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THE INFLUENCE OF PULSE SHAPE ON HOLE GEOMETRY DURING Nd:YAG LASER DRILLING OF STAINLESS STEEL SHEETS

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ABSTRACT

Laser drilling has been used for making large number of cooling holes in gas turbine engine industry due to its benefits in saving cost and time. In single pulse laser drilling, a hole can be formed in thin metallic sheets by one laser pulse with enough energy, in which the hole making may take just few milliseconds. Pulse shaping is one of the important factors that could affect the hole characteristics. In the present study; three types of pulse shapes; rectangular, ramping up, and ramping down, with pulse width of 2 ms were used to drill through holes in 1mm thick stainless steel sheets. Scanning electron microscope (SEM) was used to capture the necessary images of the laser-drilled holes at the different pulse shapes. An image processing technique was applied to identify the spatter around the drilled holes. It was also used to calculate the inlet hole diameter and its associated spatter deposition area. Optical microscope was utilized to measure the exit hole diameter. The hole taper was evaluated by calculating the inlet to exit hole diameters ratio. Finally, the prescribed holes are reproduced using two pulses having the same total energy as the one pulse used before. A comparison between the two drilling techniques was established. It was found that the pulse shaping could have a remarkable effect on the measured hole configurations when the two types of laser drilling were applied on the used stainless steel sheets. Also, the two drilling techniques produced holes with different final geometry.

KEYWORDS

pulse shape, single pulse, spatter, and hole taper

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1. INTRODUCTION

Laser drilling has become the accepted economical process for drilling thousands of closely spaced holes in structures such as aircraft wings and gas turbine engine components [1, 2]. There are a number of reasons why lasers have advantages over other drilling techniques, such as the absence of tool wear, and the ease with which hole can be drilled at angles to the surface of the workpiece, and the high aspect ratios. The high power intensity of laser beam in addition with the programmable nature of laser systems allows for very high speed drilling applications where such great number of holes is required in short cycle time [3].
During laser drilling of metals, material is commonly removed both via vaporization and by ejection of molten droplets. The ejection of molten metal occurs due to rapid build-up of vapor pressure inside the hole cavity [4].

Generally, there are three types of laser drilling; namely, single pulse, percussion, and trepan drilling [5] (see Fig.1). Trepan drilling involves cutting around the circumference of the hole to be drilled, whereas in percussion drilling the laser pulses are directed to the same spot on the workpiece to form the required hole without any relative movement between laser beam and workpiece. In single pulse (shot) drilling thin material is penetrated with one laser pulse. Such thickness is found in blades and vanes of gas turbine engines (of order of 1 mm thickness) [3]. Another application of single pulse laser drilling is to form pattern of holes in thin metallic sheets that used as filtering elements in hydraulic systems. The latter type of laser drilling could be considered the most time saving technique when compared with the other two types.

Laser drilling process has its limitations. Spatter formation around the hole rim is one of the inherent problems associated with the laser-drilled holes. It is undesirable especially in drilling of cooling holes in the aerospace industry. For drilling closely spaced arrays of holes, spatter overlapping between the adjacent holes could reduce the repeatability of the drilling process, which leads to bad accuracy of the drilled-holes [6]. Forming tapered holes is also a feature associated with laser drilling.

The standard pulse shape from recent types of pulsed YAG lasers is rectangular pulse with an initial spike (Fig. 2). Shaping a pulse is simply adding sectors of certain power and width to build it up, like taking building of blocks of different sizes and laying them next to each other. A standard pulse shape has a single sector called the main sector and the shaped pulse has two or main sectors [8].

Studies of the effect of pulse shaping of laser pulses in laser material processing have proved to be benefited for certain applications, particularly in laser welding. It can have benefits in reducing cracks and porosity in welds, helping in welding high reflective materials with very high thermal conductivity such as high purity copper alloys, and for welding materials that have low melting and boiling point [8]. Todate, little investigations have reported the effect of pulse shaping on the material interaction during laser drilling process or its effect on the laser-drilled holes configurations. Roos [9] compared the drilling performance with a normal pulse consisting of a 200 μs continuous emission proceeded by a few relaxation oscillations with of a 200 µs train of 0.5 µs pulses. It was shown that the use of pulse train is much superior to the normal pulse for drilling aluminum and similar metals.

