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Laser Microdrilling and Nanodrilling of Pure Titanium using Nanoparticles

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Abstract: A Q-switched Nd: YAG laser (1064 nm) interplay with pure titanium utilizing nanoparticles produces microdrilling and nanodrilling holes. With pure titanium material, two types of nanoparticles were employed. These are tungsten carbide (WC) and silica carbide(SiC) nanoparticles. In this research, various laser pulse energies (600, 700, and 800 mJ), two repetition rates (5Hz and 10Hz), and different nanoparticle concentrations (90%, 50% and 5%) were used to obtain microholes and nanoholes. The results show that when the laser pulse energy is 600mJ, the laser repetition rate is 5Hz, and the nanoparticle concentration (for both types of nanoparticles) is 5%, microholes and nanoholes will be obtained. With increasing the laser pulse energy and repetition rate while utilizing a high concentration of nanofluid, the cracks are created and the sizes of holes are increased to millimetres.

Keywords: Microholes, Nanoholes, Nanoparticles, Nanofluid, Nd:YAG Laser, and pure titanium.

1- Introduction

Laser drilling is one of the few techniques for producing high aspect ratio holes [1]. Laser drilling is a crucial industrial process to produce various sizes of holes for important applications, such as cooling holes in turbine components, guide vanes, casings, aerospace, biomedical, communication, electronics and automotive industries[2]. The microhole drilling by laser ablation is crucial to control material removal rate (MRR), ablation depth, and aspect ratio. Important process parameters include laser pulse width, pulse repetition rate, pulse energy, and the material properties [3]. The micro holes drilling on materials with high hardness and brittleness could be a challenge for most conventional drilling methods or impossible in some occasions. The important problems with conventional drilling methods include tool wear, burr formations and lower material removal rates. Therefore, in order to increase the capability to drill holes in complicated shapes and hard to machine materials, non-conventional drilling processes were introduced [4], Microdrilling is also known as Micro-electromechanical Systems (MEMS), due to a technology extensively used for Integrated circuits manufacturing (IC), advanced electronics and precision machine components [5]. 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 [6]. In many cases, laser micromachining is a less expensive alternative to other processes like 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. Laser microhole drilling process provides access to world leading precision hole drilling technology [7]. This process can be used by Femtosecond Laser Micromachining with very high peak powers which provides minimal thermal damage to surroundings and high aspect ratios [8]. Generally, pulsed mode is used for laser micromachining with high resolution in depth and lateral dimensions. Q-switch Nd:YAG lasers with pure titanium have been carried out to study the effect of process parameter such as pulse energy, pulse frequency, pulse width and focal length [9]. Additionally the properties of nanoparticles are very influential and enhance the properties of holes [10]. The laser drilling process can be used on a variety of materials, including of super alloys, and sophisticated materials such as nanoparticles which its properties like higher toughness, ductility, high temperature stability, strength and wear resistance make tungsten carbide (WC) and silica carbide (SiC) nanoparticles materials highly competitive against other conventional materials. These properties enhance the properties of holes[6]. The mechanical properties of pure titanium are characterized by a good combination of strength and ductility. For example, pure titanium has tensile strength to(275 -735)MPa, heat capacity equivalent to approximately 60% of stainless steel and thermal conductivity equivalent to approximately 8% of aluminium [11].

2-Optimization of microhole drilling characteristics of titanium during Nd:YAG laser pulse

Laser drilling becomes of increasing importance when hole diameter is in the range of 10 to 50 µm, for which conventional alternative approaches are becoming difficult and cost inefficient [12]. Pulsed laser machining technology is now an important tool for microhole drilling in many industrial applications. In laser microhole drilling of titanium material, the holes taper optimized using range of process parameters such as laser power, frequency, standoff distance and pulse width during laser machining [13]. Lase drilling is the preferred method for a variety of composite and hard materials that are difficult to treat with contact mechanical instruments at the microscopic level [12]. Material such as titanium has appealing characteristics with high strength-to-weight ratio, excellent mechanical properties and high corrosion resistance. The major use of titanium material is in the aerospace industry in manufacturing of airframes, landing gear components and engine parts [14]. High tool wear and poor surface integrity are associated with the machining of titanium material. The difficulty in machining of titanium material is due to poor heat conduction, high heat stress and low thermal conductivity which generates extensive heat at tool and workpiece interface. Therefore, it is difficult to drill titanium and its alloys [15]. There is change in surface roughness and deviation of heat affected zone (HAZ) was occurred on drilled hole. The material removal rate (MRR) was calculated by Eq. (1):

$$MRR = \pi t r^2 / \text{time} \quad (1)$$

Where, t is the thickness of the titanium plate, r is the radius of the drilled hole and time is in seconds [13]. In laser drilling process, a high-energy infrared laser beam is focused on a spot of the workpiece and causes melting, vaporization and chemical degradation throughout the depth of the titanium material. The laser parameters and the characteristics of the material are significant factors in performance characteristics, quality of holes in terms of circularity at entry and exit, taper of the hole and spatter formation on titanium [16].

3-The experimental setup

The experimental setup for creating microholes and nanoholes in various materials using nanoparticles with laser can be shown in Figure(2).

