Iraqi J. Laser, Part A, Vol. 10, pp. 15-21 (2011)

IRAQI
JOURNAL
OF
LASER

Laser Hole Drilling of Stainless Steel 321H and Steel 33 Using 3D CO2 Laser CNC Machine

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(Received 18 September 2011; accepted 13 October 2011)

Abstract: In present work an investigation for precise hole drilling via continuous wave (CW) CO2 laser at 150 W maximum output power and wavelength 10.6 µm was achieved with the assistance of computerized numerical controlled (CNC) machine and assist gases. The drilling process was done for thin sheets (0.1 – 0.3 mm) of two types of metals; stainless steel (sst) 321H, steel 33 (st). Changing light and process parameters such as laser power, exposure time and gas pressure was important for getting the optimum results. The obtained results were supported with computational results using the COMSOL 3.5a software code.

Introduction

Laser drilling is applied to a wide range of components with different materials (metals and non-metals), thicknesses, and shapes [1]. It is extensively used in aerospace gas turbines to drill a huge number of holes (<1mm) providing a cooling mechanism for the turbine blades, nozzle guide vanes, combustion chambers and afterburner [2].

Numerous high-density electronic packages employ laser-drilled vias for interconnecting layers; automobile injection nozzles, baby’s teats for milk bottles and irrigation pipes all contain laser-drilled holes; specialist holes in surgical tooling; inkjet nozzles; CD discs and many more combine to form a huge and growing market for fine precise holes all made at high speed by laser [3].

Laser drilling is not restricted by the hardness, strength and brittleness of materials. CO2 laser drilling has become one key technologies of the advanced machine field for its high speed, no tool loss, low cost, strong currency and adapt to group of holes so widely used at the field of the mentioned applications [4]. Drilling procedures involves a high intensity, stationary laser beam focused onto a surface at power densities sufficient to heat, melt, and subsequently eject the material in both liquid and vapor phases.

The erosion front at the bottom of the drilled hole propagates in the direction of the line source in order to remove the material [5]. As indicated in Figure 1, laser drilling is performed by several different types of lasers having a wide range of wavelengths and pulse durations [6]. The produced holes are characterized with high accuracy and smaller dimensions of diameters between 0.018 mm and 1.3 mm [7].

An assist gas jet may be pumped at high pressure by mean of a nozzle opening and in a coaxial direction with the laser beam into the interaction region to remove molten and ejected materials from the machining region, to shield the lens from the expelled material and to obtain a clean edge [8].

Using oxygen as assist gas in ferrous metals releases a certain degree of heat, which is an added energy to the energy of the focused laser beam. As an average, the amount of energy supplied by the exothermic reaction is about 60% for stainless steel and mild steel up 90% for reactive metals [9].

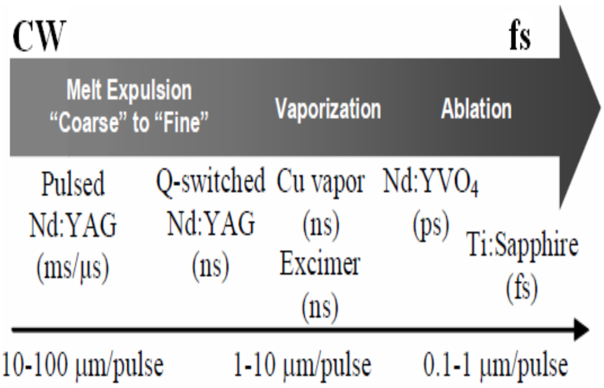

Fig.(1): Laser drilling covers a broad range of applications and laser types, from ultraviolet to infrared wavelengths and from long to short pulse durations [6].

Hole geometry such as taper, roundness and variation between holes must be within certain limits if the component is going to be used in a precise device.

Other important factors with respect to hole quality are metallurgical issues concerning recast layer and micro cracking with in the hole [10].

The CO2 laser drilling quality was decided by the parameters of the chosen laser such as power, pulse width, repetition rate, assist gas, etc. [11].

Experimental Work

Figure 2 shows a schematic diagram for the setup that used for drilling materials. A cw 150 W maximum output power CO2 laser (of 10.6 µm wavelength) was adapted to an open loop three dimensional computerized numerical controlled CNC machine to facilitate producing precise single and arrayed holes.

The machine model is CMA-1080 KII manufactured by YueMing Laser Technology Co. Ltd, China.

