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MODIFICATIONS IN SURFACE STRUCTURE AND MECHANICAL PROPERTIES OF ALUMINIUM ALLOY BY ND-YAG LASER IRRADIATION

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ABSTRACT

Aluminium alloy target samples were irradiated with different number of shots of Nd-YAG laser ranging from 100 to 500 with incremental steps of 100 shots under vacuum (10^{-6} torr). The optical, structural and tensile properties of Al (Alloy) irradiated by Nd-YAG laser were investigated by optical microscope, X-ray diffractometer (XRD) and tensile testing machine. Laser ablation of the specimen resulted in boiling, splashing and crater formation on its surface. The crater size increases initially and then decrease gradually by increasing number of laser shots. The crater depth of laser irradiated Al (Alloy) increased by enhancing the laser shots. An anomalous trend of crystallite size, peak intensity, and dislocation line density of the irradiated specimen with different number of shots was observed by XRD comparison analysis. Mechanical properties of both irradiated and un-irradiated specimens were investigated using tensile testing machine. The average value of surface hardness 28.4 MPa of un-irradiated specimens was found. Increasing the number of laser shots, ultimate tensile strength and fracture strength were also varying.

Keywords: Aluminium Alloy,Nd-YAG Laser, Hardness Analysis, X-ray Diffraction, Optical microscopy.

Introduction

Electromagnetic radiation interconnecting with material possibly will disturb the optical properties of matter. This interface is only with the electrons of the particles of the substantial because the much lighter nuclei do not track the high frequencies of observable radiation. This energy is then moreover removed to the lattice. Transfers are based on the physical and material characteristics of the targeted device and the range of test equipment when the study depends on the subject of the targeted device [1, 2].The variation in the laser fluence intensities results in formation of surface structures ranging from micro to Nano size. The interaction of ultraviolet laser pulses with target material results in modification of surface morphology without inducing any significant damage to the target material [3].

In progressive years, a quantity of efforts has been completed to explore variation in the laser induced microstructural properties of metal alloys. Meanwhile mechanical and optical properties of crystalline constituents are dependent upon microstructural censures like crystallite size, d-spacing and micro strain, the accurate quantity of such parameters is of boundless significance [4, 5]. The absorption of the material is determined by the absorptivity and reflectivity of the material e.g. metals absorb an increasing fraction of beam power as the wavelength decreases [2, 6]. Metals with large percent reduction in area show high ductility. Metals having elongation more than 15% are ductile and those 5 to 15% elongations have midway ductility. But metals less than 5% elongation are brittle. An associated property of materials is malleability. Malleability is the property of the materials by which they can be hammered, pressed or rolled into sheets without breaking [7, 8].

Several methods have been discovered for investigation of crystallite size through the XRD pattern but The Scherer method is an eminent to determine the crystallite size. In this method, neglects peak broadening due to inhomogeneous strain and influential contribution. On the other hand Williamson-Hall method includes the broadening of peaks due to the in homogeneous strain and instrumental contribution for evaluation of crystallite size [9]. Recently, W-H method is devised to calculate lattice strain and grain size [10]. Huang et al.[11] had investigated keyhole in stability and porosity formation mechanism in laser welding of aluminum alloy and steel. The bubble formation leads to the instability of keyhole. Many scholars put their efforts into the combination of simulation and experimental methods and investigate the laser ablation factors such as laser repetition rate [12], pulse duration [13] and dendrite growth [14]. Yet, the interaction between nanosecond laser and aluminum alloy such as thermal diffusion and materials that sublimed are not investigated in detail. However, there are few researches about surface structural and mechanical properties of aluminum alloy, especially the laser irradiation regarded as thermal shield to isolate the thermal diffusion in the axial direction and wide range of strain rates.

The prime objective of present work was to analyze surface, structural, and mechanical alteration of irradiated Al targets with increasing the laser shots. In previous literature, no research work has been carried out to co-relate structural, mechanical and surface properties of laser irradiated Al (alloy). Modifications in surface morphology, structural change, and mechanical belongings of laser irradiated Al (alloy) with increasing laser shots was investigated by Optical microscope, X-Ray diffraction, and tensile testing.