French et al [1] studied the drilling mechanism of different pulse shapes; two rectangular pulses, ramp down pulse with two sectors, and ramp up pulse with two sectors also. It was found (using high speed filming technique) that the first two shapes have almost identical drilling mechanism. For the last shape; it was seen that it has a visibility different drilling mechanism. The initial coupling of the pulse into the surface appears to be more controlled than with other two shapes, the growth of hole is very uniform and no plasma forms. During the second half of the pulse most material is removed, which time the plasma is excited.

In the present study, work is conducted to determine the influence of pulse shaping on hole characteristics produced Nd:YAG laser drilling. Pulse widths of 2 ms and 1 ms were used to form through holes on stainless steel sheets (1 mm thickness) with varying of pulse energy. There are three types of pulse shapes; rectangular; ramping up, and ramping down. The effects of pulse shaping and drilling type on the spatter deposition area, inlet hole diameter, and hole taper were carried out.

2. EXPEREMINTAL WORK

2.1 Laser drilling and parameters

A JK700 pulsed Nd:YAG laser (GSI Lumoincs) emitting a wave length of 1.06 µm and maximum average power of 400 W was used to drill the prescribed holes. A lens of 120 mm focal length was used to focus the laser beam waist on the workpiece with a spot diameter of 0.6 mm. Compressed air with a pressure of 3.8 bar was used as an assist gas.

Pulses have width of 2 ms, with variation of their energies, were used to form through holes in 1mm thickness of stainless steel sheets. Standard rectangular pulses, ramping up, and ramping down pulses were used at each setting pulse width and energy (Fig.3). Additionally, the holes were re-drilled with two pulses each of them has a width of 1ms in a trial to decrease the hole taper produced from the first drilling type. The total energy of the two pulses as the one pulse energy. The same peak power was used to drill the holes in comparison.

2.2. Spatter deposition area and hole geometry evaluation

Image processing was applied to evaluate the spatter deposition area [5] using Matlab 6 software. Laser-drilled substrate (including the hole and its associated spatter) is captured using scanning electron microscope (SEM) and transferred to a digitized image that saved in computer memory. Well-defined image processing procedures were used to identify the spatter around the drilled holes and so calculating its area. The same steps evaluated the inlet hole diameter.

Digital measuring microscope (made by Mitutyo) was the tool to get the exit hole diameter. The hole taper was indicated by finding the inlet to exit diameter ratio.

3. RESULTS AND DISCUSSION

3.1 Single pulse drilling

3.1.1 Spatter deposition area

The effect of pulse shaping on spatter deposition area is presented in Fig. 4. For all pulse shapes, it is shown that the spatter deposition area increases as the pulse energy increases up to a threshold value where the spatter area starts to decrease. This behavior could be due to that when the pulse energy increase (for fixed pulse width) the peak power increases also. The increase of peak power consequently increases the amount of metal vapor inside the hole cavity and the evaporated metal pressure also increases, this may give more momentum to the expulsed metal droplets and so more spatter deposition area formed. The decrease of spatter deposition area with the continuous pulse energy increase could be due to an increase of vaporized metal fraction removed from the drilled hole, so less expulsed liquid metal could adhere around the hole rim and less spatter deposition area was formed.

Fig. 4 also shows the effect of pulse structure on the spatter deposition area. The use of ramping up pulses shows less spatter area around the drilled holes than the ramping down and rectangular pulses. For ramping up pulses; the initial coupling between the laser beam and the drilled stainless steel substrate is by the lower power sector. The evaporated metal recoil pressure is low and may cause low spatter area, in addition low metal removal is the expected result to the low first sector energy. When the second pulse sector punches the workpiece, the hole top was previously created and the formation of hole continue with the higher energy sector. The latter sector energy is enough to breakthrough the hole and to form the final hole shape, this stage of the hole formation may be accomplished by the most of metal removal, which could be directed downward the hole. The clear result of increasing the downward melt ejection fraction is the decrease of the spatter deposition area.

