The Effect of Laser Parameters on The Surface Characteristic of Irradiated Stainless Steel 304

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Abstract: In these work, the effect of laser parameters such as wavelengths, number of pulses and energy per pulse were studied. The effect of number of pulses were studied in the range from 0 to 15000 at constant wavelength, the effect of energy per pulse was investigated at 3.5mJ and 6mJ. The commercial grade of polished stainless steel AISI 304 was considered as the base material in current study. Ultra violet excimer lasers at 193nm and 308nm were studied, Infra red lasers 1064nm was also tested. The superficial hardness and modulus were evaluated at different lasers parameters selected in these work to determine the optimum conditions. The total absorbed energy was calculated at all test conditions and compared with measured values. The optimum conditions to improve the mechanical properties at minimum energy were mentioned.

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1. Introduction

The use of stainless steel in building applications is not a new idea; the use of what we now know as austenitic steel can be traced back to at least the 1930'. Stainless steel is about 70% iron [1],[2]. It is special because of the presence of chromium element in the alloy. This element plays a key role in the corrosion resistance of stainless steel, but getting it into the steel is the tricky part [3],[4]. This means that the chromium atoms are an integral part of the structure of the steel [5],[6]. We describe the structure as a 'substitutional solid solution' - the chromium atoms simply substitute for iron atoms in the crystal structure. (This is opposed to the impurities in stainless steel - carbon and nitrogen - which are in 'interstitial solution' - where they fit in between the iron atoms). How much chromium is the next important Over the years, materials engineers have determined that at least 12% (by weight) of chromium is necessary to make stainless steel. This created some new problems; however, this composition had low ductility (the ability of a metal to be permanently stretched by plastic deformation) and toughness (resistance of the material to growth of a crack). These qualities were the result of the crystal structure of the material. Most iron-chromium alloys, like iron, are body-centered-cubic configuration. This crystal orientation prevented good forming and flexibility [7],[8].

The most common stainless steel is "AISI304" austenitic stainless steel. The "18-8" means that it contains 18% by weight chromium and 8% by weight nickel. This composition has the face-centered cubic crystal structure (FCC). It is almost always ductile, readily drawn into wire [9]:[15].

Stainless steel is increasingly being sought out for structural applications. Engineers and architects are particularly drawn to the competitive life-cycle cost, potentially high strength, high corrosion resistance and aesthetically pleasing finishes of the material. Evidence of growing industry demands are seen daily in applications like plane and three-dimensional trusses, mullions in facade structures, canopies, roof sheeting, silos, portal framed overhead wiring structures (for railway services), and general construction in chemical, marine and other corrosive environments[16],[17].

The materials were chosen primarily for the resistance to corrosion that they could provide in what was considered to be a harsh service environment. There are many other examples of the use of stainless steels in the construction industry, on both a small and large scale. However, most of the common examples of the use of stainless steel as a primary structural engineering material have been in buildings or as critical components in structures as opposed to the widespread use as structural engineering materials in their own right [18].

Many designers and client bodies are more open to the use of stainless steel. The drivers for this apparent change in attitude do not appear to be clearly defined but include:

• An increased awareness of the future burden of using materials that is not inherently durable in the service environment [19].

• An increase in desire to reduce or eliminate the need for maintenance (both planned and unplanned) that can arise with accepted structural materials.

• In some applications it is now perceived as politically undesirable to produce structures that are not inherently durable.

These factors do not necessarily provide an "open door" for the use of stainless steel as a structural material as there will be competition from other materials; however; this change in attitude does provide a climate in which stainless steels may be considered more favorably than in the past[13],[15]. The problem of durability with conventional construction materials in relation to bridges but could be applied equally to other building, architecture and structures and the possible scope for increasing replacement of these materials with various types of stainless steel[20],[21].

2. Experimental work

Laser Surface Irradiation

The irradiation is done on one side of the sample and covers all the surface area of the sample. The main goal of this work is optimize condition for laser irradiation of the samples by Excimer laser at 193nm and 308nm Table (1) shows data for used rare gas halide Excimer laser.