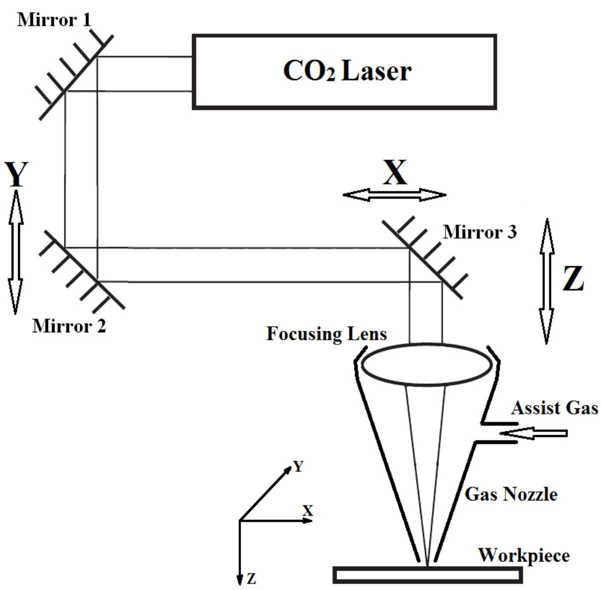

Fig. (2): The laser CNC machine setup.

The laser beam is directed via one stationary mirror (mirror 1) and two movable mirrors (Mirror 2 & 3) to the laser head. The focusing lens was built in the head to focus the beam on the workpiece.

The assist gas nozzle was attached to the head to direct and focus the assist gas to the interaction zone to achieve the required optimum results.

Simulation Work

COMSOL Multiphysics program was used to simulate the laser drilling process and estimating the temperature distribution in the tested samples during drilling process. In this part of the work two cases were investigated for examining two types of metals St.St 321H and St 33. The first case, with the assist of O2 gas using stepped laser power of 5W from 40W-90W and 100ms of exposure time.

The second case was executed in the absence of the assist gas at different values of exposure time and 90W of laser power. This model considers stationary laser source perpendicular to the sample surface. The sample is considered to be homogeneous and isotropic having constant average thermal properties and of finite thickness.

Results and Discussion

A) Simulation Results

For the above two cases, the hole diameter for each value of power in the first case and for each value of exposure time in the second case was determined from the temperature distribution model of each instant case. All these values were plotted as a separate plots between the hole inlet diameter (µm) versus the laser power and the hole outlet diameter (µm) versus the laser power for the first case. The same plots were done versus the exposure time for the second case.

By analyzing the results of the first case it is noticed that the hole diameters (inlet and outlet) are increased when the laser power is increased due to the increase of the vapor pressure (recoil pressure), thus a greater amount of material is removed. The hole taper and aspect ratio are decreased with increasing the laser power.

The hole taper depends on the hole diameter thus higher power produces larger inlet diameter but at the same time produces larger outlet diameter since the laser beam inside the material has more effect on the hole outlet than the hole inlet resulting in less hole taper. The aspect ratio represents the ratio of the hole depth to the hole diameter .Thus when the laser power increases the hole diameter increase and the aspect ratio decrease at constant depth.

The results of the second case shows that the hole diameters (inlet and outlet) are increased as the exposure time increased because more energy is added when the exposure time is increased. Thus a greater amount of material is removed. The hole taper and aspect ratio are decreased as the exposure time increased since more energy is added.

B) Experimental Results

In this part of the work the samples of St.St321H & St33 were exposed first to the laser beam focused on the surface in the presence of O2 gas pressure of (5, 3, and 1bar) at different laser powers (40-90 W) for a constant exposure time of 100ms. In the absence of the assist gas for the second case same samples were exposed to the laser beam focused on the surface of a constant power of 90W and different exposure times.

Concerning the first case, analyzing the results show that the inlet and outlet hole diameters are increased as the laser power is increased due to the increase in vapor pressure (recoil pressure), thus a greater amount of material is removed. Moreover, the hole taper is decreased by increasing laser power and the aspect ratio is decreased as the laser power increased. Under microscopic inspections, the holes that are produced at 5 bar O2 gas pressure show the best quality and regularity comparing with the holes produced at 3 or 1 bar.

