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INFLUENCE OF MICROSTRUCTURAL CHARACTERISTICS ON ELECTRICAL DISCHARGE WIRE CUTTING CONDITIONS OF A390 Al-Si HYPEREUTECTIC ALLOY

تأثير البنية المجهرية لسبيكة الالومنيوم- سيليكون فوق اليوتكتية A390 على متغيرات التشغيل الخاصة بطريقة القطع بالسلك بالتفريغ الكهربي

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ملخص البحث

فى هذا البحث تم دراسة تأثيرالبنية المجهرية للسبيكة الالومنيوم- سيليكون فوق اليوتكتية A390 (16.47% سيليكون) على متغيرات التشغيل الخاصة بطريقة القطع بالسلك بالتفريغ الكهربي. لقد تم بالتحديد دراسة تأثير عمليتى التعديل و تصغير الحبيبات على البنية المجهرية للسبيكة A390. و قد وجد ان اختلاف البنية المجهرية للسبيكة و خصوصا حجم حبيبات السيليكون له تأثير كبير على متغيرات التشغيل بطريقة القطع بالسلك:بالتفريغ الكهربي مثل معدل التغذية و سرعة القطع و معدل أزاله المعدن.

ABSTRACT

The paper presents the results of an experimental investigation on the machinability of A390 hypereutectic Al-Si alloy using wire electrical discharge machining (WEDM). The effect of the modification and grain refinement treatments on the microstructure and also on the machining conditions has been evaluated. The process parameters taken into consideration are the average gap voltage (A_j), surface finish type (SF), pulse frequency (F), cutting speed (CS), material removal rate (MRR) and finally the kerf size (KS). The results show that the modification process of A390 alloy has a significant effect on the electrical discharge wire cutting (EDWC) parameters. It has a great influence on the improvement of MRR, CS, and KS. The modified alloy exhibits better machinability conditions when compared with both the as-cast and the grain refined A390 alloys. The grain refined A390 alloy shows lower machinability conditions when compared with the as-cast A390 alloy.

KEYWORDS: Wire electrical discharge machining (WEDM), Al-Si hypereutectic alloys.

INTRODUCTION

Hypereutectic alloys such as A390 exhibit several very specific and interesting properties, such as high wear resistance, high strength and hardness, and low thermal expansion coefficients [1]. As a result, they are used in heavy wear applications, often at elevated or medium temperatures, such as in pistons, cylinder blocks and AC compressors. Unfortunately, the machinability of these alloys is poor, because the extreme hardness of the silicon combined with the relative softness of the matrix tends to wear the tool very rapidly [2].

In Al-Si alloys, the eutectic phase usually has an irregular shape because silicon is a faceted phase. Many efforts have been made in the microstructural modification of casting Al–Si alloys in order to achieve fine Si phases with

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beneficial shapes and distributions. For instance, by adding Na and Sr or with a cooling rate exceeding approximately 5 ^{o}C/s, the eutectic is changed from the flake to a fibrous appearance. Eutectic modification is carried out to improve both the mechanical properties and the machinability of Al-Si alloys [3]. Another treatment is carried out on aluminum alloys which is known as grain refinement. Grain refinement has been an important technique for improving the soundness of aluminum products by minimizing shrinkage, hot cracking, and hydrogen porosity [4]. The addition of the grain refiners, usually master alloys containing potent nucleant particles promotes formation of a fine equiaxed macrostructure by suppressing the growth of columnar and twin columnar grains. For a given alloy composition, castings with columnar or large grains are believed to have poor castability and mechanical properties compared with castings with fine equiaxed grains.

Amongst the various non-conventional machining methods which nowadays find a wide range of applications, WEDM. is the most extensively used cutting technique on the production of die-making, precision machining, the cutting/separation of sheet materials and for the manufacturing of prototypes. WEDM is a spark erosion process used to produce complex two-and three dimensional shapes through electrically conductive workpieces. Newer and more exotic materials created and/or demanded by space technology sometimes cannot be economically cut using conventional cutting tools, but are cut effectively by WEDM. The process wastes very little workpiece material due to its small kerf size, coupled with the fact the process can accurately cut unusual shapes. In modern manufacturing industry, WEDM has been extensively used to machine complicated shapes on advanced materials with high accuracy. WEDM is an electrothermal process where the material removal mechanism is achieved by electrical discharges occurring between an anode (wire) and a cathode (workpiece). Due to the very high thermal power concentration, the material removal mechanism is based on melting and evaporation.