The holes produced by ramping down pulses have greater spatter deposition area. When using such pulse shapes, we have an opposite behavior about that associated with ramping up pulses; the initial coupling between the laser pulse and workpiece is done by the sector of the higher power, this may cause more metal removal and more vapor pressure and consequently more spatter deposition area than the holes produced with ramping up pulses.

The standard rectangular pulses give the most spatter area produced as shown in Fig. 5. This may be due to that most of pulse energy is consumed in hole formation before the beam breakthrough, so the majority of material is removed from the inlet hole diameter as a result of recoil pressure creation, the result is a greater spatter deposition area.

Fig.5 presents two drilling holes with two pulse structures; rectangular and ramping up formed with 11 joule energy pulses. The effect of pulse shape is clear on the spatter formation between the two types.

3. 1.2 Inlet hole diameter.

Fig.6 shows that the inlet hole diameter is proportionally increasing with the increase of pulse energy for all pulse structures. The increase of pulse energy will cause more thermal damage at the drilled surface and this may cause an enlargement of the inlet diameter. The increase of laser pulse energy will also cause greater recoil pressure produced, this may produce more force exerted against the surface tension force exerted by the drilled surface and as a result a mechanical damage will occur at the drilled surface and more inlet hole diameter is produced.

The ramping down pulse shape produced the maximum inlet hole diameter for most of the pulse energies used. That can be easily referred to the higher initial power coupling occurs between the laser light and the stainless steel sheets when using such shape when compared with the other two shapes. As mentioned before the higher peak power the higher pressure force and higher thermal energy produced and more inlet hole diameter is the gotten result.

For the other two pulse shapes it is clear from Fig.6 that the rectangular pulses produce holes with inlet diameter less than those produced by ramping up pulses. It is noticed that at low energy pulses the rectangular pulses produced the lowest inlet hole diameter, it is thought this result is due that when using ramping up pulses at these low energies the effect of the high power second sector dominates due to the decreased low power first sector, this high power second sector, of course, will increase the inlet hole diameter.

3. 1. 3 Hole taper

The effect of pulse energy and structure is presented in Fig.7. Generally, it clear that the hole taper decreased as pulse energy increased for all pulse shapes used. This result could be due to the more metal removed from the hole bottom as the pulse energy increased.

The rectangular pulse shape produced holes with low taper angle (for most energies used) when compared with the ramping up and ramping down pulses. This is the natural result to the minimum inlet diameter produced with that shape. The ability of rectangular pulses to make through holes at low energies decreased the taper angle (with respect to the shaped pulses) with a remarkable amount when using pulses have little energy during drilling the required holes.

3.2 Double pulse drilling

Although the single pulse drilling could be considered as the most time saving laser drilling technique, the problem of producing holes with large taper angle may make this type of drilling undesirable when nearly cylindrical holes are needed. R. E. Wagner [10] said that the shape of hole produced by laser is largely dependent upon the laser beam energy density, so it is considered that one of the most important factors affecting the hole taper in single pulse laser drilling is the high amount of energy used to form the hole by one pulse. This high energy laser pulse strikes the workpiece surface causing an enlargement to the inlet hole diameter and consequently, a hole with large taper angle is formed.

According to that the previous holes are reproduced with two pulses instead of one pulse. The total laser energy produced from the two pulses equals that concerned to one pulse, and the total duration of the two pulses is the duration of the one pulse. The pulse repetition rate was adjusted to be 4 Hz (to reduce the effect of pulse frequency). Fig. 8 shows that the inlet hole characteristics when using two pulses in drilling are the same as single pulse laser drilling. The rectangular pulse produced the smallest inlet hole diameter after that the ramping up pulse, and finally the ramping down shape.

The spatter deposition area shows the same behavior as the previous technique of drilling.

Fig. 9 illustrates the effect of different pulse shapes on the hole taper; the ramping up also produced the minimum hole taper, after that the rectangular pulse and finally the ramping down pulses.