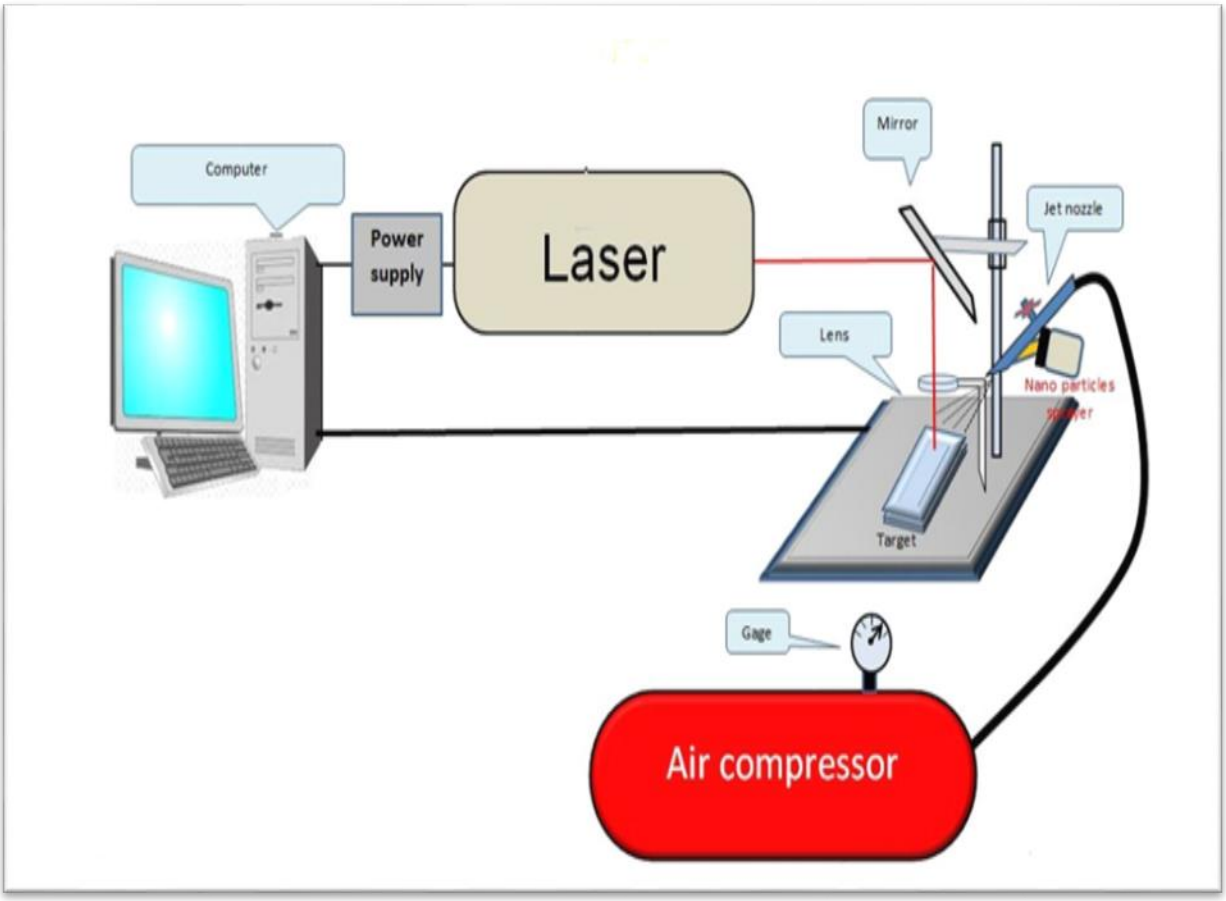


Fig.2: Schematic diagram of the experimental setup for laser metal microdrilling with nanoparticles.

The system includes a Q-switched Nd:YAG laser (1064nm) source, as well as an air compressor that pumps air to the jet nozzle. Two types of nanoparticles (tungsten carbide with a grain size of 55nm and silicon carbide with a grain size of 50nm) were employed, a convex lens with a focus length of 100mm, and a target of pure titanium with a thickness of 0.1 mm. The laser pulse width was (10 ns), the pulse repetition rates were (5 and 10)Hz, and the laser pulse energy were (600, 700 and 800)mJ.

Preparation of the nanofluid was made by mixing different amounts of nanoparticles with water (base fluid) in room temperature by the magnetic stirrer bar (mixing capsule) in a small container. This solution is stirred for 20-30 minutes at 50°C to produce a homogeneous suspended particulate solution with varied nanoparticle concentration ratios (90%, 50 %, and 5%).

The nanofluid is placed in the jet nozzle (through a small container). which is coupled to the air compressor with air pressure of (150-200)psi. The nanofluid is sprayed onto the material's surface using the jet nozzle. At the same moment, the laser beam is focused on the nanofluid spray on the titanium material's surface. This approach is used with two distinct types of nanoparticles, as well as the same laser settings but with different exposure times.

4-Result and discussion

1-Laser- Titanium interaction 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(3).