In WEDM, a thin wire of diameter ranging between 0.05 and 0.3 mm acts as the electrode. The wire unwinds from a spool, feeds through the workpiece, and is taken up on a second spool. A pulse generator delivers high frequency pulses between the wire and the workpiece. The gap between the wire and workpiece is flooded with deionized water, which acts as the dielectric. Material is eroded ahead of the traveling wire by spark discharges. Either the workpiece or the wire can be moved to cause the wire to cut similar to a band saw. There is no mechanical contact between the wire and the workpiece in WEDM. The wire-workpiece gap usually ranges from 0.025 to 0.05 mm and is constantly maintained by a computer-controlled positioning system [5,6].

However, the machinability of hypereutectic Al-Si alloys and effect of modification and grain refining processes have been extensively studied using conventional methods of machining such as turning, drilling...etc. Unfortunately, few investigations have studied the machinability of these alloys using non-conventional methods [2,7]. The main purpose of the present paper is to determine the effect of modification and grain refinement treatments of A390 Al-Si hypereutectic alloy on electrical discharge wire cutting parameters.

2. EXPERIMENTAL WORK

2.1 Materials

The matrix (base) material used in this work is an industrial age-hardenable A390, which is a cast hypereutectic

Table 1 Chemical composition of A390 alloy

Alloy	Chemical compositions (wt%)								
	Si	Fe	Cu	Mg	Mn	Ni	Zn	Ti	Al
A390	16.47	0.36	4.29	0.62	0.132	0.149	0.019	0.017	Bal.

Al-Si alloy. The chemical composition of the alloy is listed in Table 1.

The modification and the grain refining were carried out using Na and Al-Ti-B master alloy, respectively. The procedure for casting including melting of the matrix A390 aluminum cast alloy was carried out in a crucible furnace having 3 kg capacity. When reaching the desired temperature (approximately 680°C), the melt was degassed with Argon inert gas. When the degassing process was completed, the modifier or the grain refiner was added, after which the melt was cast into a permanent steel mould. The modification process consists of adding a small amount of Na (about 0.01% by weight of the charge) to the melt just before casting. In case of grain-refined alloy, grain refinement was achieved by the addition of Al–5Ti–1B master alloy (about 1% by weight of the charge) to the melt prior to casting.

2.2 Heat Treatment And Hardness Measurements

All the investigated alloys were heat treated at T6 condition [8]. The alloys were solution treated at 495 ± 1°C for three hours and then quenched in cold water. After cooling the alloys were artificially aged at 175 ± 1 °C for 8 hours. Vickers macrohardness measurements, with a load of 10 kgf, were carried out on the alloys specimens with a *Hoytom* macrohardness tester. The hardness measurements were taken after the heat treatment of the alloys.

2.3 Metallographic Observations

Microstructural evolution studies were carried out on the samples to investigate the morphological changes of the phases due to the modification and grain refining processes. The microstructure of the alloys was investigated by means of optical microscopy. The micrographs were captured using a high resolution digital camera. The porosity contents of the alloys and also the size of the primary Si particles were calculated by image analysis technique using quantitative analysis methods [9].

2.4 Machining Experiments

High precision 5 axis CNC wire electrical discharge machine (Robofil 300), manufactured by Charmilles Technologies Corporation was used to perform the machining experiments. In the beginning stage of the machining operation of Robofil 300, the operator chooses the input parameters according to the workpiece material and its height from a manual given by the WEDM manufacturer. Finally, the operator inputs the shape and dimensions of the required components (x,y). In this work, deionized water as a dielectric fluid and hard brass wire of 0.25 mm diameter were used.

From the monitor of the machine, the following values must be recorded:

(i) Duration of pulse (A) in μs.
(ii) The time between two pulses (B) in μs.
(iii) Average gap voltage (A_j) in volt.
(iv) The offset value (the distance between the center of the wire and workpiece surface) in mm.
(v) The average feed rate of machining (V_f) in mm/min.