Table (1) Data for Excimer Laser (rare gas halide)

Gas type	λ (nm)	r(A)	ω (Cm^{-1})	σ (Cm^{2})	τ (ns)
ArF	193	2.2	-	12	4.2
XeCl	308	2.9	194	50	11

λ = transition wavelength
r(A) = equilibrium inter-nuclear separation
ω = fundamental vibration frequency of the excited state
σ = stimulated emission cross section
τ = radiative life time (pulse duration)

The number of pulses and the effect of energy per pulse on the hardness were recorded to indicate the energy required (fluence) to improve the mechanical properties. Beam in the shape of a rectangle with width (w=4mm) and length (l=10mm) was used in the laser process the power density ranges from (0.75 W/Cm^2 to 0.1 W/Cm^2) without any focusing. The laser irradiation condition is listed in Table (2)

Table (2) Laser Irradiation Conditions

Type	Wavelength nm	No of pulses	Energy per pulse mJ	Repetition rate (Hz)
Excimer	UV 308.6	0,2000,5000,10250, 15000,50000	6	200
Excimer	UV 193	0,2000,5000,10250, 15000,50000	6	200
Nd-YAG	IR 1064	5000	1.9:2.2	10
duration time=6nano second & total energy =energy per pulse*number of pulses				

Superficial Hardness

The hardness of the specimens were measured by using Superficial Rockwell hardness tester with ball diameter 1/16" at load 30Kg. Each hardness value is at least an average of 5 readings and they are good to ± 4%.

Elastic modulus

To obtain the elastic modulus, the unloading portion of the depth-load curve is analyzed according to a relation, which depends on the contact area:

$$C = v^{0.5}/(2E_rA^{0.5}) \quad (1)$$

where C is the contact compliance and E_r is the reduced modulus defined by

$$1/E_r = (1-v_s^2)/E_s + (1-v_i^2)/E_i \quad (2)$$

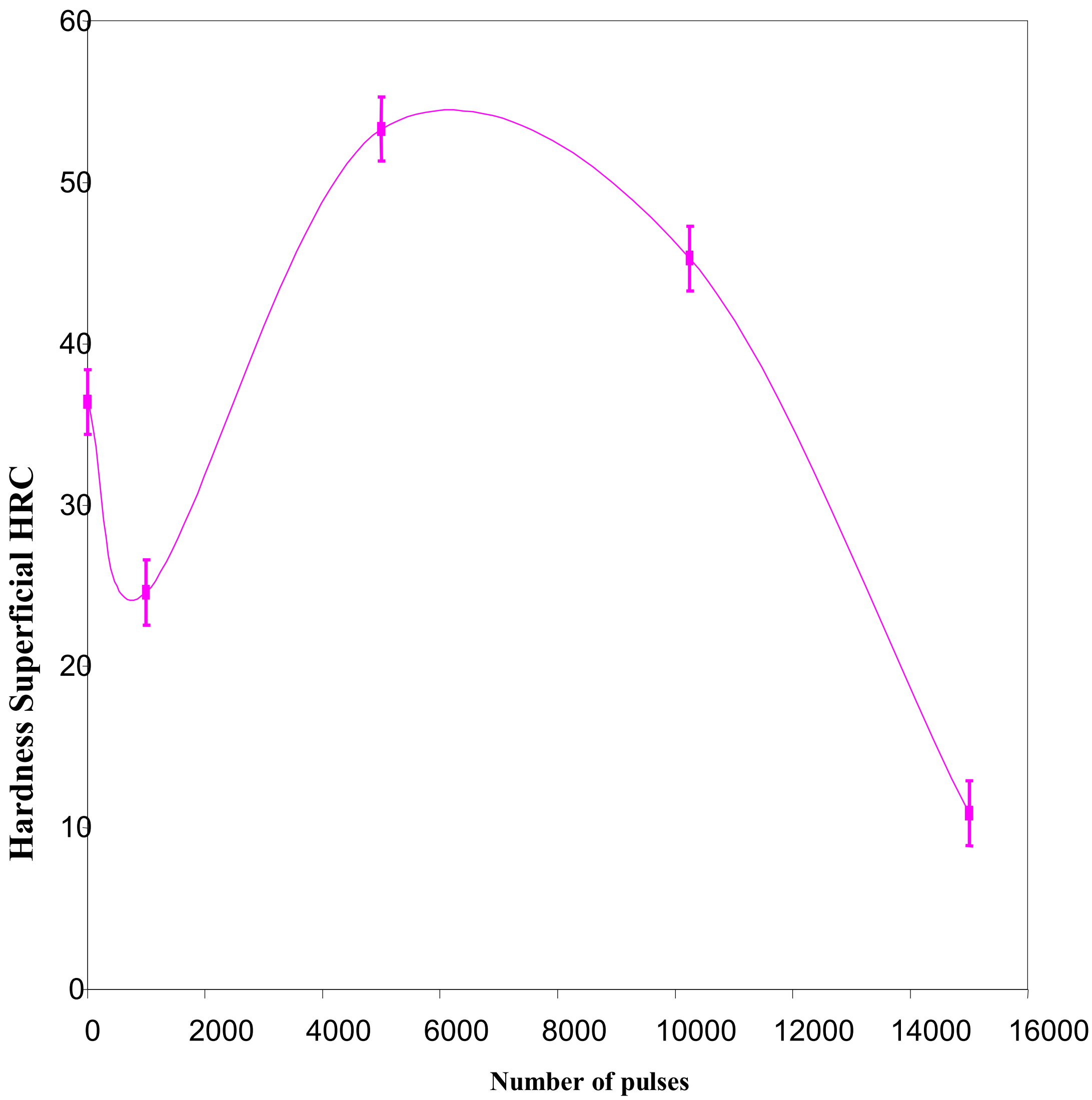
where v_s the Poisson's ratio for the sample, v_i, the Poisson's ratio for the indenter (0.07), E_s the Young's modulus for the sample and E_i, the Young's modulus for the indenter (1141 GPa).