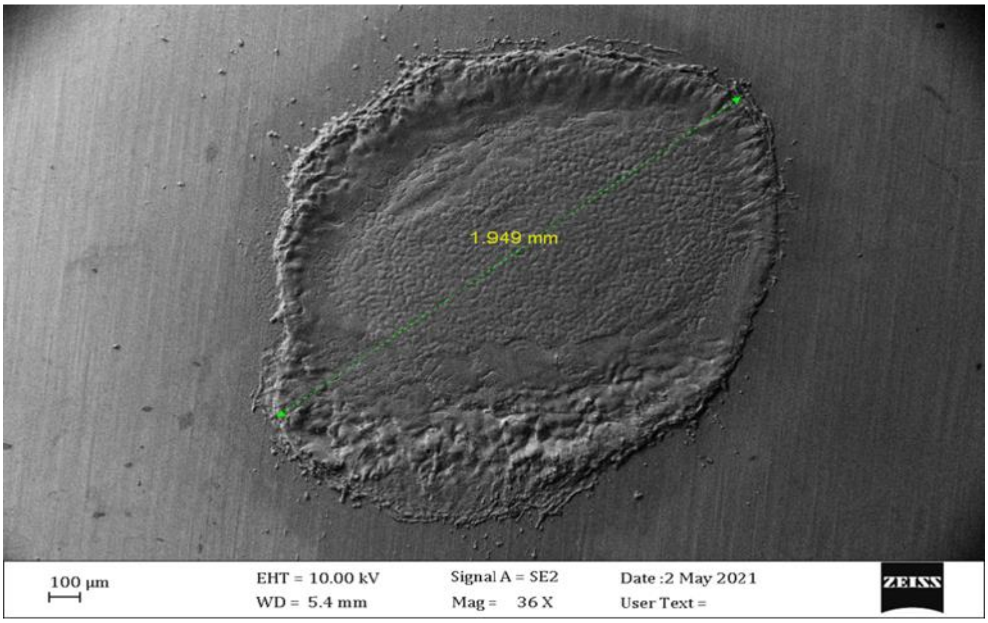


Fig.3: FESEM of laser- titanium interaction without using nanoparticles.

2-Laser- Titanium Drilling Using 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 cracks are formed, as shown in Figure(4) and aggregations of nanoparticles are obtained on the target, as shown in Figure(5).

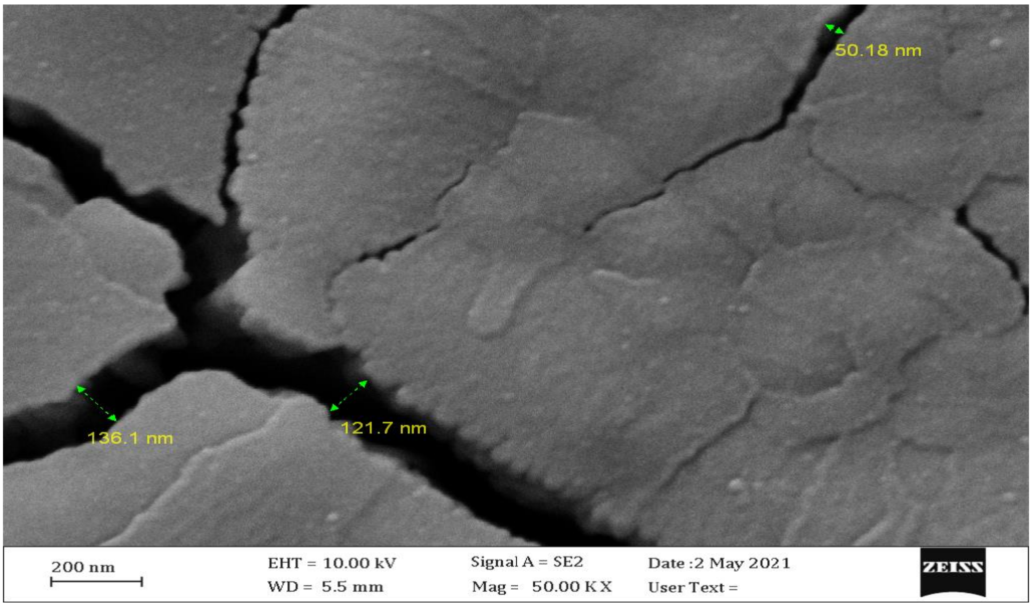


Fig.4: FESEM shows cracks in titanium using pulsed laser and high concentration of silicon carbide nanoparticles.