Wire electrical discharge machining parameters considered are; cutting speed which is defined as the area cut by the electrode wire in unit time in mm^2/min, material removal rate which is defined also as the volume removed by the electrode wire in unit time in mm^3/min, kerf size in mm and resulted surface roughness. The cutting speed and material removal rate can be calculated from the following formulae [10], in order to determine the machine settings of the EDWC process, and were displayed during the running time on the monitor of the machine.

$$CS = V_f H \qquad \text{.....(1)}$$

$$MRR = (d_w+2S_b)\, V_f H \qquad \text{.....(2)}$$

Where:

d_w = wire diameter, mm.
S_b = spark gap, mm.
V_f = machining feed rate, mm/min.
H = workpiece height, mm.

The pulse frequency can then be calculated from the following relationship:

$$F= 1 / (A+B) \qquad \text{...(3)}$$

In this investigation, four levels of surface roughness (rough, semi-fine, fine and very fine) are selected. Kerf size was calculated as twice the offset value which is recorded from the monitor of the machine.

4. RESULTS AND ANALYSIS

4.1 Microstructural Evaluation

Figure 1a shows the microstructure of the as-cast A390 alloy. As shown the microstructure of the alloy consists of three phases, typically, the α-alpha (light), eutectic (flake like) and primary silicon (dark) phases. The microstructures of the alloy after modification and grain refining are illustrated in Figures 1b and 1c respectively.

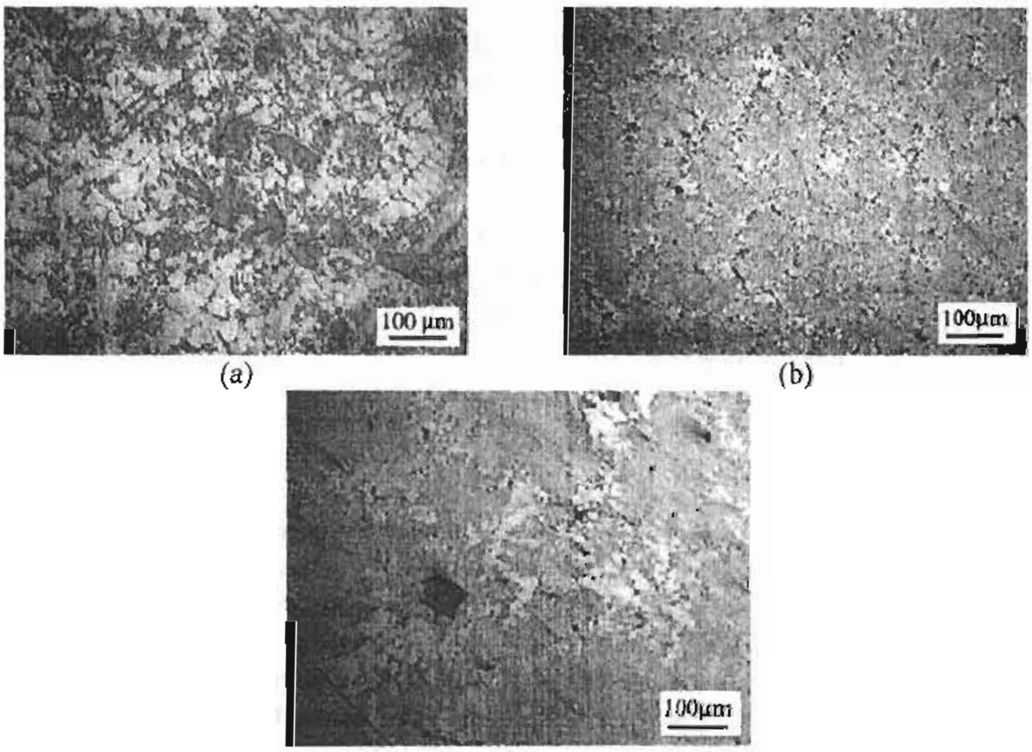


Figure 1. Microstructure of the A390 alloy at different conditions (a) As-Cast, (c) modified and (d) grain refined.

It is clear from Figure 1b that the addition of Na has a great influence on the microstructure of the alloy. The shape of eutectic phase is changed from the flake to a fibrous one. Also, the bulk primary silicon particles were broken to very fine particles. The modification process delays the precipitation of silicon when the normal eutectic temperature is reached. It is thought that Na collects in the liquid interface with the newly-formed silicon crystals, inhibiting and delaying their growth. Thus, under cooling new silicon nuclei are formed in large numbers resulting in a relatively fine-grained eutectic structure [11]. Examination of the microstructure of the grain refined alloy revealed that the addition of Al-Ti-B master alloy has a significant influence of the shape of both alpha and eutectic phases. However, it has little or no effect on the shape of the primary silicon particles. Figure 2 shows the effect of modification and grain refining on the size of the primary silicon particles. The porosity contents of the investigated alloys are shown in Figure 3. The modification process has been found to increase the porosity content and pore size and also to change the porosity distribution.