3. Results and discussions

The effect of both number of pulses and energy have been investigated in order to select the best irradiation conditions and the alloy potential for producing improvement in mechanical properties

Effect of Number of Pulses

Table (3) shows the effect of the number of pulses on the superficial hardness at constant wavelength of 193nm Excimer laser and constant energy ratings 6mJ/pulse for austenitic stainless steel 304.



Fig(1) The Variation of Superficial Hardness HRC with Number of Pulses for Stainless Steel 304 Irradiated by Excimer Lasers at,193nm,3.5mJ,200Hz.

Table (3) the superficial hardness as a function of the number of pulses for austenitic stainless steel 304

Number of pulses	**0**	**1000**	**5000**	**10250**	**15000**
Hardness	36.4	24.6	53.3	45.3	10.9

As shown in Figure (1) the hardness decreases gradually with the increasing number of laser pulses, after about 1000 pulses the hardness was increased gradually with the increase in number of pulses. Significant improvement in hardness was recorded around 5000 pulses. Rapid decrease in hardness was recorded at 10250 pulses, which continued with increasing in the number of pulses.

Effect of Laser energy

In order to study the effect of laser energy, different energy values were investigated (3.5mJ/pulse & 6mJ/pulse) at constant wavelength of 193nm and constant number of pulses of 5000pulses. Table (4) shows the superficial hardness of the austenitic stainless steel 304 at different power rating.

Figure (2) shows the significant improvement in the hardness at 3.5mJ/pulse. At 6mJ/pulse, the hardness was decreased and became less than that of the base metal before laser irradiation. Accordingly, a power value of 3.5mJ/pulse was selected for the work conducted throughout the research.

Table (4) Effect of Power changes on superficial hardness for stainless steel 304 at constant number of pulses of 5000 and 193nm.

Energy/pulse mJ	**0**	**3.5**	**6**
Hardness	36.4	53.3	13.9

Effect of Laser Wavelength

Nd-YAG is one of the most commonly used laser types in Egypt, stainless steel 304 was irradiated with the fundamental beam 1064nm to show the effect of IR irradiation on the superficial hardness. The number of pulses was 5000 pulse, Table (5) shows the average hardness values of the measured specimens with scattering less than $\pm$ 2%.

Table (5) Effect of laser irradiation by Nd-YAG 1064nm on superficial hardness for stainless steel 304,5000pulse,2mJ/pulse

Conditions	**Hardness**
Untreated	30
Treated part	45.1

Figure (3) shows superficial hardness of stainless steel 304 before and after laser irradiation with Nd-YAG 1064nm and Excimer laser 193nm & 308nm respectively.

From the above results, Ultraviolet laser irradiation of stainless steel 304 is better. Excimer laser produces improvement in the hardness about 66.5%. The improvement in hardness was higher than the improvement with IR laser (50%) for the same number of pulses 5000 and same energy 6mJ/pulse. The phenomena occur because the energy of the Excimer laser is higher than that of the Nd-YAG laser. Excimer laser has low wavelength and higher frequency while Nd-YAG laser has higher wavelength and lower frequency.