These holes (at 5 bar) exhibit low hole taper and large aspect ratio. In principle, an appropriate Oxygen pressure can ensure a sufficient flow of gas molecules to the work zone for the oxidation of the molten metal. In addition an appropriate gas pressure can ensure proper removal of the molten metal and other reaction products and support the walls from collapse keyhole, which will enhance the material removal rate and permit holes of large aspect ratio to be drilled. On the other hand, the high pressure gas can cool the material by means of forced convection, thereby lengthening drilling time.

Moreover, the microscopic inspection indicated that the holes drilled at 5 bar are of good diameter circularity, little debris and recast layers compared with the holes drilled at 3bar and 1 bar (Figures 3 and 4).

The microscopic inspection shows that holes produced in the absence of the assist gas (the second case) are of bad quality and there are a lot of debris and recast layers.

Comparison Between Experimental and Theoretical Result

Figures 5 to 14 show the comparison between the experimental (red line) and theoretical (blue line) works of the inlet hole diameter, outlet hole diameter, hole taper, aspect ratio and hole circularity of St.St 321H and St 33 samples respectively that were drilled in the presence of 5 bar O2 and that achieve the best quality as it is improved by the microscopic inspection test. From these figures the optimum parameters for St.St 321H occur at 50W/5bar of O2 and at 80W/5bar of O2 for St 33.

The difference between St.St 321H and St 33 in power and hole diameter is due to their different thermal conductivity (St 33 has higher thermal conductivity than that of St.St 321H). Moreover, the melting temperature of the St.St 321H (1430ºC) is less than the melting temperature of the St 33 (1527ºC).

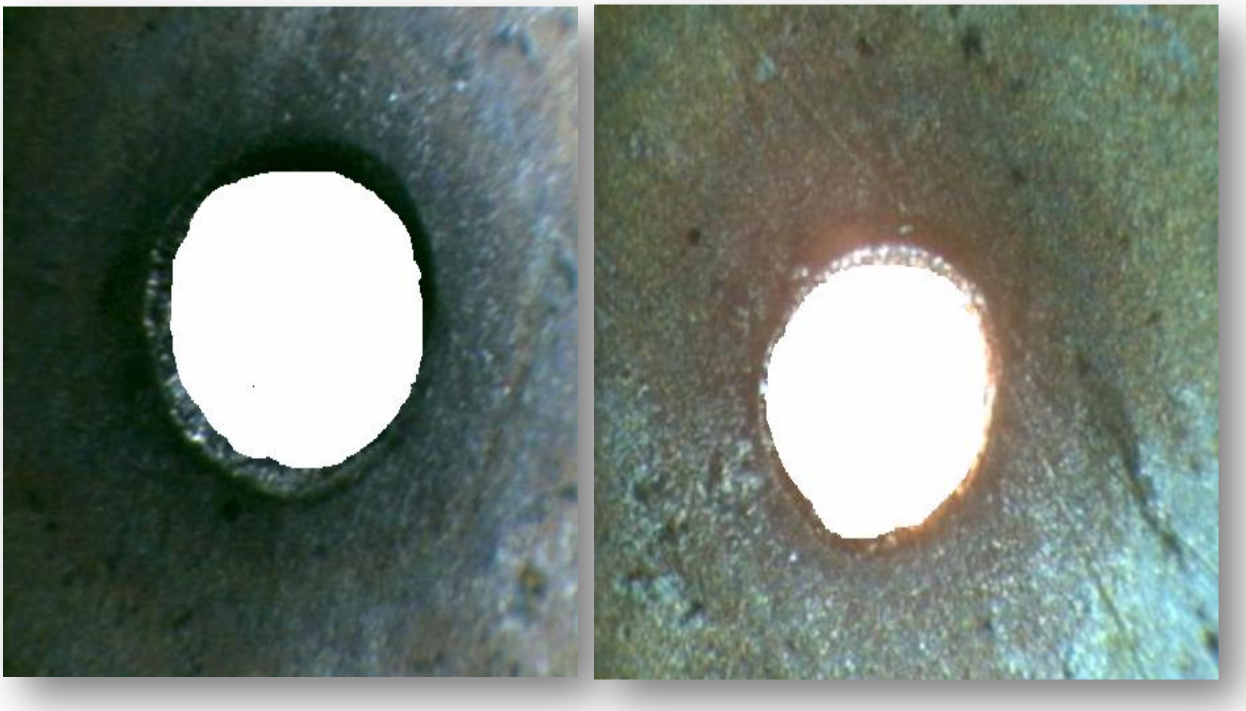

Fig.(3): St.St 321H -5bar-100ms-50W.