Experimental Work

Six rectangular shaped Al alloy targets were used in the experiment with dimensions (2mm×500 mm×2mm). Five specimens were irradiated with a Nd-YAG laser and leaving, one specimen as a reference. Emery papers are used to smooth the hard or irregular surfaces. The samples were cleaned in the presence of water to avoid overheating, scratches from extra created particles and to clean the surface of the Sic paper. The Sic paper put on the grinder holder and allow to water

flow on it. We used different micron diamond pastes which gave the mirror like shiny surface to the samples. Diamond polishing compound was used for that purpose. Diamond polishing compound is diamond dust particles in a cream base soluble in water. Al alloy specimens were kept in hand and polished by rubbing diamond paste of 6 microns and 1 micron successively with a velvet cloth. After that the specimens were washed with running water and cleaned with cotton. The polishing process was carried out until a uniform, flat, mirror like and smooth scratch free surface was obtained.
The exposing rectangular specimens were attached on target holder and then it was kept in the target chamber of Nd: YAG Laser, which attained vacuum (10^{-6} torr) by using different types of pumps.

The target is placed at an angle of 90º, according to the direction of beam as shown in figure 1. A Q-switched Nd-YAG laser (532nm, 6 ns, 100 mJ, and 10 Hz) was used to ablate targets and the plasma formation. Energy of the laser beam was measured by an energy meter which was attached by a detector.

The distance between laser and specimen was kept 150 cm. Laser beam used to focus the target was IR with lens of principal focal length 50 cm. The incident laser impinged on target at the 90º with target normal. The number of laser shots used on five specimens was 100, 200, 300, 400 and 500, respectively. 0.01178 cm^2 was approximately measured laser spot size experimentally on the target and corresponding flounce was measured using the relation. X'Pert PRO Analytical diffractometer (XRD diffractometer) employed to investigate the crystallographic structure and phase analysis of laser irradiated target. The irradiated specimen was investigated by Optical Microscopy (Olympus DP2) for surface morphology analysis. The tensile strength of laser irradiated Al (Alloy) was measured by using a universal testing apparatus (50 kN AG-I Shimadzu).

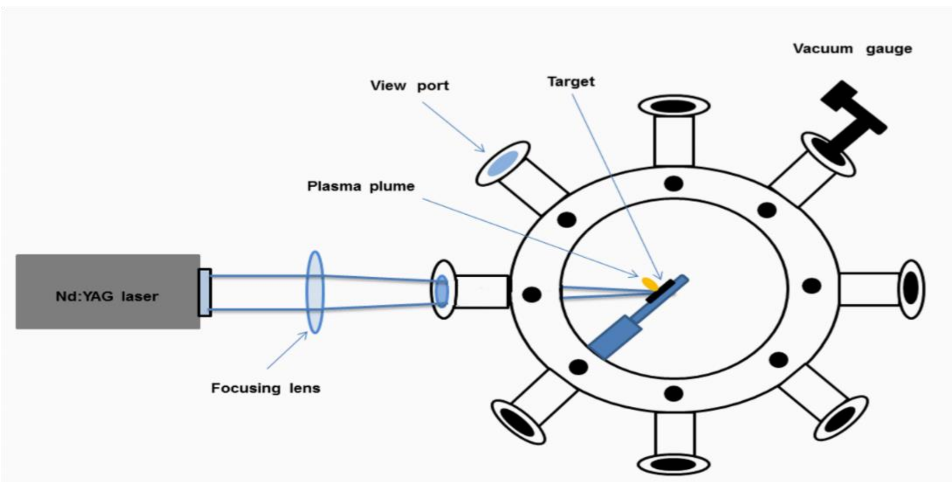

Fig. 1: Schematic diagram of laser irradiation

Hardness can be defined as the resistance to deformation. In sense of the mechanics of materials the word hardness is mostly referred to as the resistance to the indentation of the material. The hardness testing of un-irradiated and laser irradiated Al targets was carried out by (SUNTEC

Corporation CV-700AT Clark) Vickers Hardness tester. The hardness was calculated in two directions around the crater up to 3.0 mm with an increment of 0.5mm with a load of 0.3Kg for 10s.

Results and Discussion:

The following analysis were employed for the detection of changes happened in the structure of Aluminium alloy.