From the pilot study mentioned above, the austenitic stainless steel produces promising improvement in hardness when irradiated by UV lasers. The depth of penetration and reduced modulus should be measured for this type of steels to identify the laser irradiation effect on the mechanical properties.

The effect of laser types on the mechanical properties

The variation of hardness at maximum load with number of pulses at 308nm and 193nm Excimer laser irradiation was shown in Fig (4). The hardness value at 2000 is very close to the non irradiated samples. Improvement in the hardness was significant only at pulses between 5000 and 15000. When the number of pulses increased the hardness value decreased due to sample burning. Fig (5) shows the variation of Modulus at maximum load with number of pulses, the value of modulus increased until 2000 pulses, the modulus value almost remained constant between 2000 and 15000 pulses. The decreasing rate in modulus after 15000 pulses was very slow. The effect of the number of laser pulses on the hardness and modulus when stainless steel 304 was irradiated at 193nm. The maximum improvement in hardness was shifted to about 2000 pulse and another peak appears near 15000 pulses. The beam energy at 193nm pulses is larger than the beam energy at 308nm. According to the energy equations and principles[(12),(13)]. low wavelengths means higher frequency and higher amount of energy absorbed.

Laser irradiation works as method of hardening and softening at the same time. The initial microstructure of the irradiated alloy (the room temperature microstructure) plays the significant role in that case. The decrease in hardness of stainless steel after laser irradiation is due to the formation of higher energy phases but these phases have lower hardness.

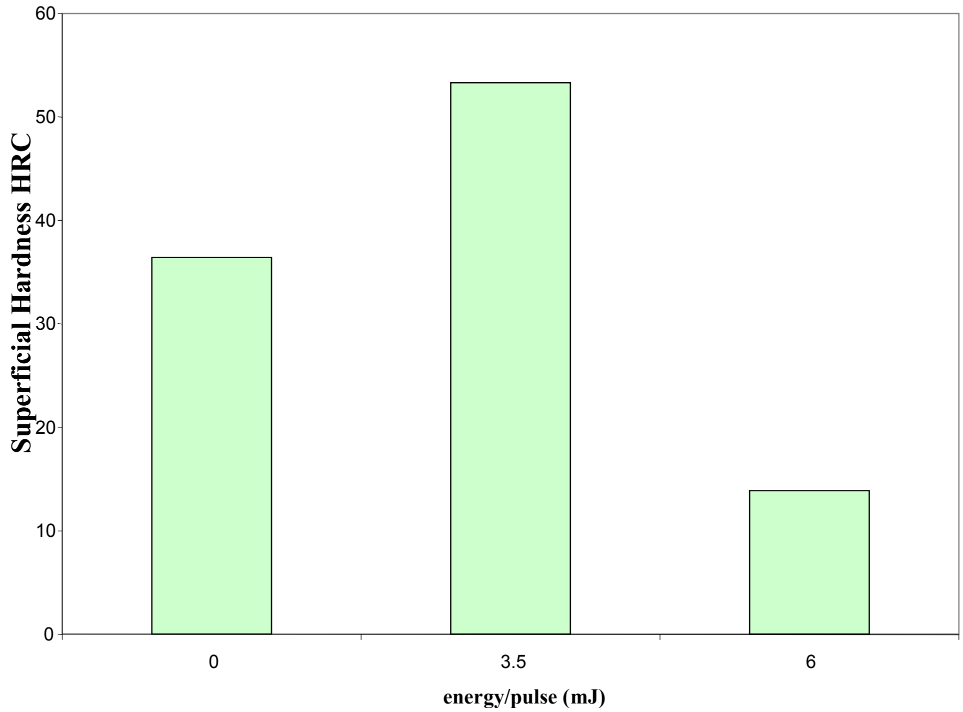


Fig (2) The variation of Superficial Hardness HRC with Power for Austenetic Stainless Steel 304 Alloy Irradiated by Excimer Lasers at , 193nm,5000 Pulses,200Hz

