of the variability in the data. The empirical model for *MRR* of DC53 tool steel was *MRR* = 1.79 $x^{0.2436}$ with R^2 = 0.9112 where x in both equations represented (IP^2*ON).

Using experimental results tabulated in Table 3, *EWR* of SKD11 and DC53 tool steels are plotted against ON and IP as illustrated in Fig. 4.

From both plots, maximum *EWR* occurred at a low electric-discharge time and high electric-discharge peak current. This can be explained that when the electric-discharge time is longer, the energy density of the discharge sites will be reduced due to an expansion of the plasma channel. As a result, the molten materials cannot be removed effectively from the electrode by the circulated dielectric fluid. Consequently, the wear volume of the electrode decreases. The difference between the removed volumes of workpiece and electrode becomes higher for longer electric-discharge times for which solidification already occurs in copper electrode due to its high thermal conductivity but not yet in tool steels, which possess relatively low thermal conductivities.

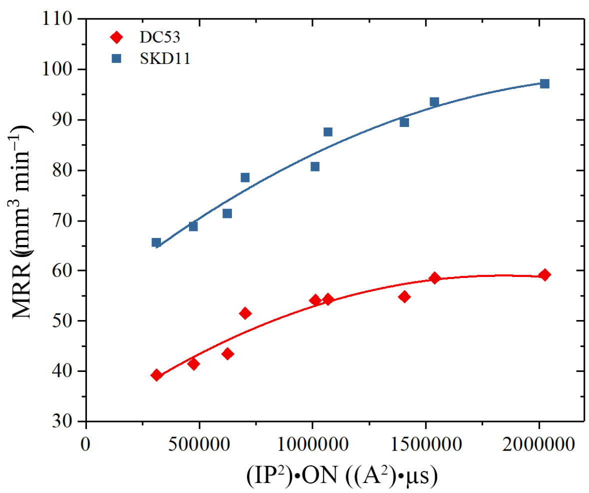


Fig. 3 MRR of SKD11 and DC53.

After considering the slopes of the graphs in Fig. 4, it is found that the effect of electric-discharge time and electric-discharge peak current on *EWR* did not reveal a significant difference. Fig. 5 shows *EWR* plotted against parameter (IP/ON), and this graph leads to an empirical *EWR* model for each type of steel. The empirical model found from this plot is in the form expressed in Eq. (4). The values of the constants *a*, *b* and *c* were determined by fitting the curves by the least-squares method.

$$EWR = a\left(\frac{IP}{ON}\right)^2 + b\left(\frac{IP}{ON}\right) + c \quad (4)$$

For *EWR* of SKD11 tool steel, the experimental results followed the equation *EWR* = 15.367 x^2 – 5.6085 x + 1.3395 with R^2 = 0.9865. The empirical model for *EWR* of DC53 tool steel was *EWR* = 11.229 x^2 – 1.0117 x + 0.6454 with R^2 = 0.9847 where x in both equations referred to (IP/ON).

Fig. 5 shows plots of *EWR* for SKD11 and DC53 at various machining conditions. The plots did not reveal a significant difference to each other; however, a paired comparison test with 95% confidence level, confirmed that the two tool steels provided different EWR's. At the same machining condition, the machining of DC53 produced slightly higher *EWR* than SKD11. This implies that the manufacturing cost of tools made for DC53 will be more expensive than that of SKD11 because DC53 takes a longer time to be machined due to its lower *MRR*, and it consumes a larger amount of electrodes.

Table 3 *EWR* of JIS SKD11 and JIS DC53 tool steels.

ON (µs)	IP (A)	Electrode wear ratio (%)					
		SKD11			DC53		
125	50	1.82	0.96	0.98	2.31	2.84	2.25
125	75	3.71	3.64	2.86	3.27	3.96	4.23
125	90	5.98	5.11	4.80	5.70	6.35	5.58
190	50	0.90	0.93	0.86	2.15	0.55	0.53
190	75	1.36	2.05	2.14	1.72	1.70	2.56
190	90	1.60	2.69	2.50	2.43	2.97	2.20
250	50	1.05	0.52	1.06	0.83	0.89	0.84
250	75	1.66	0.42	0.84	2.06	0.67	1.38
250	90	0.79	1.52	1.52	1.27	1.29	2.49

