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# Laser Micro and Nano Drilling of Aluminium Alloy Using Tungsten Carbide and Silica Carbide Nanoparticles

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**Abstract:** The micro and nano drilling holes are produced by a Q-switched Nd :YAG laser (1064 nm) interaction with 8009 Al alloy using two kinds of nanoparticles. Nanoparticles are tungsten carbide (WC) and silica carbide (SiC). The micro and nano holes have been investigated with different laser pulse energies (600, 700 and 800)mJ, different repetition rates (5Hz and 10Hz) and different concentrations of nanoparticles (90%, 50% and 5% ). The results indicate that micro and nano holes have been achieved under conditions of 600 mJ laser pulse energy, 5Hz laser repetition rate, and 5% concentration of the nanoparticles (for the two types of nanoparticles). The diameters of holes are increase to millimetres and cracks are formed with increasing of the laser pulse energy, laser repetition rate and high concentration of nanofluid.

**Keywords:** Laser Microdriling and Nanodrilling, Al-Alloy, Nanoparticles

## 1. Introduction

Drilling is one of the most common machining operations in the manufacturing industry [1]. Laser microdrillings give high aspect ratio than tool micro drillings. Minimum microhole sizes can be as low as 1 micron in thin materials. Microdrilling is not characterized just by small drills but also a accurate rotation technique of the special drilling cycle. The laser systems can be used for micromachining, microdrilling microcutting, precision machining, and fine cutting, microfabrication, marking, engraving and milling [2].

In laser beam machining process (LBM) the material removal rate (MRR) is not reliant on mechanical or physical properties of material but thermoptical properties of the material. In many cases, laser micromachining is a more cost-effective alternative to the processes such as electrical discharge micro machine (EDM). In most cases laser micromachining works best if the feature to be produced is less than 1mm in depth. For example, microhole drilling is normally limited to materials less than 1.5 mm thick and aspect ratios less than 30:1 [2, 3]. Laser microhole drilling processes provide access to world leading precision hole drilling technology. This process can be used by femtosecond laser micromachining with very high peak powers which provide for minimal thermal damage to surroundings and high aspect ratios [4]. Microdrilling process has a great use for manufacturing of sophisticated items. Laser microdrilling gives a high aspect ratio than tool micro drillings [5]. Generally, pulsed mode is used for laser micromachining with high resolution in depth and lateral dimensions. The parameters of laser beam such as pulse energy, pulse frequency, pulse width and focal length, additionally the properties of nanoparticles are very influential and enhanced the properties of holes. Laser drilling process can be applied on a wide range of different materials including of super alloys and irradiated on advanced materials like nanoparticles which its properties like higher toughness, ductility, high temperature stability, high strength and wear resistance make tungsten carbide(WC) and silica carbide(SiC) nanoparticles materials highly competitive against other conventional materials [4].

Pulsed Nd:YAG laser microdrilling on different materials have been carried out to study the effect of the process parameters which effect on material removal rate (MRR), formation of holes and heat affected zone (HAZ) width [6].

## 2. Laser interaction with nanoparticles

The interactions of the laser's electromagnetic wave with the electrons of a particle lead to absorption and scattering of the particle's electrons by the laser's photons. The particle warms up if the energy of the electrons can be quickly transferred to the crystal lattice due to excellent heat transfer between the electrons and the phonons.

The particle can melt and gradually fade away if enough energy is absorbed. The amount of energy that a particle absorbs from the pulse laser beam is calculated by [7]:

$$E_{abs} = \frac{E_o}{A_o}\sigma_{abs}^{\lambda} \quad \ldots (1)$$

where $J = E_o/A_o$ and is laser fluence, $E_o$ is pulse energy, $A_o$ is spot size area and $\sigma_{abs}^{\lambda}$ is the particles absorption cross section, which strongly depends on the laser wavelength, so the energy of the particle´s absorb is equal to [7]:

$$E_{abs} = J\sigma_{abs}^{\lambda} \quad \ldots (2)$$

For a spherical shape of nanoparticles the amount of energy absorbed by nanoparticles can be calculated [7]:

$$Q_{abs}^{\lambda} = \frac{4\,\sigma_{abs}^{\lambda}}{\pi d_p^2} \quad \ldots (2)$$

Where $d_p$ the diameter of nanoparticle, Q is the absorption efficiency (unit less) and both Q and σ also strongly depend on laser wavelength, particle size and shape [7]. Tungsten carbide (WC) and Silica carbide (SiC) have hard-facing nanoparticles offer a distinct combination of high hardness and high toughness [8], with melting point (2870°C and 2730°C) respectively [9].