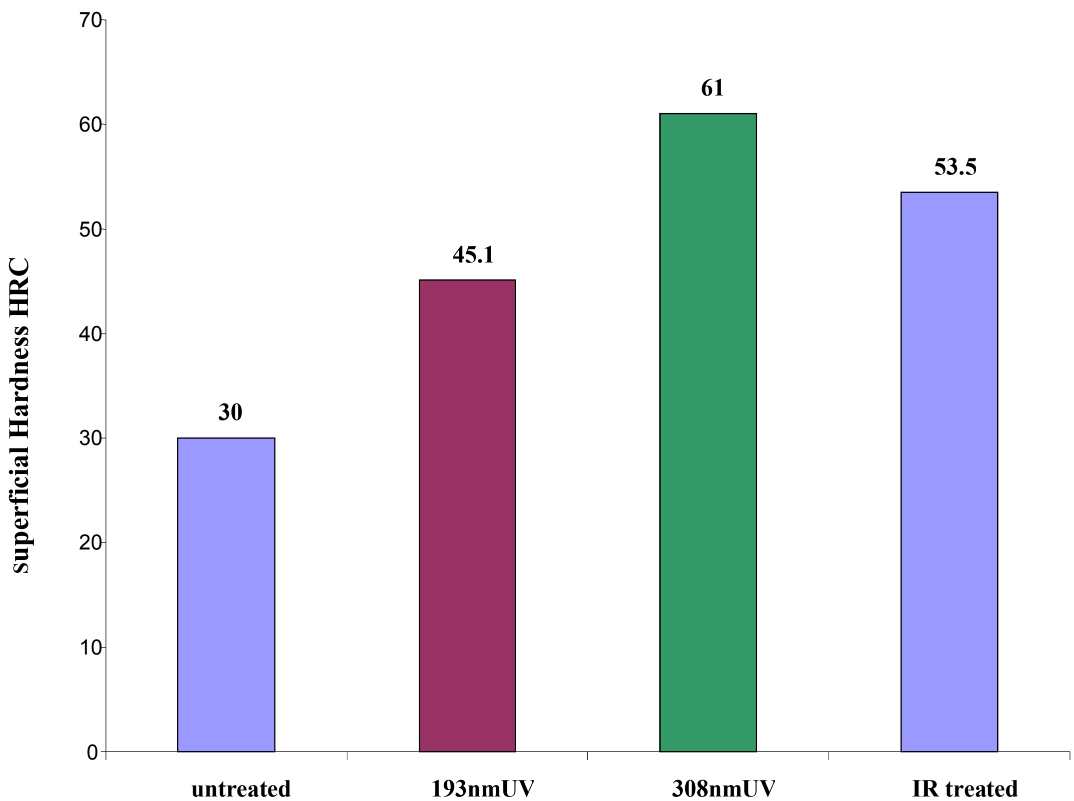
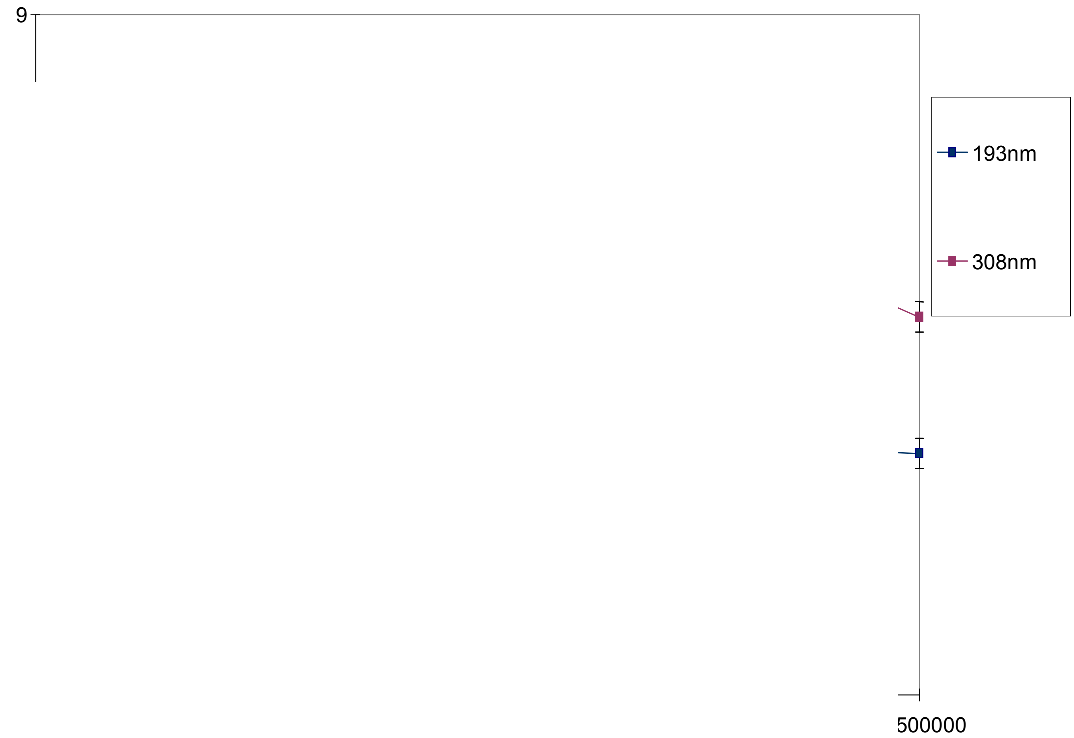
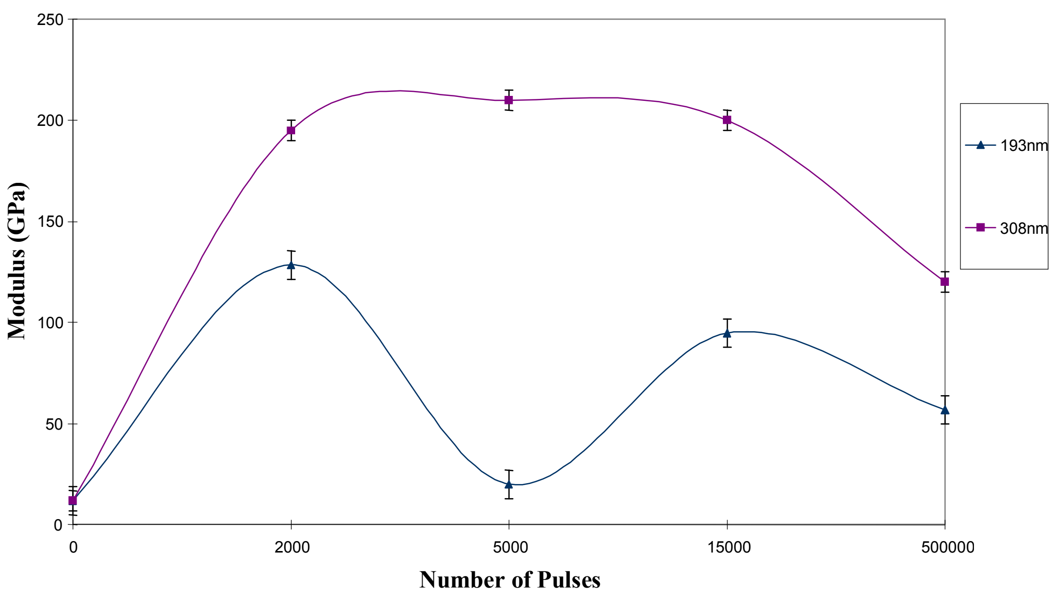