Structural Analysis

X-ray diffractometer was used to examine the structural changes that occur in Aluminium alloy specimen before and after laser irradiation.Comparison of un-irradiated and irradiated Aluminium alloy XRD patterns of specimens revealed in Figure 2. shows for 100 laser shots for (111) and (200) planes it is clearly indicating that the peak intensity increases, the increase is due to ascendency of annealing procedure that causes gradual decline in the structural deficiencies, but (220) and (311) planes, intensity gradually deceases due to domination of structural defects [15]. For 200 laser shots the intensity of the planes (111) and (220) increases but the intensity of the planes (200) and (311) decreases due to the gradual reduction in structural defects. For 300 laser shots the intensity of the planes (111), (200) and (311) deceases but small increase in the intensity of (200) the peak intensity reduces due to recrystallization and solidification. Big size grains breakdown into the slighter ones after treatment and caused the diminution in the peak intensity. For 400 laser shots the intensity of the planes (200), (220) and (311) gradually increases. The increase in peak intensity is because of increase in solidification of irradiated target. The increase in crystal growth is because of increase in atomic diffusion in the grain boundaries after laser irradiation but the intensity of the plane (111) decreases due to the structural defects [16]. For 500 lasers shots, the intensity of all the planes decreases gradually [17]. This decrease in intensity is due to the energy deposition of incident laser in the material. When laser shots increase or energy deposition increases then these faults are annealed, more rise in laser shots caused the generation of greater faults.

Hence the peak intensity of different planes initially increases and then decreases showing an inconsistent behavior. This inconsistent behavior shows in a crystallite size and dislocation density. Laser inciting annealing effects in Aluminium alloy make the crystal planes strain free, thus causing intensity discrepancy in diffracted x-ray. A preeminent temperature polygonization plays the part of creating strain free and bewildered block which effect in the intensity changes.

For all XRD pattern the intensity of the peak was not similar to each other reproduces the comparative strength of spreading intensity from (111), (200), (220) and (311) of Al alloy as a function of laser shots shown in figure 2 [18] Souza et.al have reported that the ultimate deflection powers of x-ray depend upon the absorption of the point defects. They found that the peak strength reductions by increasing vacancy concentration. It is observed that there was no extra peak found by increasing number of laser shots and maximum intensity was observed at (200) plane for all laser shots because of the domination of annealing process and minimum intensity observed at (220) planes relative to other the major reasons for this decrease in intensity value was the structural defect formation [19]. Therefor the (200) plane is more intense peak than expected and it provide microstructure information of the sample. Intensity values of each plane as a function of dose are given in table 1.

Table 1: Intensity values of each plane as a function of dose

Laser Shots	Intensity (cps)			
	(111)	(200)	(220)	(311)
0	733.9665	1310.9665	111.2576	626.6490
100	2249.633	3866.1290	0	87.2434
200	2005.865	932.3313	308.1378	55.4245
300	620.7624	415.4838	389.8240	219.6480
400	245.8944	2851.6829	290.6891	1109.3841
500	231.3782	909.6774	70.9677	323.1671