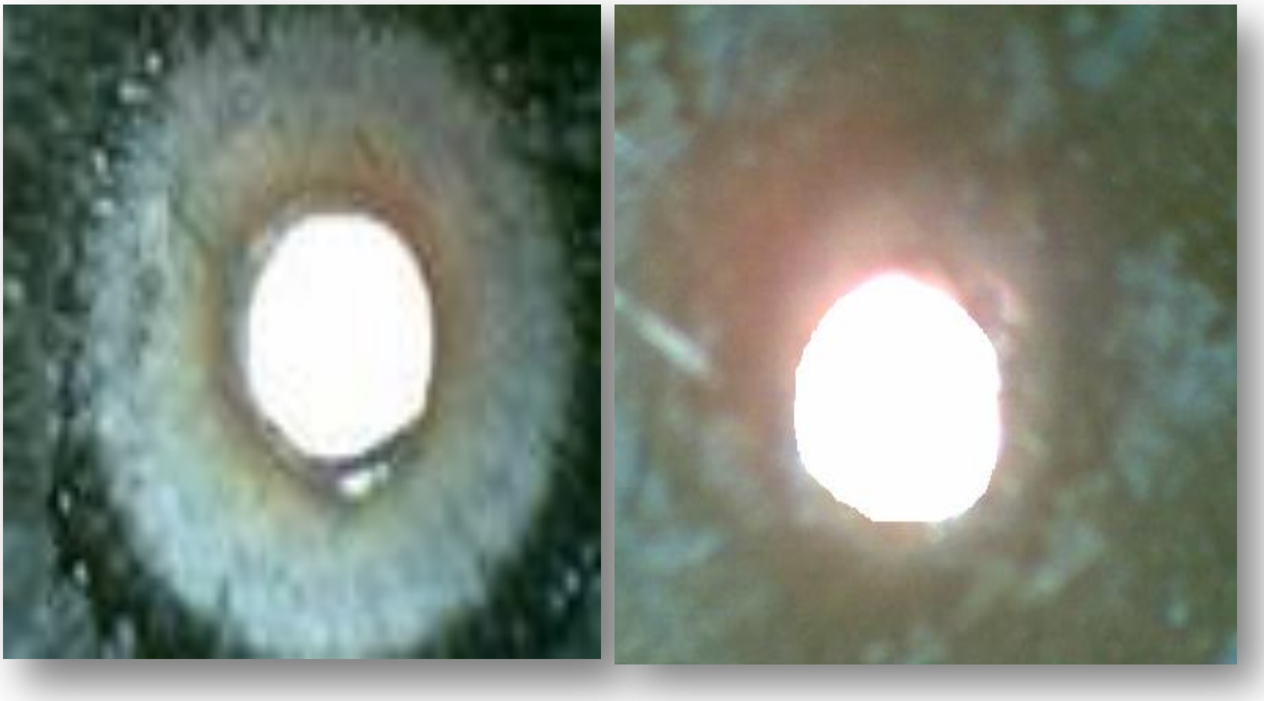

Fig.(4): St 33 -5bar-0.1s-80W.

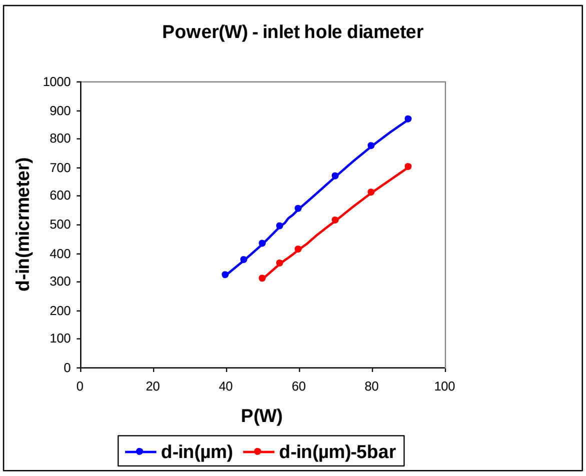

Fig. (5): Comparison between the experimental and theoretical of the inlet hole diameter St.St321H