4.2 Hardness Measurements

The hardness measurement results are illustrated in Figure 4. The figure indicates that there is a slight difference in the hardness values for the investigated alloys. However, the as-cast A390 alloy exhibited higher hardness values as compared with both the modified and grain refined alloys. The as-cast, grain refined and modified alloys showed hardness values of 120±10, 113±7and 100±8 VHN, respectively.

4.3 Machining Results

The results obtained indicate that A390 alloy can be machined effectively using the EDWC process. The EDWC process is however slow and the material removal rate does not exceed the value of MRR = 62.843 mm^3/min for the modified A390 alloy under the conditions used.

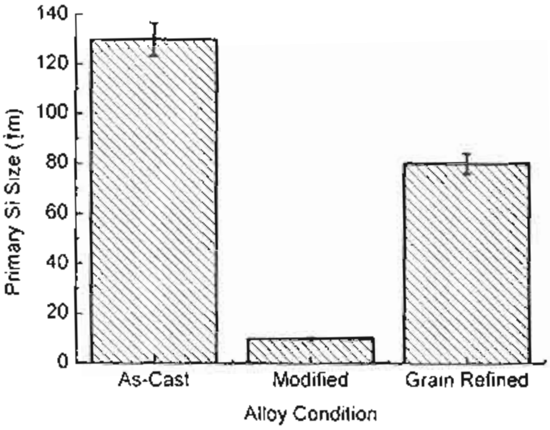


Figure 2. Primary Si size of A390 alloy conditions.

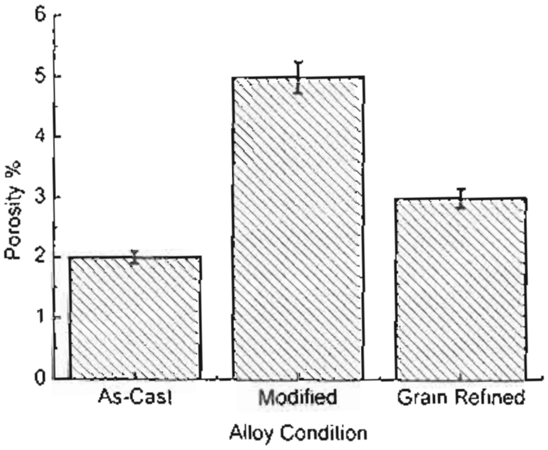


Figure 3. Porosity contents of A390 alloy conditions.

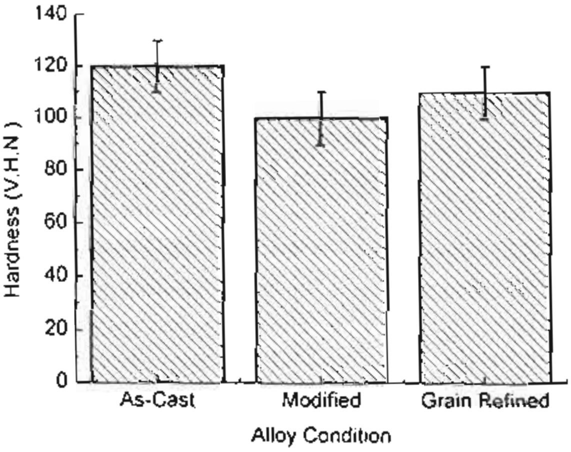


Figure 4. Hardness values of the A390 alloy conditions.