The absorption curves, Qabs = Qabs(dp) for the particles can be calculated when the absorption efficiency (or absorption cross section) was known. The amount of energy absorbed by a particle of any size from the laser pulse can be calculated using Eq. (1). According to the equation, this energy is spent for the particle heating–melting–evaporation process. If the amount of absorbed energy is rather small, only particle heating can be expected. And with more absorbed energy, melting occurs as can be shown in figure (1) [7].

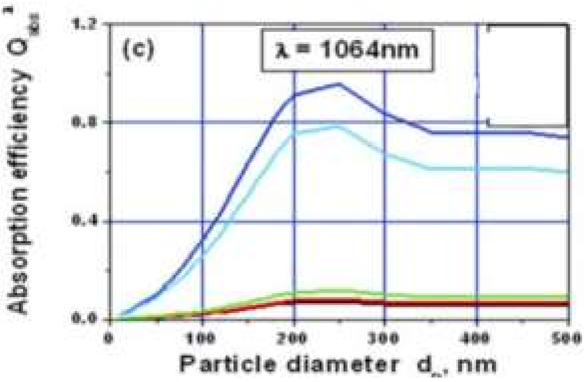



**Figure (1):** particle –size dependence of absorption efficiency for Nd:YAG laser[7]

There are three inherent problems. These problems are the high reflectivity of aluminium to light even down to short ultraviolet wavelengths (as shown in figure (2)), the high thermal conductivity of aluminium, and the self oxidation [10].

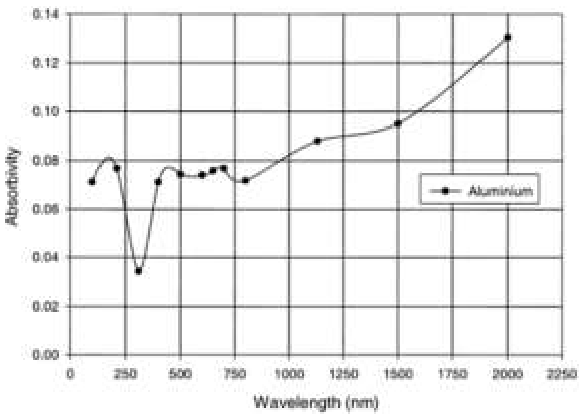



**Figure (2):** Absorptivity of aluminium as a function of incident wavelength [10]

Aluminium is the third most prevalent element in the Earth's crust. It is the chemical element of the 3rd group in the periodic table of the elements [11]. It has low melting and boiling point. The plasma formed above the surface of aluminium, will be responsible for changing the dimensions of the laser-drilled holes due to the transfer of heat to the material surface. This will therefore affect the precision obtainable. The emission of vapour and particulates from the surface during the interaction event will also be responsible for scattering the incoming radiation. Melt erosion of the sidewalls of the drilled hole caused by the high vapour pressure above the surface of the material during laser irradiation of the surface will push the melt up and out of the hole. This will also alter the geometry of the percussion-drilled the hole [10].

In this work, 8009 Al alloy was used because of the importance of this alloy in manufacturing a new supersonic aircraft, missile fins (it is the bases in which a 30- 40 % of weight saving may be expected), the helicopters transmission shafts, and many other different applications [12, 13]. Aluminium 8009 alloy has excellent heat resistant properties [14]. Additionally aluminium 8009 alloy can possess a desirable combination due to high temperature specific strength, corrosion resistance, electrical, thermal conductivity, and creep resistance at temperatures in excess of 300°C [15]

## 3. The experimental setup

The experimental setup for obtaining the micro and nano holes based on nanoparticles in different materials can be shown in figure (3).