Fig (3)The Effect of Laser Wavelength on The Hardness of Austenetic Stainless Steel 304



Fig(4)The variation of Hardness at Max Load with Number of Pulses for stainless steel 304 irradiated with Excimer Laser at 200Hz,6mJ



Fig(5) The variation of Modulus at Max Load with Number of Pulses for stainless steel 304 irradiated with Excimer Laser at 200Hz,6mJ

When comparing these figures with the similar graphs at laser wavelength 308nm. The samples show a decrease in the hardness and in the reduced modulus as the indentation load increases; probably the higher hardness near to the surface. The effect of laser irradiation at 193nm was more pronounced than at 308nm. The UV laser has less wavelength and higher frequency so more energy has been resulting from UV light for the same power and number of pulses. High power rating produces higher improvement in the properties at the same laser wavelength and number of pulses.

The effect of laser energy (calculated)

Figure (6) shows the variation of energy absorbed versus the increase in number of pulses at energy per pulse 6mJ and 3.5mJ respectively. When the number of pulses increases, the absorbed energy increases. At 6mJ, the amount of total energy at the same number of pulses was increased. At low value of energy per pulse 3.5mJ, the amount of absorbed energy at the same number of pulses was low. The gap between the two values at 6mJ and 3.5mJ increases linearly with the increase in number of pulses.