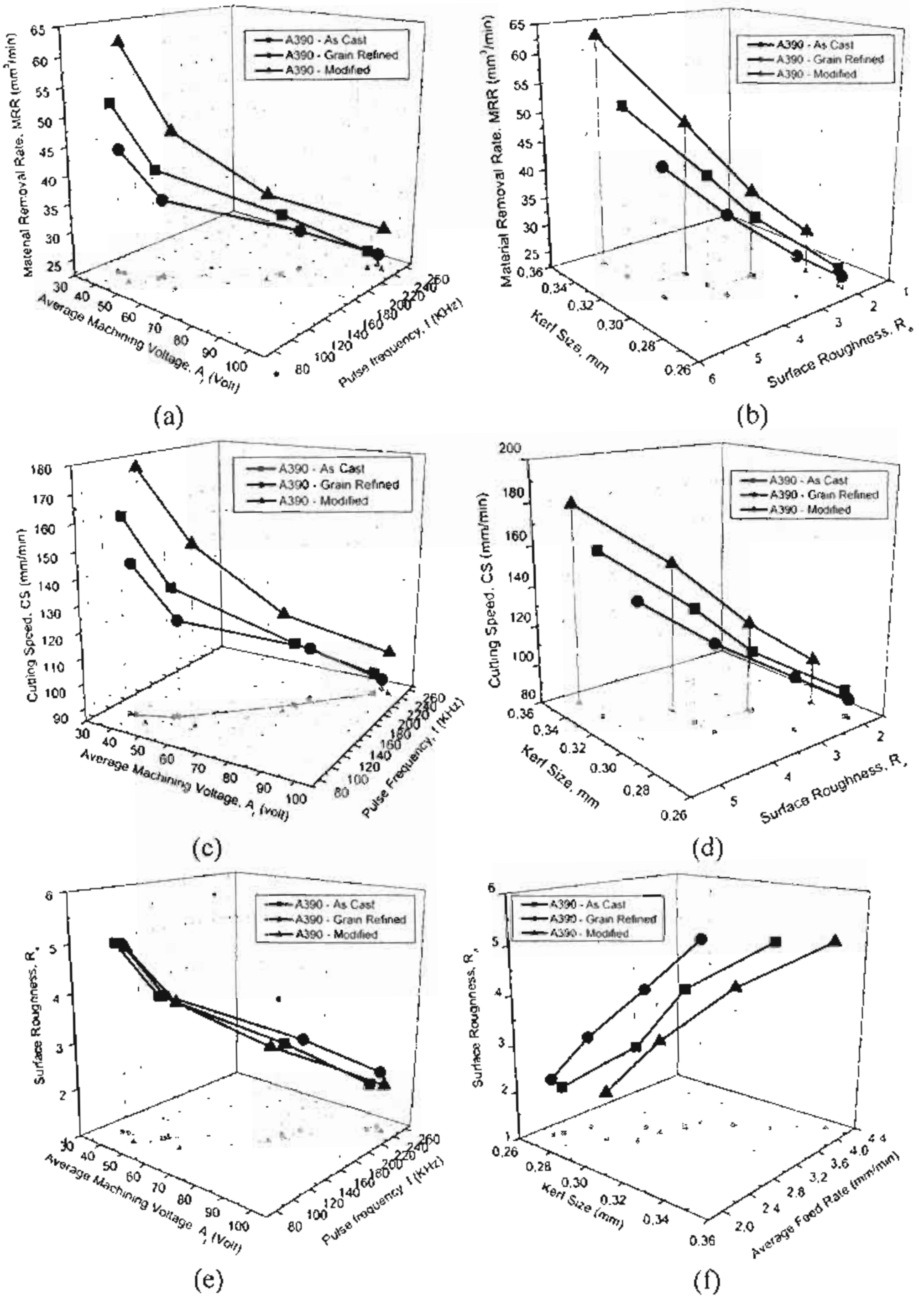
Figure 5 shows the relationship between machining parameters (material removal rate, cutting speed and surface roughness) with pulse frequency, average gap voltage, kerf size and average feed rate for A390 as-cast, grain refined and modified alloys.

The material removal rate decreases with increasing the pulse frequency and average gap voltage for all material conditions as shown in Figure 5a. It can be shown also that the material removal rate values for the modified alloy are higher than those for the as-cast one. This can be explained by the break down of large Si primary particles, due to the modification process, to very fine particles combined with the redistribution of these particles in the weak matrix (alpha) phase. Another reason for the improved machinability exhibited by the modified alloy is the fact that modification has displaced the eutectic point, originally at 11.6 % Si, to the right (14% Si) so that the composition of the alloy under consideration is near the eutectic composition and the structure still consists of primary α-alpha, eutectic and smaller particles of primary silicon. The eutectic is now extremely fine-grained [11].