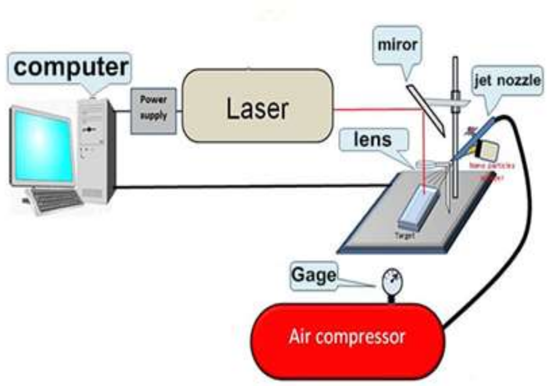



**Figure (3):** Schematic diagram of the experimental setup for laser metal micro and nano drilling by nanoparticles

The setup consists of Q-switched Nd:YAG laser (1064nm) source, air compressor which is pumping air to the jet nozzle. Two types of nanoparticles (tungsten carbide of 55nm grain size and silicon carbide of 50 nm grain size) were used separately; convex lens with 100mm focal length and the target was 8009 Al alloy of 0.1 mm thickness. This alloy has good thermal stability, high temperature strength and high wear resistance and good thermally properties [16]. The chemical components of this alloy are aluminium, manganese, titanium, iron, silicon, zinc and vanadium [17]. The laser pulse width is (10 ns), pulse repetition rates were (5 and 10) Hz, laser pulse energies were (600, 700, 800) mJ.

The initial step was to prepare the nanoparticle fluid by combining various percentages of nanoparticles with water to increase the performance and heat transmission characteristics of nanofluids [18]. This solution is placed on a magnetic stirrer device at 50°C for 20-30 minutes to create a homogenous suspended particulate solution with different nanoparticle concentration ratios (90%, 50%, and 5%)It is difficult to make the nanofluid to be totally homogeneous during the experiment because it needs time to take the nanofluid from the magnetic stirrer and then putting it in the container of jet nozzle and then using it for drilling.

The nanofluid is placed in a small container in the jet nozzle. This jet nozzle is connected to a compressor with air pressure (150-200) psi. The second step is using the jet nozzle to spray the nanofluid on the material's surface. The laser beam is focused on the nanofluid spray above the surface of aluminium alloy at the same moment. This method is applied with the two types of nanoparticles and with the same laser parameters but with different exposure time.

## 4. Result and discussion

### 4.1 Drilling of Aluminium alloy without using nanoparticles

When the laser pulse energy was 600mJ, and increased to (700-800)mJ, repetition rate is 10Hz and exposure time is (40sec), the drilling holes were not obtained, as shown in figure (4). This figure shows the effect of the laser pulse on the alloy. There is only a thermal effect (without obtaining any holes on the target). This means that the laser with its maximum energy, with high repetition rate and with a long exposure time, couldn't make any hole in the target.

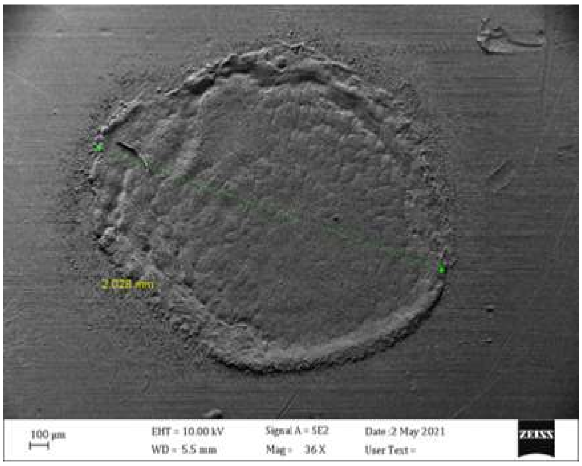



**Figure (4):** The FESEM test of aluminium alloy without nanoparticles (laser energy is 800mJ, repetition rate is 10Hz and exposure time is 40 sec

### 4.2 Drilling of Aluminium alloy with silicon carbide (SiC) nanoparticles

When the concentration ratio of nanofluid is 90% (of nanoparticles), the laser pulse energy is 800mJ, repetition rate is 10Hz and exposure time is (5-10) sec, the aggregations of nanoparticles and microcracks were obtained on the target, as shown in figure (5). This case can be attributed to the high concentration of nanoparticles and high laser energy leading to very large numbers of (SiC) nanoparticles are melted in a very short time (5sec.) and falling on the target. Some of them cause cracks and others cause agglomerations on the surface.