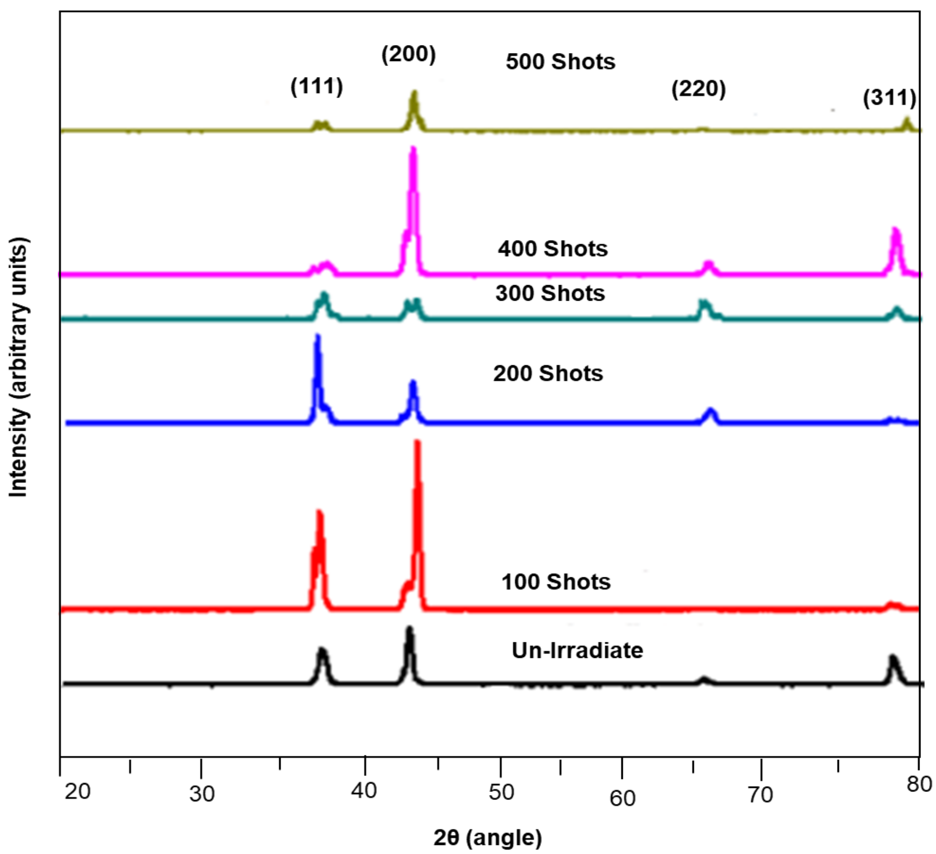

Fig. 2**:** Comparison of XRD patterns for un-irradiated and laser irradiated Al (Alloy) with various number of laser shots

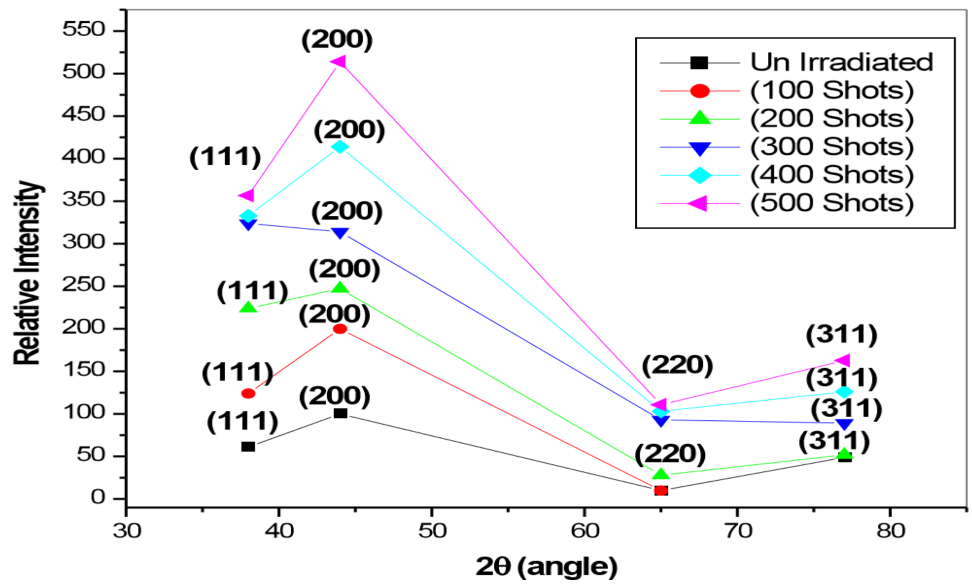

Fig. 3: Relation b/w relative intensity and 2θ of irradiated & un- irradiated Al alloy specimens

If all trends are randomly calculated, the model does not have any structure. The irradiated Al target shows preferred orientation, then it can be converted to weak, moderate or strong texture. Almost all of the engineering materials are forged and may have a big impact on physical properties. Texture coefficient ρ (hi ki li) is determined by using Harris analysis for un-irradiated and laser irradiated Al alloy targets. Following relation was used [20].

Where summation in the denominator is for all the peaks as mentioned in the XRD pattern i.e. (111), (200), (220) and (311), shows the standard intensity of the plane, is the observed intensity for the texture coefficient (h_i k_i l_i) should be > one for a better oriented plane. Table: 1 summarizes and along with the texture coefficients (h_i k_i l_i) evaluated using the above Equation 1.

Referring to Figure 4: The texture coefficients (hkl) are incorporated into each of a meaning of 2θ for a given laser shot. For all laser points, the (hkl) has been found to have practical parallel transport. The individual modification is the change in the size of texture coefficients on contamination.