Fig. 10 gives a clear comparison between the inlet hole diameter produced by the two drilling techniques. These results as predicted; when the energy of the initial coupling between the laser pulse and the drilled-surface decreased this leads to less thermal damage and decreased hole diameter and consequently less hole taper. This could also be verified when comparing the results obtained from Fig. 9 and 7.

5. CONLUSION

Using pulses with different shapes (rectangular, ramping up, and ramping down) and energy may have their influences during single pulse Nd:YAG laser drilling of stainless steel sheets:

- The spatter deposition area has the minimum values when the ramping up pulses used, while the maximum values are obtained at the rectangular pulses.
- The lowest taper angles, and the smallest inlet hole diameters are concerned to the holes drilled with the ramping up pulses, and the highest are produced by the ramping down pulses
- Increasing the pulse energy could decrease the hole taper and increase the inlet hole diameters for all three pulse shapes used.

The high taper holes produced by the single pulse drilling technique could be improved by using two pulses with the same total energy as the single pulse type for drilling the prescribed holes. This improvement may be due to the low energy initial coupling between the laser beam and the stainless steel sheets that could decrease the inlet hole diameter.

6. REFERENCES

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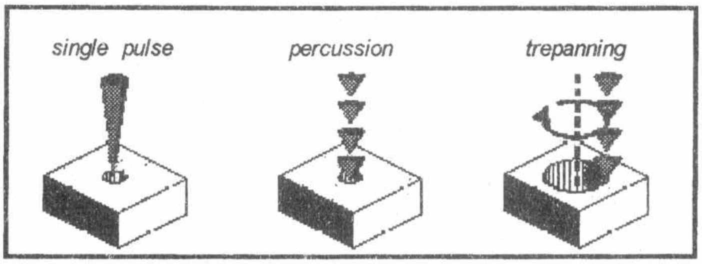


Fig.1. Typical types of laser drilling [7]

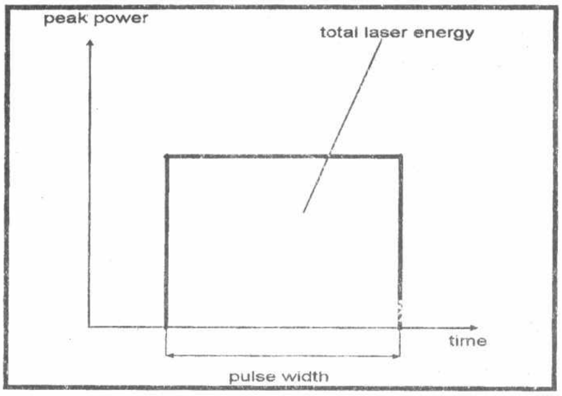
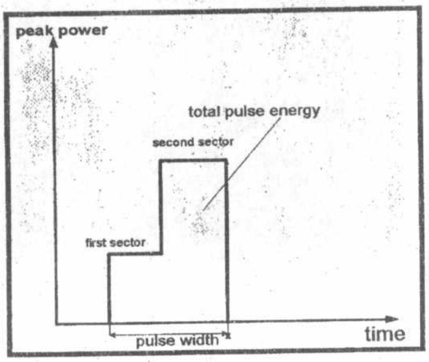
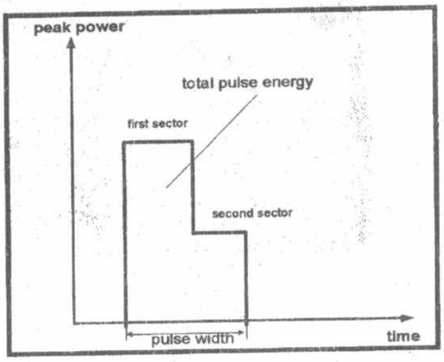


Fig. 2. Temporal distribution of standard rectangular laser pulse



(a)



(b)