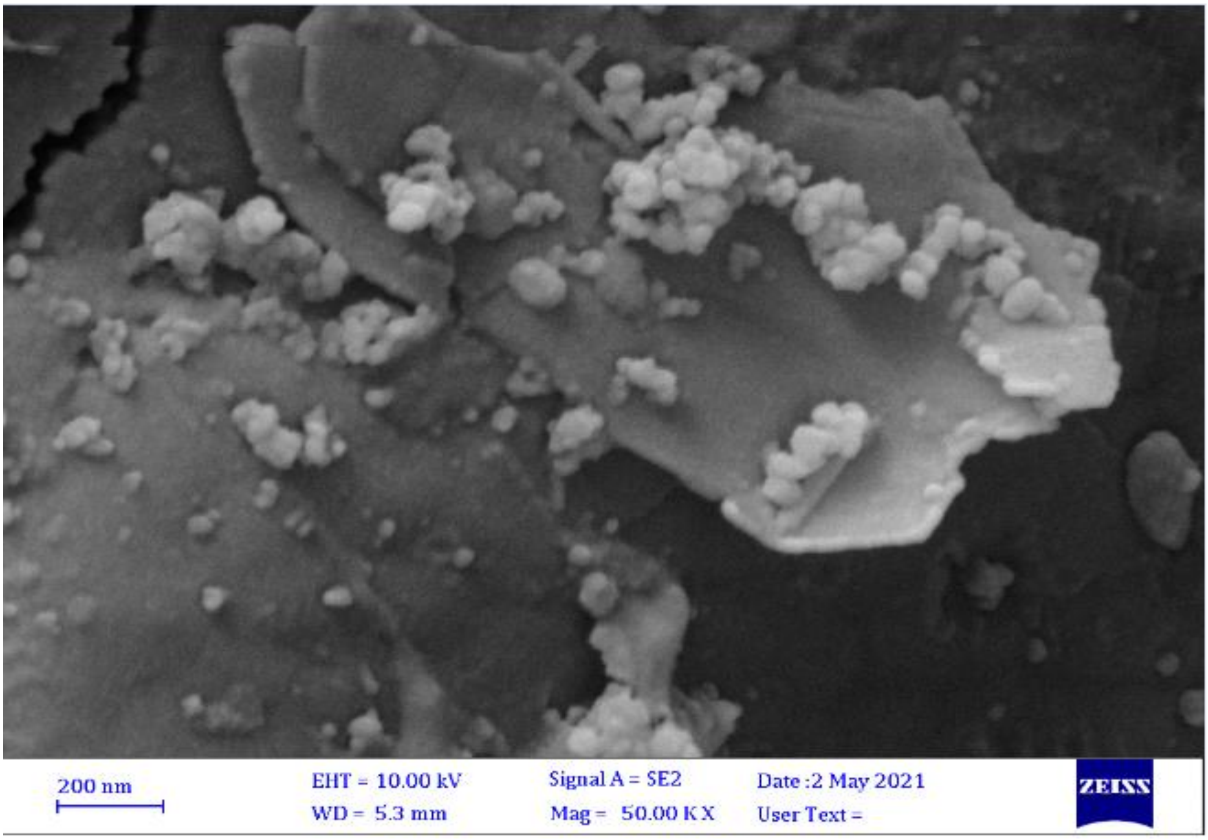


Fig.5: FESEM of laser-titanium interaction with a high concentration of silicon carbide nanoparticles shows aggregation.

When the nanofluid concentration ratio was lowered to 50% (of nanoparticles), the laser pulse energy is 600mJ, repetition rate is 5Hz and exposure time is (5-10)sec, the irregular microholes on titanium are formed, as shown in Figure(6) and Figure(7(a,b)).