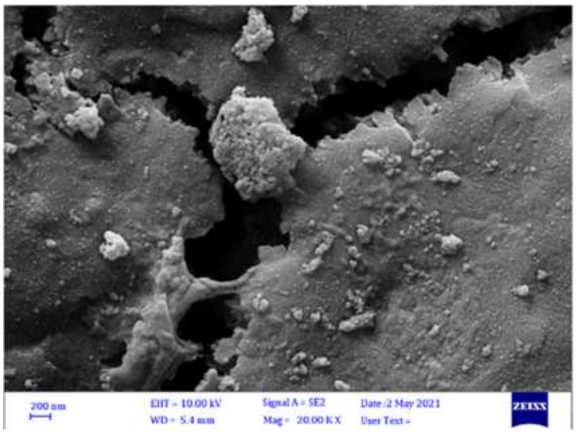


**Figure (5):** The FESEM test Aluminium alloy drilled by pulsed laser and high concentration of silicon carbide nanoparticles (laser energy is 800mJ, frequency is 10Hz, exposure time is 5sec and 90%concentration ratio)

When the concentration ratio of nanofluid was reduced to 50% (of nanoparticles), the laser pulse energy is 600mJ, repetition rate is 5Hz and exposure time (5-10) sec, the microholes were obtained on the target. The FESEM image of Aluminium alloy (figure (6)) shows some amount of (SiC) nanoparticles are melted in and come down to surface to drill micro holes and some of (SiC) nanoparticles accumulated sufficiently forming cracks on the target.

If the concentration ratio of the nanofluid is reduced to 5% (of the nanoparticles), the laser pulse energy is 600mJ, repetition rate is 5Hz and exposure time is (5-10)sec, the micro and nano holes for aluminium alloy are achieved with the minimum heat affected zone (HAZ) width. Figure (7) shows few numbers of fine nano holes appear on the target due to light concentration of nanoparticles. The number of nanoparticles in the fluid will be small. This will lead to make the number of these particles per unit volume is also small. These small sizes of nanoparticle groups will melt in a short time according to its size and density causing these holes.

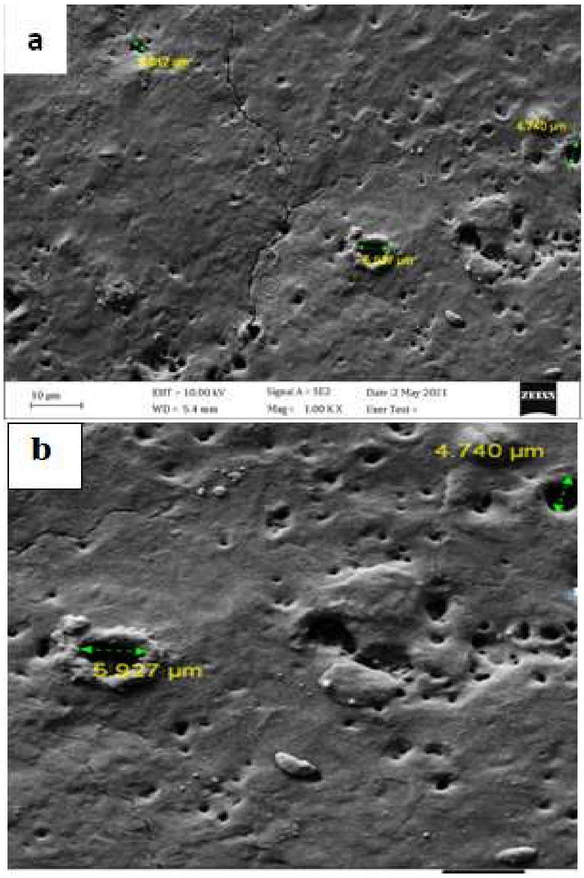



**Figure (6, a-b):** The FESEM test of aluminium alloy with laser energy of 600mJ, repetition rate of 5Hz, exposure time is10sec, and 50% concentration ratio of silica carbide nanoparticles

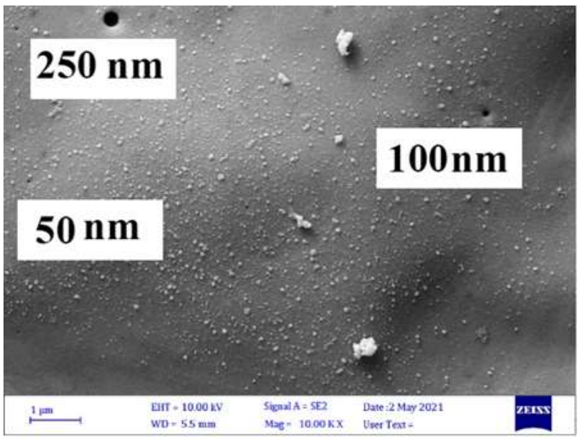



**Figure (7):** The FESEM test of nanoholes in aluminium alloy with laser energy of 600mJ, 5Hz repetition rate, exposure time is 5sec and 5% nanoparticle concentration ratio