Fig.3. (a) Ramping up and (b) Ramping down pulses

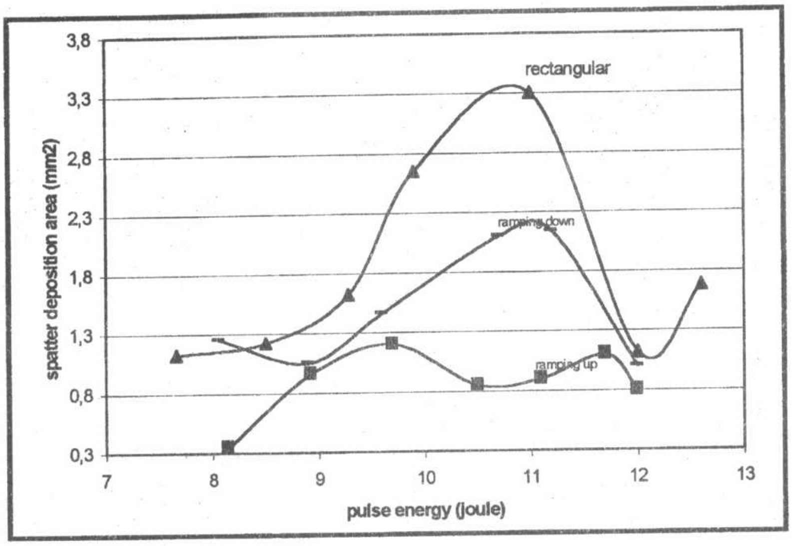
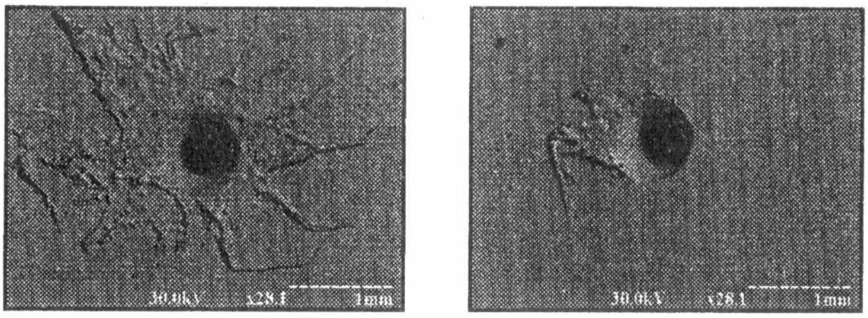


Fig. 4. Spatter deposition area for 2ms width pulse shapes



(a) (b)

Fig.5. SEM images of holes produced at 11 joule for (a) Rectangular pulse (b) ramping up pulse