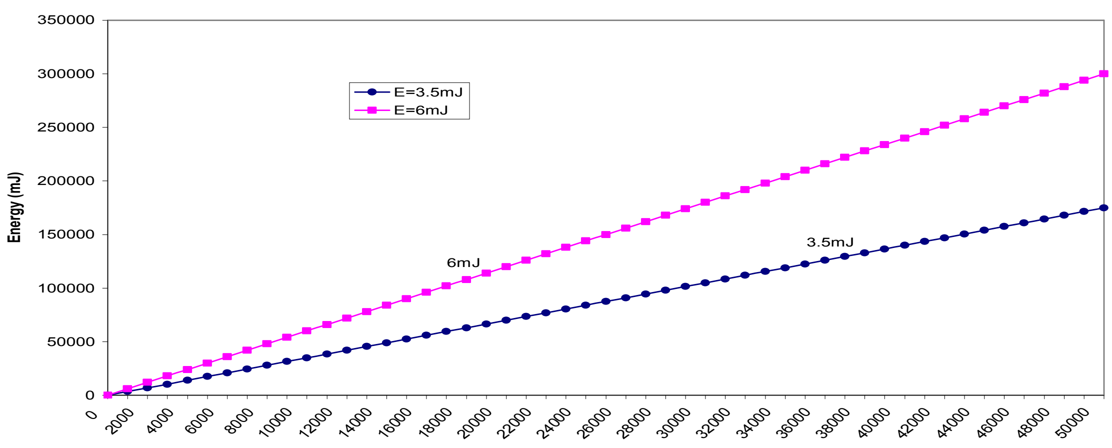
* At 5000 pulses total energy at 6mJ equals 2500mJ and total energy at 3.5mJ equals 2000mJ. At 15000 pulses total energy at 6mJ equals 10000mJ and total energy at 3.5mJequals 7000mJ. At 50000 pulses total energy at 6mJ equals 30000mJ and total energy at 3.5mJ equals 15000mJ.

There are many reasons for the disagreement between the current work and some published results [9], [10]. The beam-metal interaction and in the case where the fluence is high enough to rise the surface temperature instantaneous and reflectivity changed. This effect is quite complex, the laser rays dissipated, thus reducing the effective energy really impinging on the target. The thermal effect due to collision between lasers and atoms inside the structure when taken into account in the total energy balance, it tend to reduce the efficiency of heating and melting (i.e. the amount of heat able to form and propagate microstructure changes) ; accordingly, it affects the amount of heat actually absorbed inside the material.

The ultra violet laser is a clean source of high energy density. Surface irradiation processes involve non equilibrium phenomena due to high heating and cooling rates induced by the laser irradiation. The inherent rapid cooling due to high thermal conductivity of steel makes lasers very attractive since the irradiated parts contain various microstructures with metastable and stable phases, fine grain, minimum segregation, and extended solid solutions which improve the mechanical and metallurgical properties of the irradiated parts.

The amount of heat used for irradiation along the depth is considered to be proportional to the input heat flux along the direction of that unit depth. This assumption is based on the fact that in the absence of conduction loss, the amount of irradiated material, that is the amount of heat used for irradiation increases as the input heat flux increases and vice-verse. So the amount of heat used for irradiation can be expressed as a function of temperature and physical parameters such as thermal conductivity, density and specific heat.

The suitability of Laplace transformation analytical model was investigated by comparing simulations to experimental measurements of pulsed laser heating. The data is from laser irradiation of stainless steel 304 designed to evaluate the validity of the classical thermal diffusion model on a microsecond time scale.



fig(6) The variation of Temperature with Number of Pulses for Steel irradiated by Excimer Laser 308nm, 200Hz at different values of energy per pulse

Conclusions

1. The maximum improvement in superficial hardness were achieved at 5000 pulses.
2. More improvement in mechanical properties were recorded with ultra violet lasers 193nm and 308nm because they are high energy lasers.
3. The increase in the energy per pulse increase the total energy absorbed which have significant influence in the mechanical properties.
4. There are good agreement between the calculated and measured value of the absorbed energy at different number of pulses and different energy per pulse.
5. The total energy calculated is higher than the actual energy used in phase transition due to losses resulting from reflectivity, surface roughness and scattering due to interaction with atoms inside the structure.
6. Higher energy phases were formed when the total energy absorbed increased but sometimes in the case study considered in these work higher energy phases with low hardness values.

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