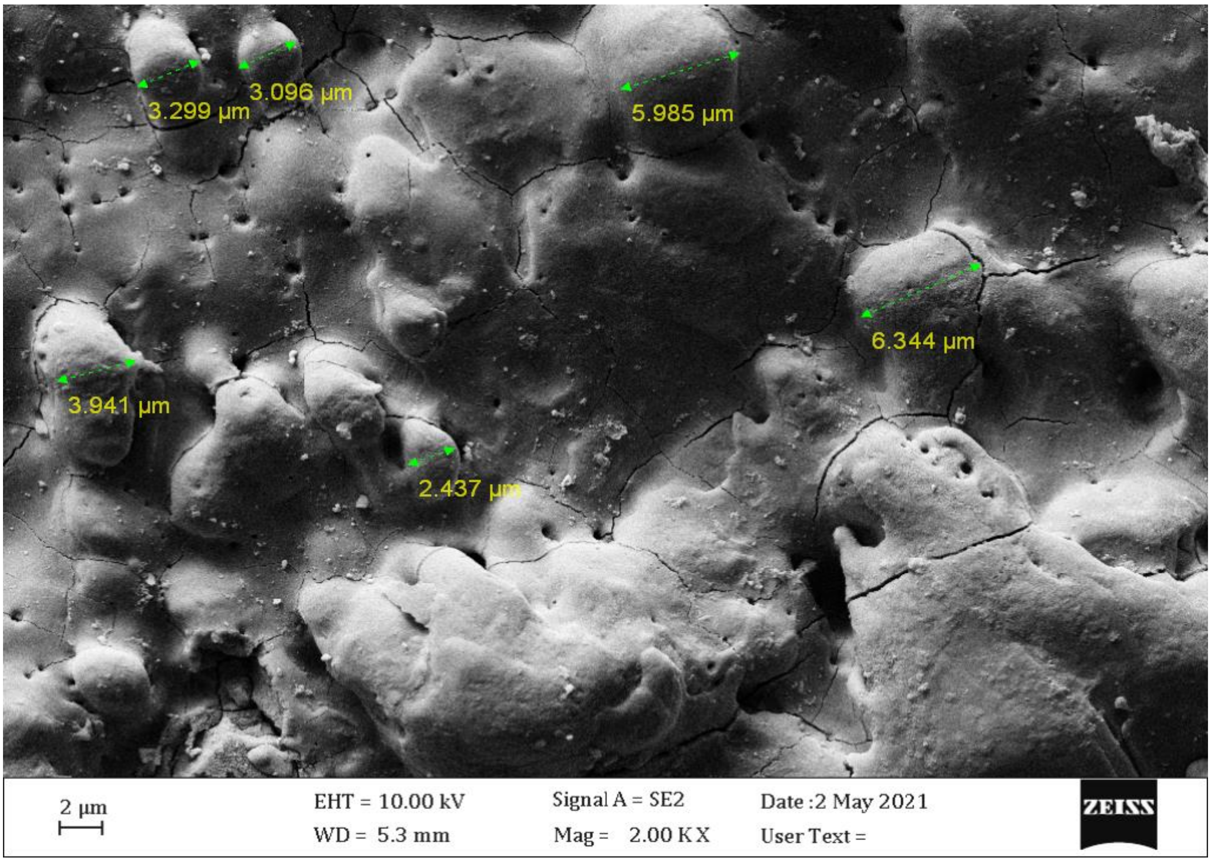
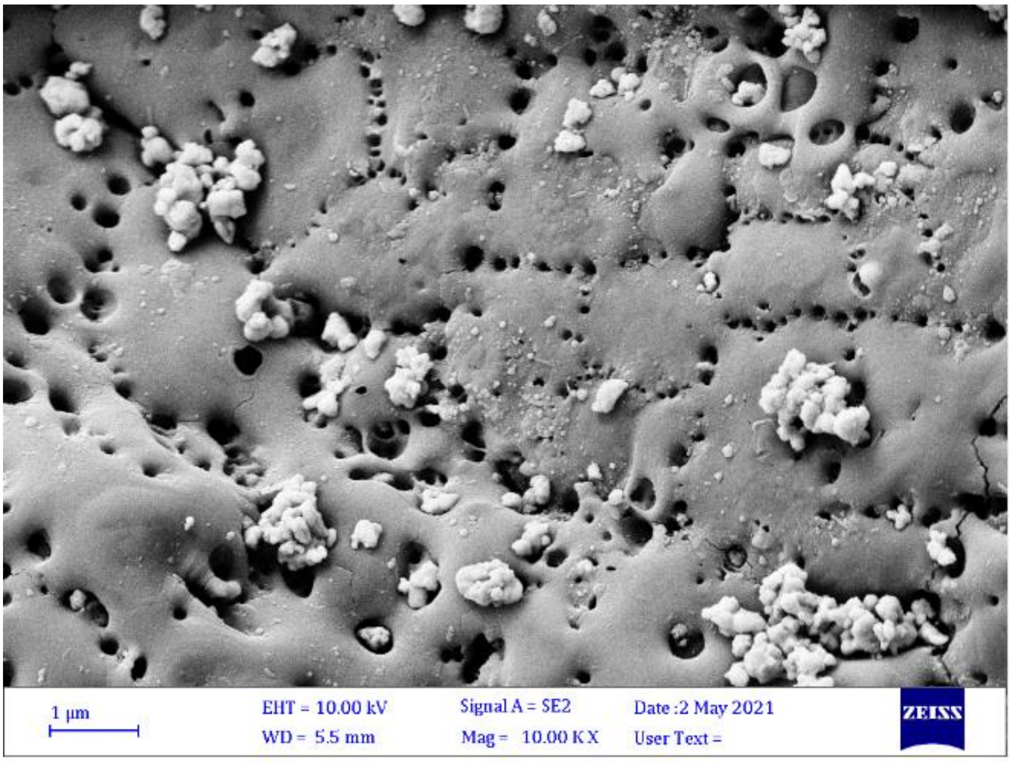
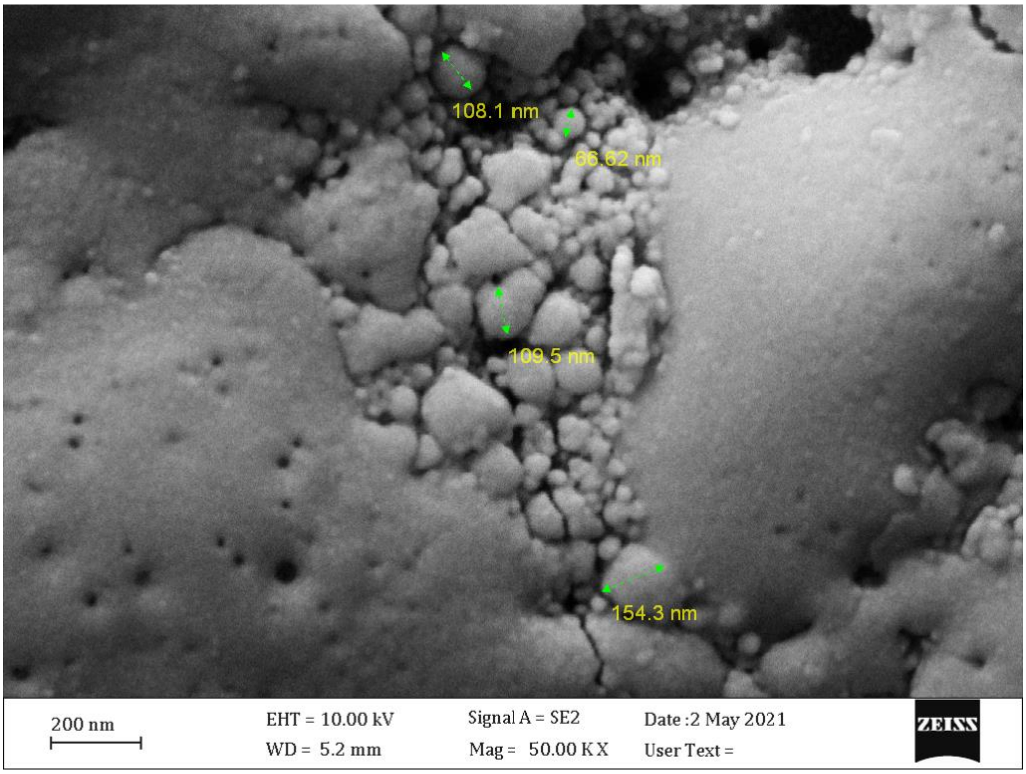


Fig.6: FESEM of irregular holes in titanium with pulsed laser and medium concentration of silicon carbide nanoparticles.



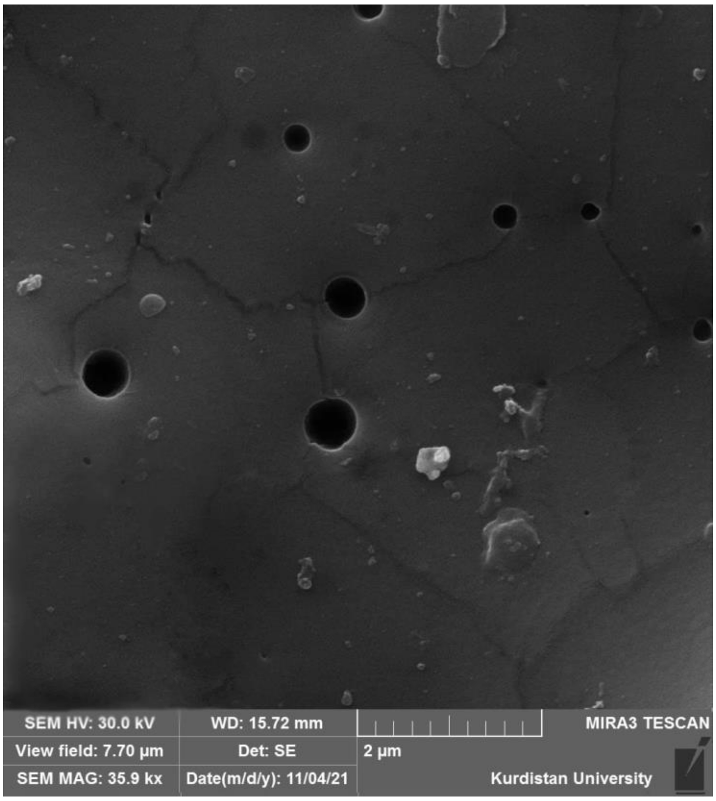
(a)