### 4.3 Drilling of Aluminium alloy with tungsten carbide (WC) nanoparticles

When the concentration ratio of nanofluid is 90% (of the nanoparticles), the laser pulse energy is 800mJ, repetition rate is 10Hz and exposure time is (30sec), the aggregations of nanoparticles were obtained, as shown in figure (8a). Irregular holes in millimetre were obtained also on the target, as shown in figure (8b). This belongs to the high laser energy, and high concentration of (WC) nanoparticles. These nanoparticles have larger grain size, higher density and different physical properties as compared to SiC nanoparticles. Therefore, large numbers of nanoparticles need more time (30sec.) to melt and drill, they accumulated and fallen on to drill the target with irregular holes and also aggregated on the surface.

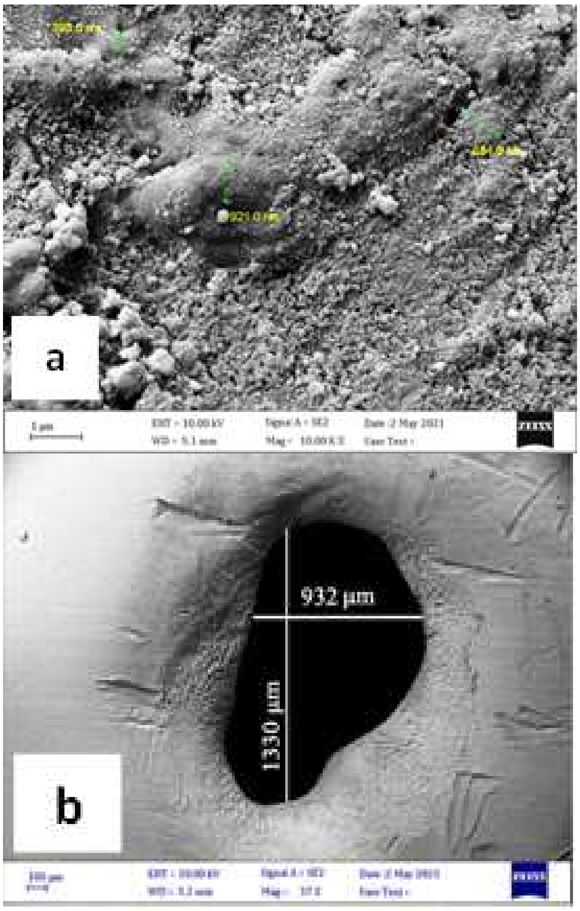



**Figure (8, a-b):** The FESEM test of aggregated nanoparticles and holes in aluminium alloy when the laser energy is 800mJ, repetition rate is 10Hz, exposure is 30sec and 90% concentration ratio of nanoparticles

Changing the concentration ratio of nanofluid to 50% (of the nanoparticles), the laser pulse energy is 600mJ, repetition rate is 5Hz and exposure time (30)sec, the microholes were obtained on the target, as shown in figure (9).

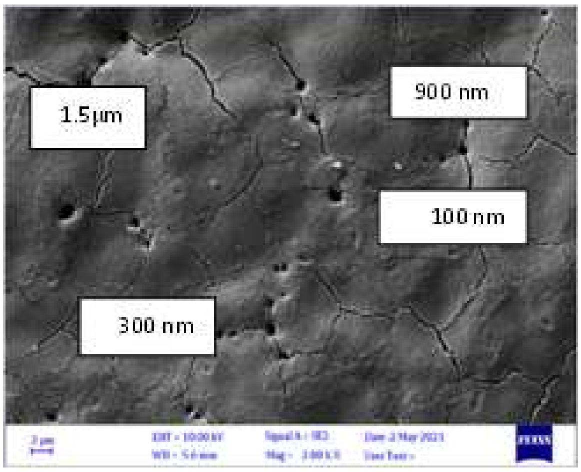
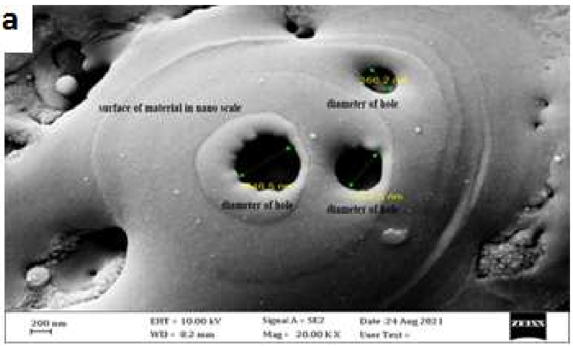