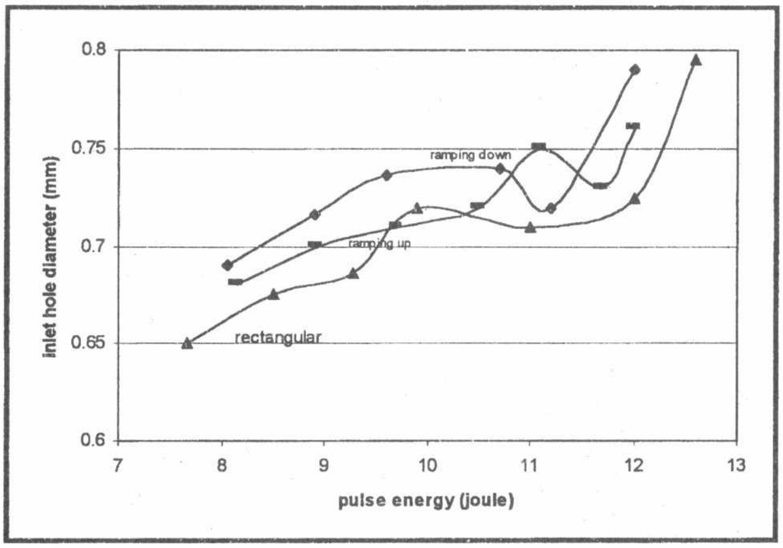


Fig. 6. Inlet hole diameter for 2 ms pulse width at different pulse shapes

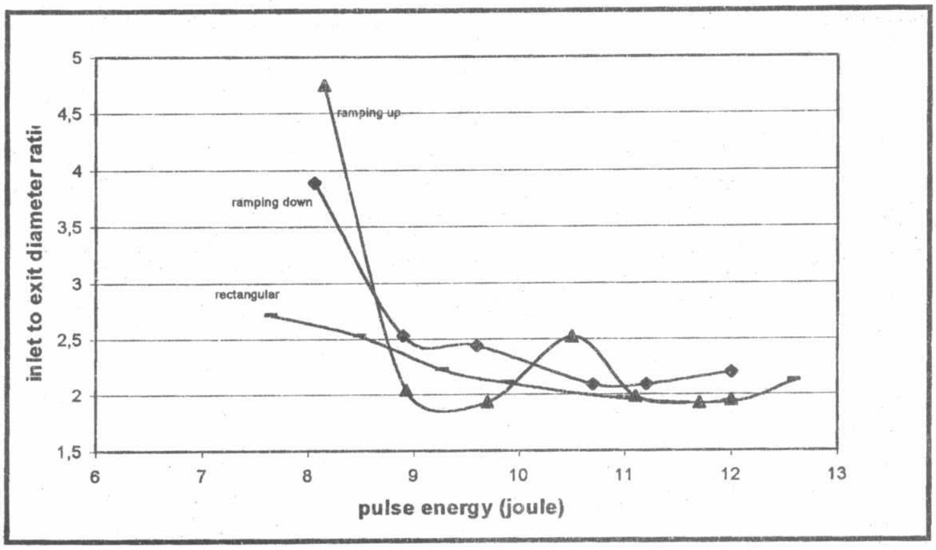


Fig. 7. Hole taper at different pulse structures

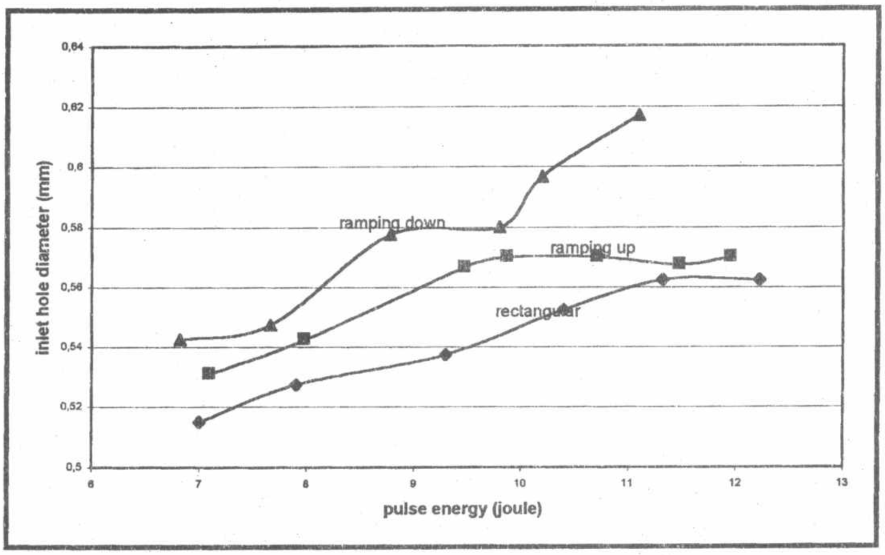


Fig.8. Inlet hole diameter at double pulse drilling type