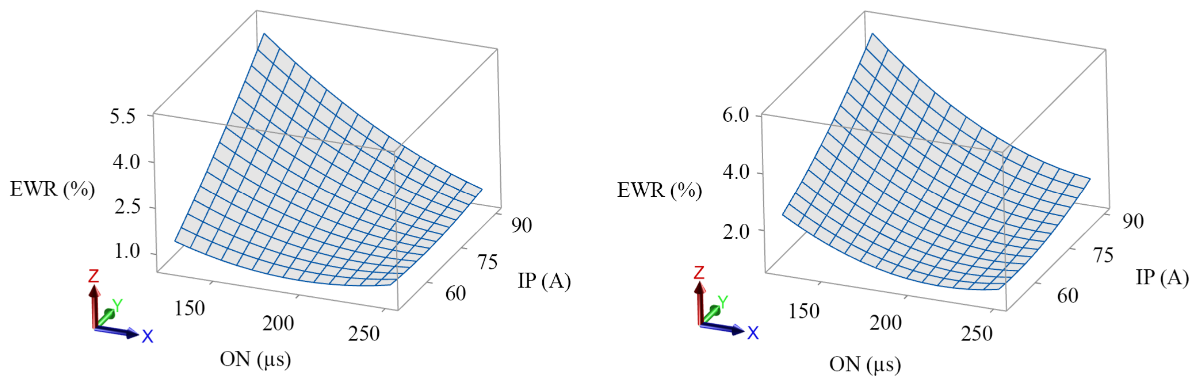


Fig. 4 *EWR* of SKD11 (left) and DC53 (right).

Using the experimental results in Table 4, arithmetic mean of values of surface roughness (R_a) of SKD11 and DC53 tool steels are plotted against ON and IP in Fig. 6.

It is observed that at R_a of SKD11 was slightly lower than that of DC53, and R_a of both tool steels tended to increase as electric-discharge time and electric-discharge peak current increased. The increase of these two machining variables raises the discharge energy resulting in the larger craters on the sparked surface. Therefore, the rougher surface was found when machining with the higher discharge energy

According to Chen *et al.* [16] and Rebelo *et al.* [18], the surface roughness of EDMed surface will be followed by an equation form expressed in Eq. (5). The values of the constants k and α were determined by fitting the curves by the least-squares method. It is also found that the constants k and α depend on the tool-work material combination.

$$R_a = k(IP * ON)^{\alpha} \tag{5}$$

In this experiment, the results agreed with findings in [16] and [18]. As presented in Fig. 7, for DC53 tool steel, the data followed the equation R_a = 0.9513 $x^{0.2244}$ with R^2 = 0.8947, and the empirical R_a model for SKD11 tool steel was R_a = 0.4389 $x^{0.2992}$ with R^2 = 0.9063 where x in both equations denoted (IP*ON). As illustrated in Fig. 7, the surface roughness increases with the rise of the product of (IP*ON). For the EDM process, electric-discharge time and electric-discharge peak current are two main variables controlling the discharge energy. During the EDM process, many craters were created on the material surface, and their size and shape depend on the discharge energy and material properties. The higher discharge energy, the larger and deeper the crater size.

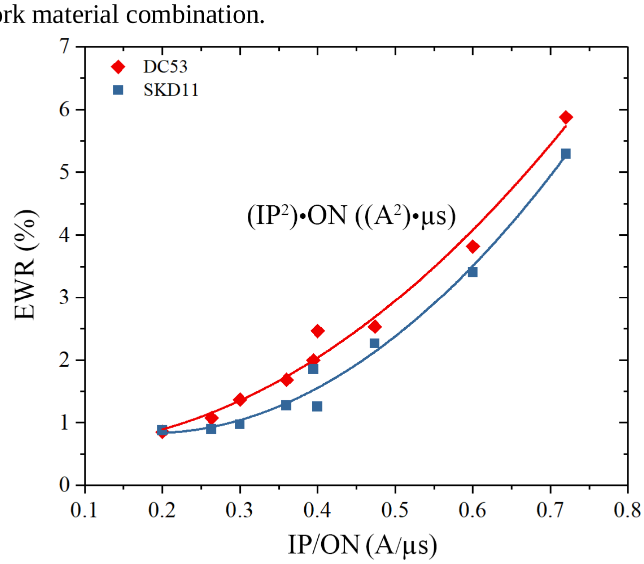


Fig. 5 *EWR* of SKD11 and DC53.