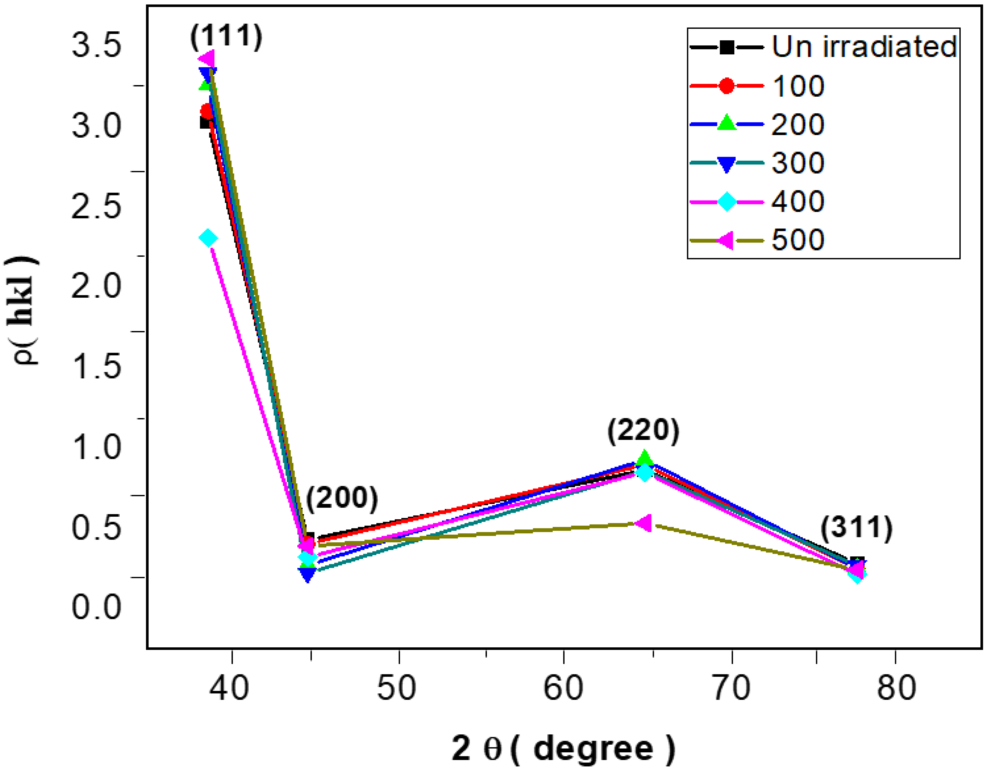

Fig. 4: Texture coefficients (hkl) as a function of 2Θ for a given laser shot

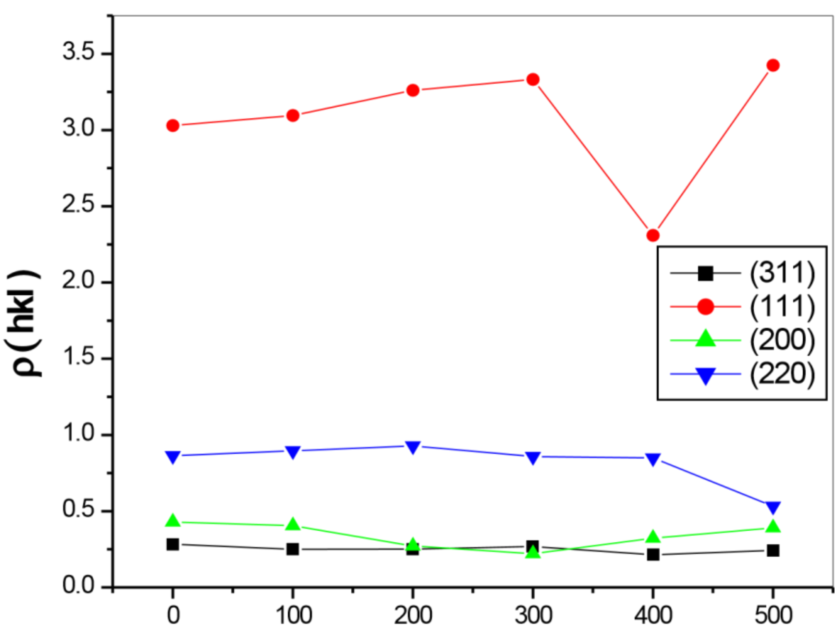

Fig. 5: Texture coefficients (hkl) as a function of laser shot

Laser Shots

d- Spacing

The d-spacing value provide the information about the lattice plane and represent the family of each lattice plane. Figure. 6 depicts a plot of d-spacing Vs 2 θ values. Laser irradiation causes some very weak stresses that are unable to enforce a substantial change [15, 21]. The *d*-values of different planes are given in Table 2.