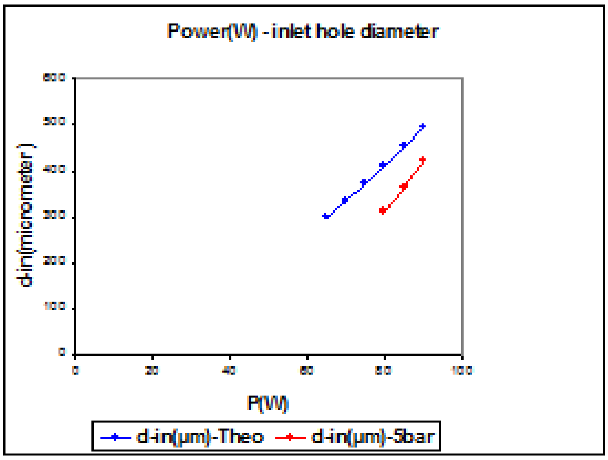

Fig.(6): Comparison between the experimental and theoretical of the inlet hole diameter St33

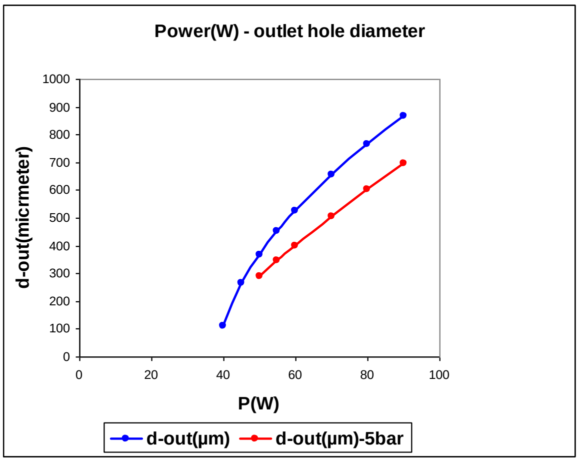

Fig. (7): Comparison between the experimental and theoretical of the outlet hole diameter St.St321H

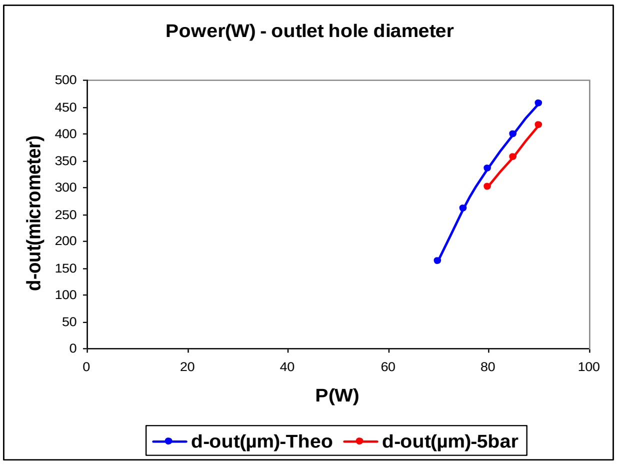

Fig. (8): Comparison between the experimental and theoretical of the outlet hole diameter St33

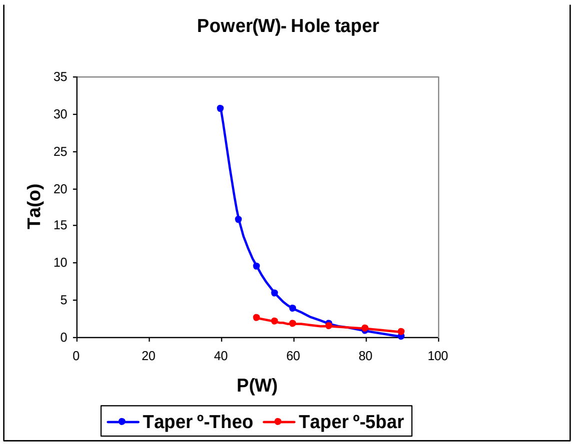

Fig. (9): Comparison between the experimental and theoretical of the hole taper of St.St321H

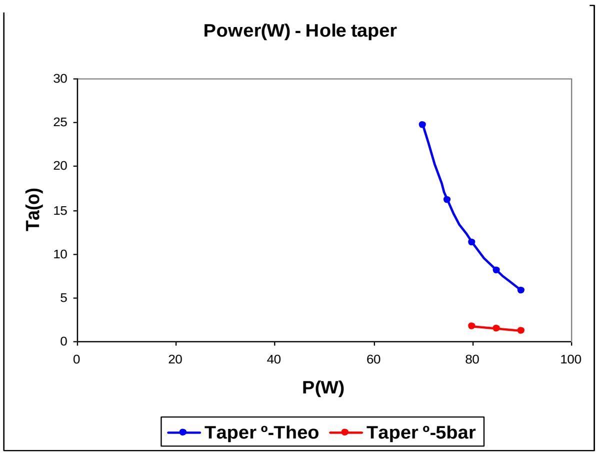

Fig. (10): Comparison between the experimental and theoretical of the hole taper St33