Table 4 R_a of JIS SKD11 and JIS DC53 tool steels.

ON (μs)	IP (A)	Surface roughness (μm)					
			SKD11			DC53	
125	50	6.33	6.01	5.44	7.29	7.76	4.62
125	75	7.78	5.86	6.16	7.24	7.34	8.31
125	90	6.73	6.42	7.02	7.24	7.59	8.02
190	50	7.60	7.06	6.79	6.97	7.82	7.29
190	75	9.63	7.34	6.71	9.54	5.12	10.05
190	90	8.19	9.39	7.73	8.35	8.19	7.94
250	50	6.20	7.72	8.69	7.84	8.82	8.25
250	75	7.86	8.37	8.81	9.37	9.62	7.65
250	90	9.32	9.24	6.73	9.32	10.24	6.73

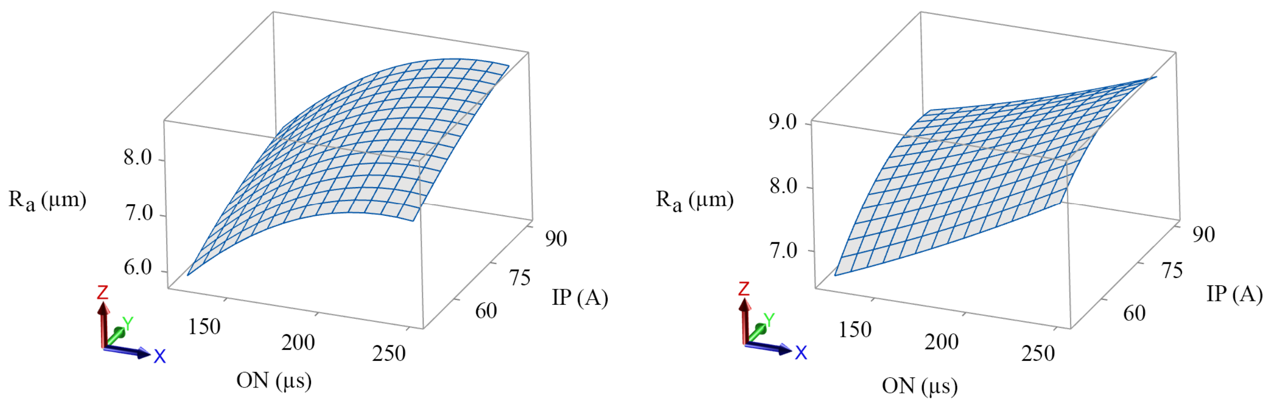


Fig. 6 R_a of SKD11 (left) and DC53 (right).

As a result, higher discharge energy initiates a rougher surface. Since these two lines in Fig. 7 did not show a clear difference from each other. Statistical data analysis was performed to determine the difference between the two data sets. From a paired comparison test with 95% confidence level, it indicated that the two tool steels provided different R_a's. SKD11 had smoother surfaces than that of DC53 when machined by EDM under these machining conditions.

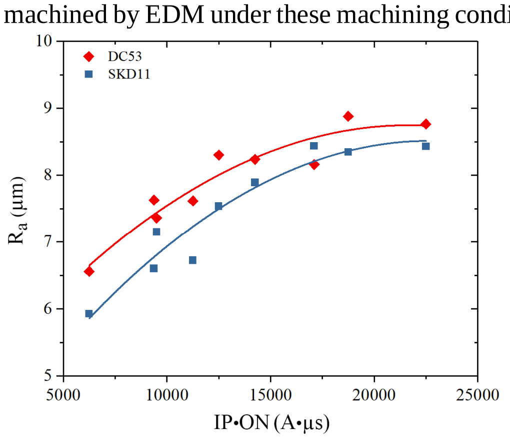


Fig. 7 R_a of SKD11 and DC53.

4. Conclusion

In this paper, the machinability of SKD11 and DC53 tool steels were studied and compared in terms of material removal rate, electrode wear ratio, and surface roughness of the specimen machined by electric-discharge machining. Results show that under the same machining condition:

SKD11 had a higher material removal rate than DC53.

SKD11 caused a lower electrode wear ratio than DC53.

SKD11 provided a better surface finish than DC53.

These results will be very useful to industries in the material selection process.

5. Acknowledgement

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