Table 2: *d*- spacing of un-irradiated and laser irradiated Al alloy.

Laser Shots	**d- spacing**			
	(111)	**(200)**	**(220)**	**(311)**
0	2.273858	2.031453	1.438961	1.23178
100	2.344968	2.015381	0	1.225338
200	2.373809	2.030775	1.427628	1.226578
300	2.273858	2.01587	1.448938	1.225338
500	2.34496	2.025393	1.43927	1.215739

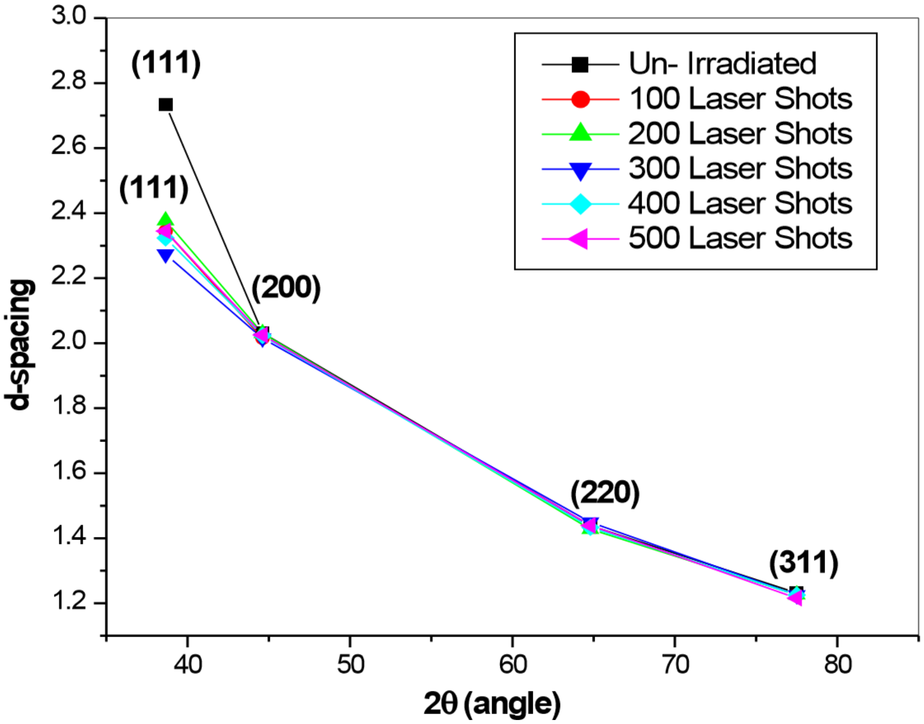

Fig. 6: d-spacing as a function of 2θ

Surface Hardness Profile for fixed Number of Laser Shots

Un-irradiated

Figure 7 depicts, the value of hardness for un-irradiated Al samples. Measurements are taken at various points having separation of 0.5mm between each straight line up to a specific distance that is 3mm from the center on, the surface of the specimen. The value of hardness for un-irradiated Al specimen lies in the range of 29.5 - 31.5MPa. Laser irradiance changes mechanical properties such as hardness of the material. The hardness analysis is conducted to investigate hardness of sample materials at different distances ranging from. The average hardness of the material at different positions is lower as compared to the laser irradiated material.