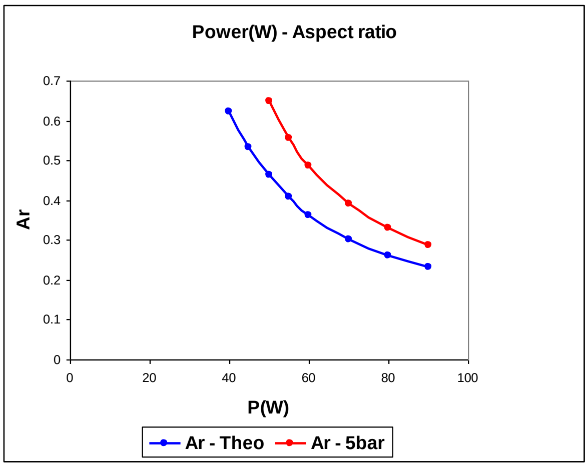

Fig. (11): Comparison between the experimental and theoretical of the hole aspect ratio of St.St321H

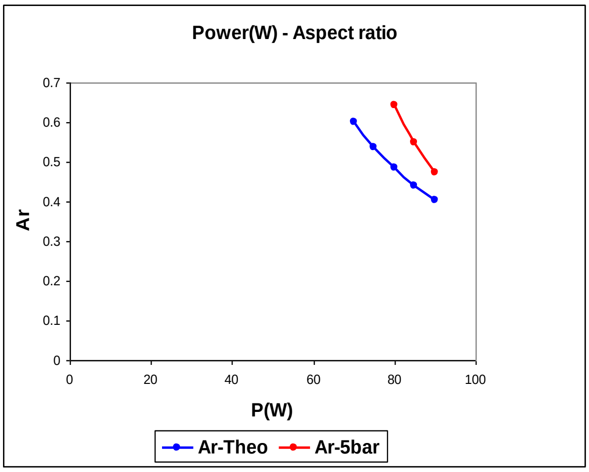

Fig. (12): Comparison between the experimental and theoretical of the hole aspect ratio of St33

Conclusion

Differences between theoretical and experimental results could be referred to:The difficulty of determining the theoretical drilling time as it is difficult to derive or measure the values of temperature dependent parameters such as material absorptivity, conduction loss, mass fraction of liquid metal evaporated and heat of reaction caused by oxidation.The material physical coefficients such as thermal conductivity, specific heat, density, and absorption coefficient assumed to be constant as they are not.The conduction heat loss by the clamping device is not considered.The optical and alignment losses and the aberration effect when the laser beam transmitted via the beam delivery system.Fluctuating of laser beam energy during drilling process.

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تثقيب فولاذ مقاوم للصدأ نوع H۳۲۱ وفولاذ كاربوني نوع ۳۳ باستخدام ليزر ثاني أوكسيد الكاربون (CO_2) وماكنة ذات تحكم رقمي مبرمج ثلاثية البعاد

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الخلاصة

في هذا البحث تم التحقق من تنفيذ تثقيب دقيق باستخدام ليزر ثاني اوكسيد الكربون (CO_2) مستمر ذو قدرة ۱٥۰ واط كأقصى قدرة وبطول موجي ۱۰,٦ مايكرومتر مركب على ماكنة ذات تحكم رقمي مبرمج (CNC) مع وجود غاز مساعد أثناء العمل . أن أجزاء التثقيب تم لصفائح ذات سمك من ۰,۱ -۰,۳ ملم لنوعين من المعادن (فولاذ مقاوم للصدأ نوع H۳۲۱ وفولاذ كاربوني نوع ۳۳). للحصول على النتائج المثلى في هذا العمل ، تم التحكم بالعديد من المتغيرات مثل قدرة شعاع الليزر وزمن التعريض مع ضغط الغاز المساعد. تم تعزيز النتائج بأستخدام برنامج حاسوبي تحليلي هو كومسول COMSOL 3.5a