**Figure (9):** The FESEM test of micro holes in aluminium alloy with laser energy of 600mJ, repetition rate is 5Hz, exposure time is 30sec and 50% concentration ratio of nanoparticles

If the concentration ratio of the nanofluid is reduced to be as 5% (of the nanoparticles) and sprayed it on the target, the laser pulse energy is 600mJ, repetition rate is 5Hz and exposure time is (30)sec, microholes and nanoholes for the 8009 aluminium alloy are achieved, as shown in Figure (10 (a,b)). In this figure, less regular holes were obtained as compared to holes achieved from SiC nanoparticles (figure (7)). The reason for this is due to the difference in the melting point and physical properties between the two nanoparticles as the tungsten carbide nanoparticle needs more time to melt and fall to drill. Due to the continues nanofluid spraying process during the work, part of the tungsten carbide nanoparticle will be heated but doesn't melt. These heated nanoparticles will come down into the metal, causing irregularities in the diameter of the holes, but do not cause aggregations (or may cause a small aggregation) because the concentration here is little.



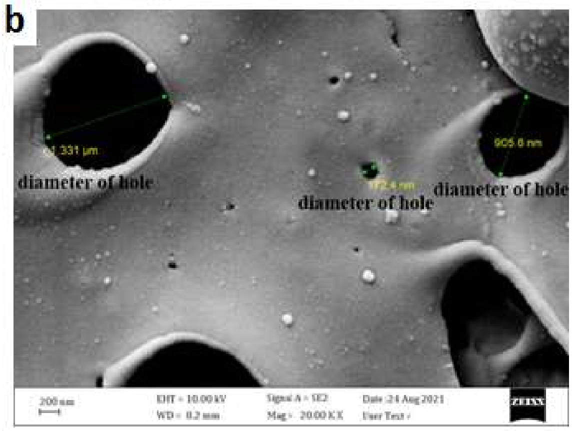



**Figure (10, a-b)**: The FESEM test of nano holes in aluminium alloy with laser energy of 600mJ, repetition rate of 5Hz, exposure time is 30sec and 5% concentration ratio of nanoparticles.

## 5. Conclusion

The micro and nanodrlling process in 8009 Al alloy were investigated. The micro and nanoholes showed a strong dependence on laser parameters, specially, when the pulse laser energy is 600, and repetition rate is 5Hz. The difference in the physical properties of the tungsten carbide and silica carbide nanoparticles used in this study, like melting point(2870°C, 1650°C), density(15.63g/cc, 3.8g/cc), and grain diameter(55nm, 50nm) respectively, lead to use different exposure time for the two nanoparticle types which play an important role in the numbers and the size of the investigated holes.

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## التثقيب المايكروي و النانوي بالليزر لسبيكة الألومنيوم باستخدام الدقائق النانوية من كربيد التنجستن و كربيد السيليكا

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**الخلاصة**

**تم إنتاج الثقوب المايكروية و النانوية بواسطة ليزر Q-switched Nd: YAG (1064 نانومتر) مع سبيكة Al 8009 باستخدام الدقائق النانوية. تم استخدام نوعين من الدقائق النانوية مع هذه السبيكة و هي كربيد التنجستن (WC) وكربيد السيليكا (SiC). في هذا العمل، تم عمل الثقوب المايكروية و النانوية بواسطة نبضات ليزرية بطاقات مختلفة (600 ، 700 و 800) مللي جول، ومعدلات تكرار مختلفة (5 هرتز و 10 هرتز) وتراكيز مختلفة من الدقائق النانوية (90٪، 50٪ و 5٪). تشير النتائج إلى أن الثقوب المايكروية و النانوية قد تحققت عندما تكون طاقة نبضة الليزر 600 مللي جول ، ومعدل تكرار نبض الليزر 5 هرتز، وتراكيز الدقائق النانوية (لنوعي الدقائق النانوية) 5٪. تزداد أقطار الثقوب إلى ملليمترات وتتشكل الشقوق مع زيادة طاقة نبضة الليزر ، ومعدل تكرار نبض الليزر باستخدام تركيز عالٍ من الموائع النانوية.**