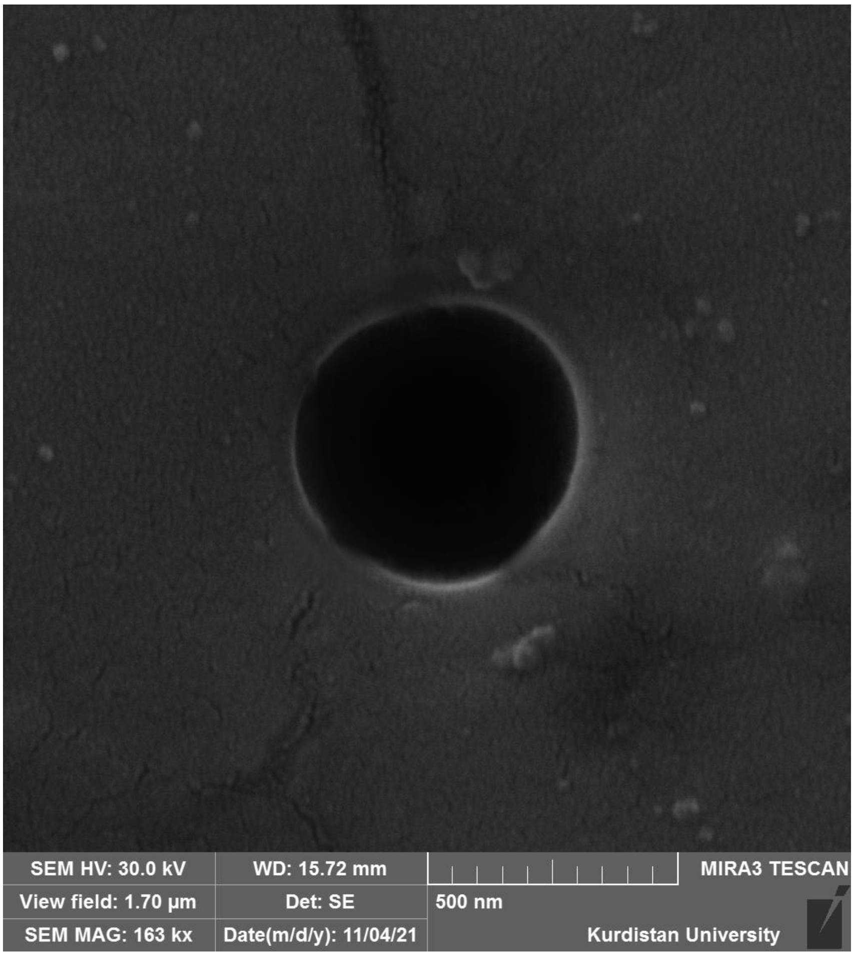
(b)

Fig.7(a,b): un uniform microholes and aggregations of nanoparticles in titanium with pulsed laser and medium concentration of silicon carbide nanoparticles.

If the nanofluid concentration ratio is reduced to 5% (of nanoparticles), the laser pulse energy is 600mJ, repetition rate is 5Hz and exposure time is (5-10)sec, the nanoholes and the microholes in titanium are achieved with the minimum heat affected zone(HAZ) width, as shown in Figure (8(a,b)).



(a)

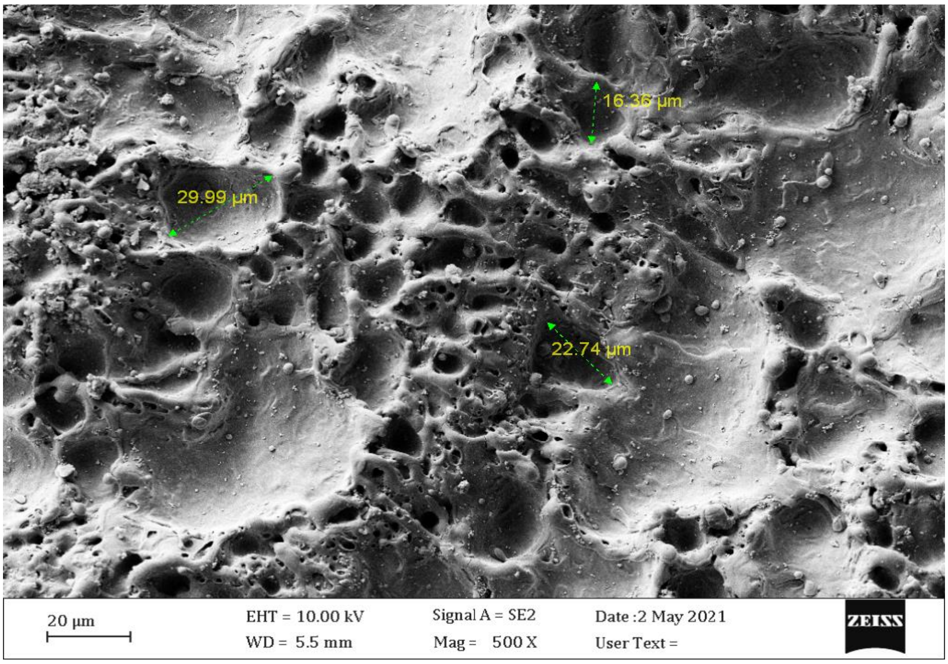


(b)