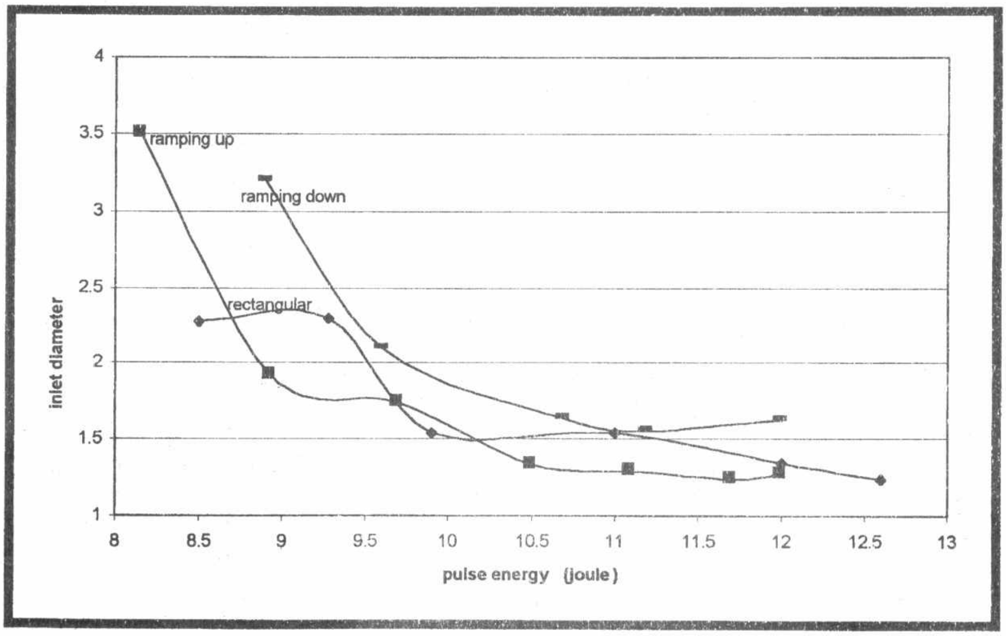


Fig.9. Hole taper at double pulse drilling type

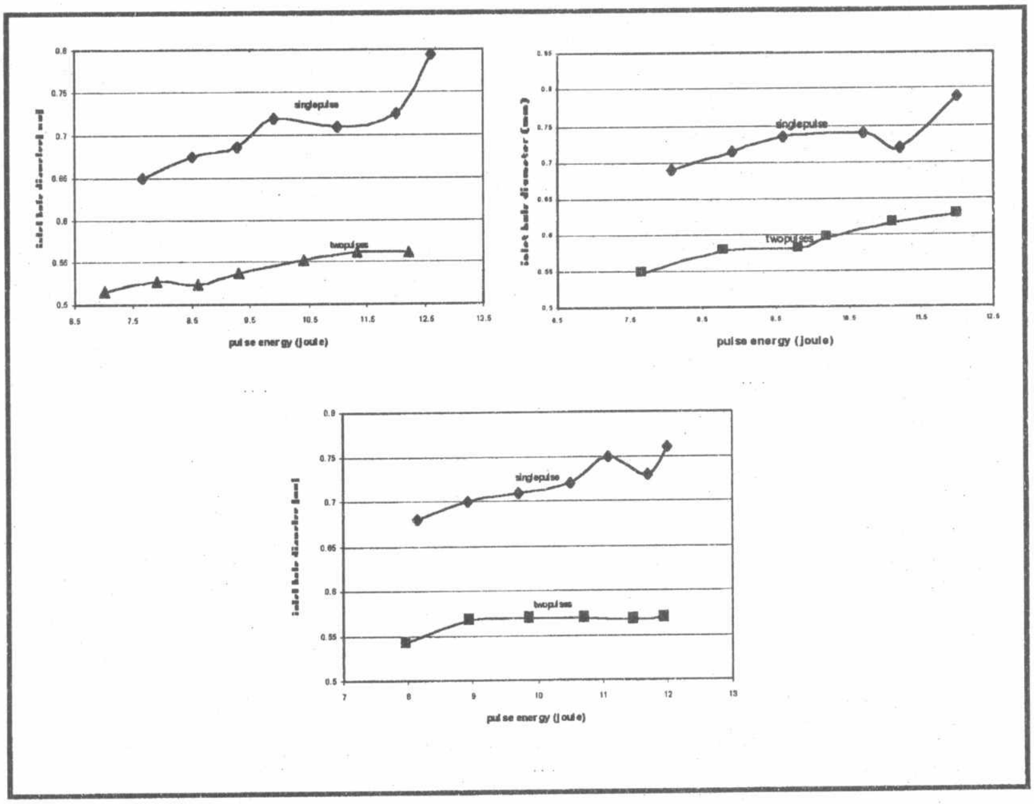


Fig.10. Comparison between inlet hole diameter when using single and double pulse drilling for (a) rectangular pulses (b) ramping up pulses (c) ramping down pulses