For grain refined alloy, the material removal rate values are smaller than those values for the as cast one. This may be due to the presence of additional phases such hard inter-metallic compounds such as Al_3Ti because of addition of the master alloy. It has been shown in the literature that the presence of high levels of silicon in aluminum foundry alloys reduces the efficiency of the master alloy additions such as Al-5Ti-1B [12,13]. In secondary Al-Si casting alloy such as A319, commonly used to cast engine blocks and cylinder heads, a significantly higher level of impurities is present compared with primary alloys such as A356. It is often assumed that for a particular silicon content, all aluminum casting alloys will produce the same grain size for equal additions of grain refiner for a given casting condition. However, it is expected that the presence of some impurity elements specially Fe and Cr can decrease the efficiency of Al-Ti-B grain refiners [14,15]. It is proposed that a complex intermetallic phase particles are formed when a grain refiner is added to the alloy, decreasing their ability to nucleate aluminum grain.

The relationship between the material removal rate with both kerf size and surface roughness is shown in Figure 5b. As the kerf size and surface roughness values increase the material removal rate increases directly for all material conditions. The second machining parameter considered in this investigation is the cutting speed. Figure 5c shows that as the pulse frequency and average gap voltage values decrease, the cutting speed values increase for all material conditions. On the other hand, Figure 5d shows that as the kerf size and surface roughness values increase the cutting speed also increases. It can be shown also that the cutting speed values for the modified alloy are higher than those for as cast one. For grain refined alloy the cutting speed values are smaller than those for the as cast one.

Figures 5e and 5f show the relationships between the surface roughness and each of the pulse frequency, average gap voltage, kerf size and average feed rate. It is clear that the surface roughness values decrease with an increase of both pulse frequency and average gap voltage values for all material conditions. Surface roughness values increase with the increase of average machining feed rate and kerf size values. This may be due to the high porosity content of the modified A390 alloy when compared with the other alloys (see Figure 3). Figure 6 shows the relationship between kerf size and alloy conditions. It can be noticed that there is practically no difference in the kerf size for all A390 alloy conditions. The kerf size values for grain modified alloy are higher than those values for the as-cast alloy by 5.5%. But for grain refined alloy the kerf size values are smaller than those values for the as cast one by about 8.5%.



(a) (b)

(c) (d)

(e) (f)

Figure 5. Relationship between machining parameters MRR, CS, and SR and each of the pulse frequency, average gap voltage, kerf size and average feed rate.

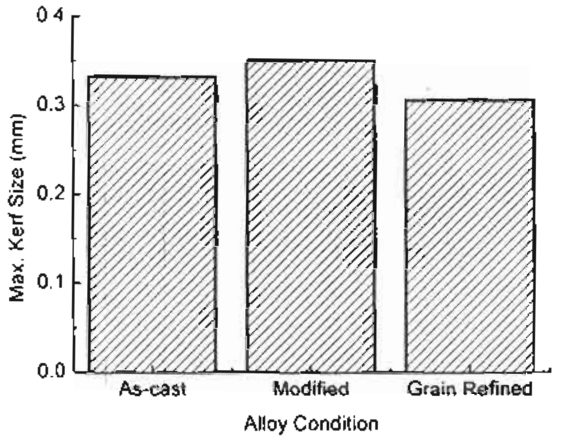


Figure 6. Kerf size values for A390 alloy conditions.

5. CONCLUSIONS

The comprehensive results obtained demonstrate primarily that the electrical discharge wire cutting process can be used effectively in cutting hypereutectic alloys such as A390 Al-Si alloy. The processes of modification and grain refining for A390 alloy have a significant effect on the WEDM parameters such as material removal rate, cutting speed, kerf size and output surface roughness. The material removal rate, cutting speed and kerf size values for modified A390 alloy are higher than those values for the as-cast one. Grain refined A390 exhibited lower values of the material removal rate, cutting speed and kerf size values when compared with the as-cast one.

The morphology of the primary silicon particles plays an important role in influencing the machining conditions for EDWC process. When the silicon particles have small sizes such as in the modified A390 alloy, they improve the machinability of the alloy. On other hand, if these particles have big sizes such as in the as-cast and grain refined A390 alloys, they reduce the machinability of this alloy resulting in smaller values of material removal rate, cutting speed and kerf size.

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