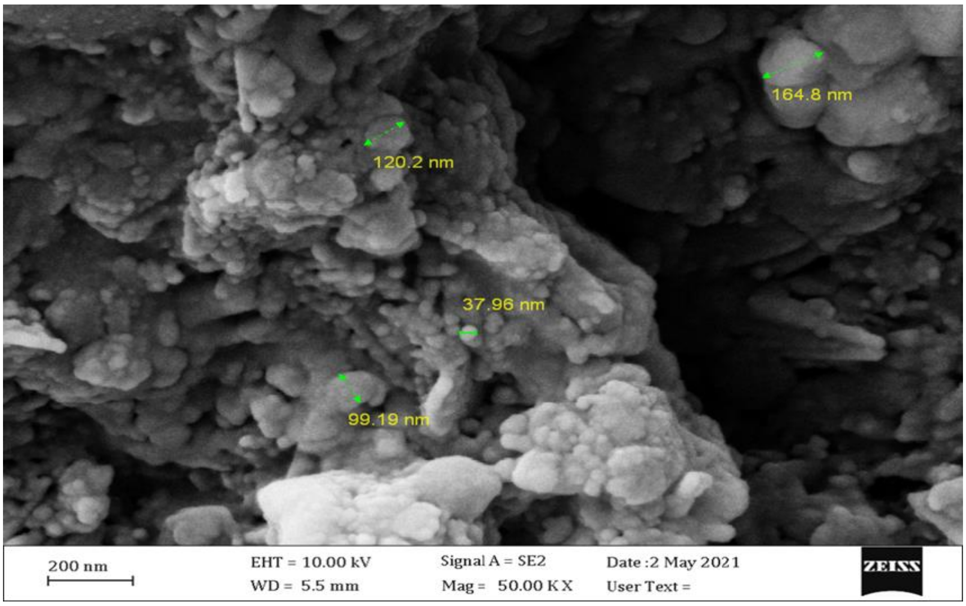
Fig.8(a,b): FESEM of nanoholes in titanium with pulsed laser and light concentration of silicon carbide nanoparticles.

3- Laser-Titanium microdrilling with tungsten carbide (WC) nanoparticle

When the nanofluid concentration ratio is 90% (of nanoparticles), the laser pulse energy is 800mJ, repetition rate is 10Hz and exposure time is (30)sec, the irregular holes and aggregations of nanoparticles are obtained in the target, as shown in Fig.(10(a,b)).



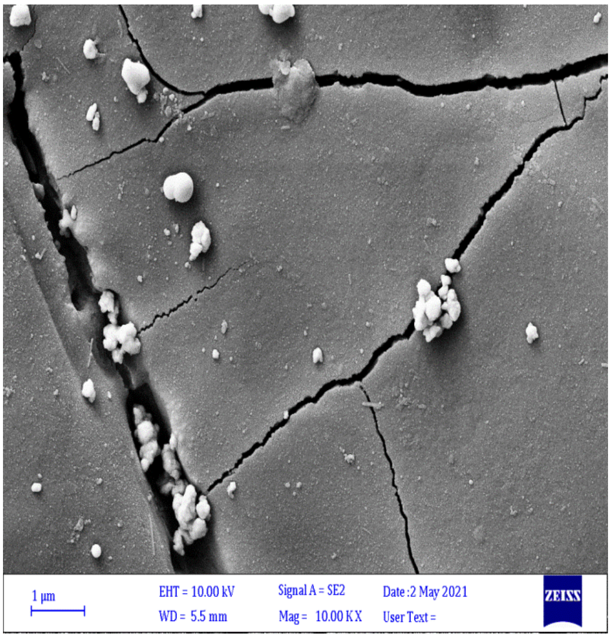
(a)

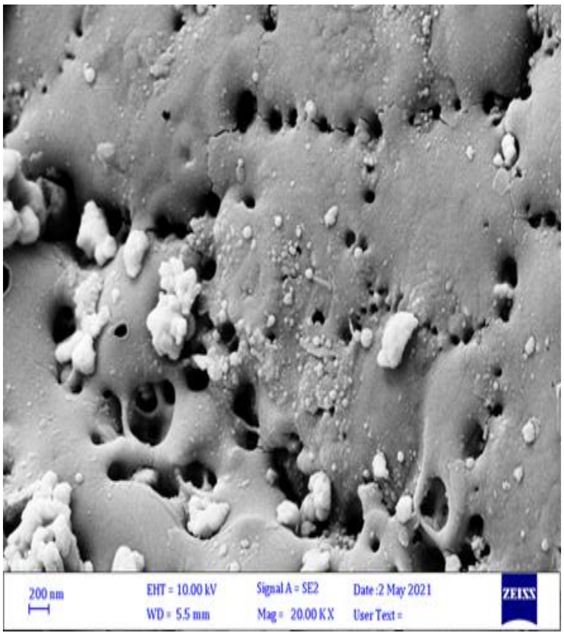


(b)

Fig.10(a,b): Titanium interaction with pulsed laser and high concentration of tungsten carbide nanoparticles.

When the nanofluid concentration ratio was lowered to 50% (of nanoparticles), the laser pulse energy is 600mJ, repetition rate is 5Hz and exposure time is (30)sec, the cracks are formed and microholes were obtained on the target, as shown in Fig.(11(a,b)).





(a) **(b)**

Fig.11(a,b): FESEM of cracks and microholes formation in titanium with pulsed laser and medium concentration of tungsten carbide nanoparticles.

If the nanofluid concentration ratio is reduced to be as 5% (of nanoparticles) and sprayed it on the target, the laser pulse energy is 600mJ, repetition rate is 5Hz and exposure time is (30)sec, the microholes and nanoholes for the titanium are achieved with the minimum heat affected zone(HAZ) and least amount of nanoparticles' aggregations, as shown in Figure (12).

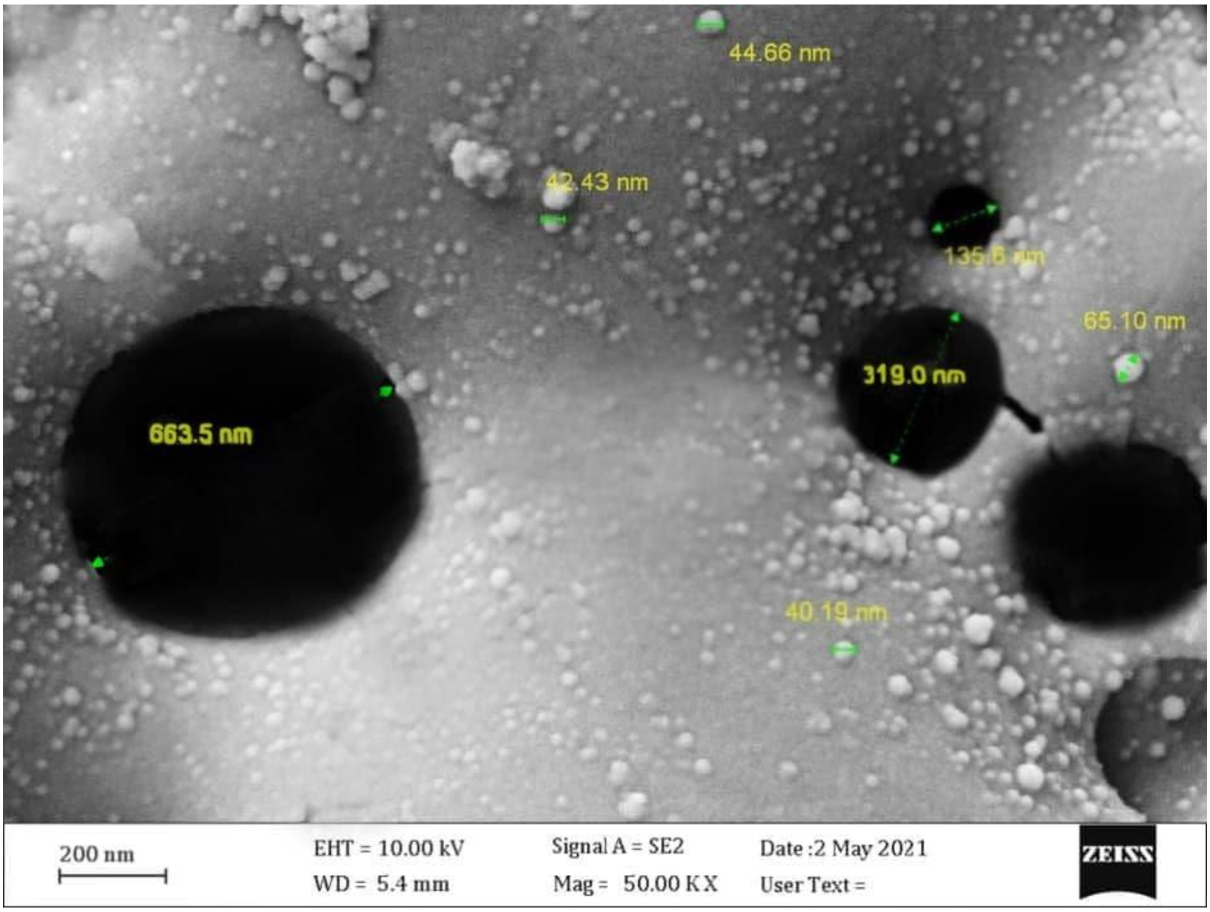


Fig.12: FESEM of nanoholes in pure titanium with pulsed laser and light concentration of tungsten carbide nanoparticles.

Conclusion

The micro and nanodrilling in pure titanium were obtained depending on laser parameters and the properties of the nanoparticles used. Additionally, the micro and nanoholes were shown to be highly reliant on pulsed laser energy, repetition rate, exposure time and nanoparticles′characteristics such as melting point, density, grain size and concentration. The laser pulse energy of 600 mJ, 5Hz repetition rate and with using of two types of nanoparticle fluids (tungsten carbide and silica carbide), with a concentration of 5%, micro and nanoholes appeared on the titanium plate (which has a thickness of 0.1mm).

The difference in the physical properties of both types of nanoparticles used in this study, like melting point(2870°C for WC and 1650°C for SiC), density(15.63g/cc for WC and 3.8g/cc for SiC), and grain size, leads to use a different exposure time for the two nanoparticle fluids which effects on the size of the investigated holes.

Large diameters of holes were sometimes obtained even at light concentrations because the nanofluid is not totally homogeneous and it is difficult to make it totally homogeneous. It takes longer for a group of grains to melt, creating a bulk and falling on the metal to drill.

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