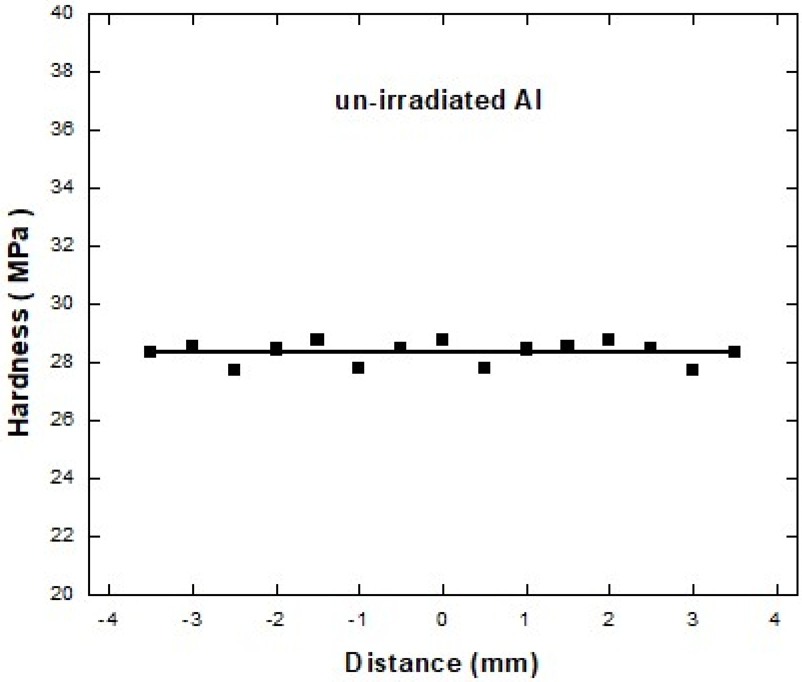

Fig. 7: Surface profile of un-irradiated Al alloy

100 Laser Shots

The surface profile of Al alloy irradiated with 100 laser shots is given below in Figure 8. The symbols denote the value of hardness at various points with a separation of 0.5mm up to a distance of 3mm from the laser spot on the target surface. The dashed line shows hardness of un-irradiated specimen. With increasing laser irradiation hardness of target surface has been increased from 29.45 MPa to almost 31.45 MPa which is 7.4% higher than the hardness value of un-irradiated specimen. Increase in hardness of specimen shows that after laser irradiation defects have been produced in the specimen [22]. The results of hardness for the laser irradiated Al is noticed that increases significantly as compared to the un-irradiated samples. The change in hardness is credited due to lattice disorder as observed in the XRD analysis. The changes in hardness is due to change in the thermal compressive stresses and crystal structure produce in the laser irradiated Al target. In laser irradiated Al due to laser induced heating effects thermal compressive stresses are produced.

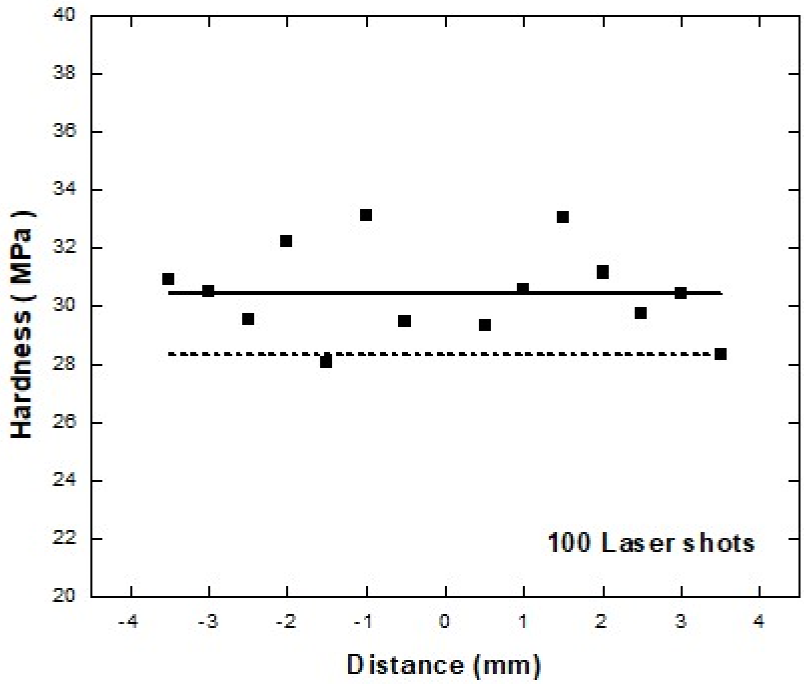

Fig. 8: Surface profile of Al alloy irradiated with 100 Laser shots

200 Laser Shots

Figure 9 shows the surface profile of laser irradiated Al with 200 laser shots. It can be seen that the average surface after laser irradiation with 200 shots has increased from 29.45 MPa to 31.9115 MPa which is 5.51% higher than the hardness of un-irradiated specimen while for 100 laser shots it has decreased by 1.79%. This decrease in hardness with respect to 100 shots might be due to the annealing process. The variation in the hardness at 200 shots is attributed to the micro structural defects. The increase in the surface hardness is due to increase tensile stresses that transforms in the compressive stresses. The transformation is due to decrease in crystalline size and increasing trend of hardness is observed.

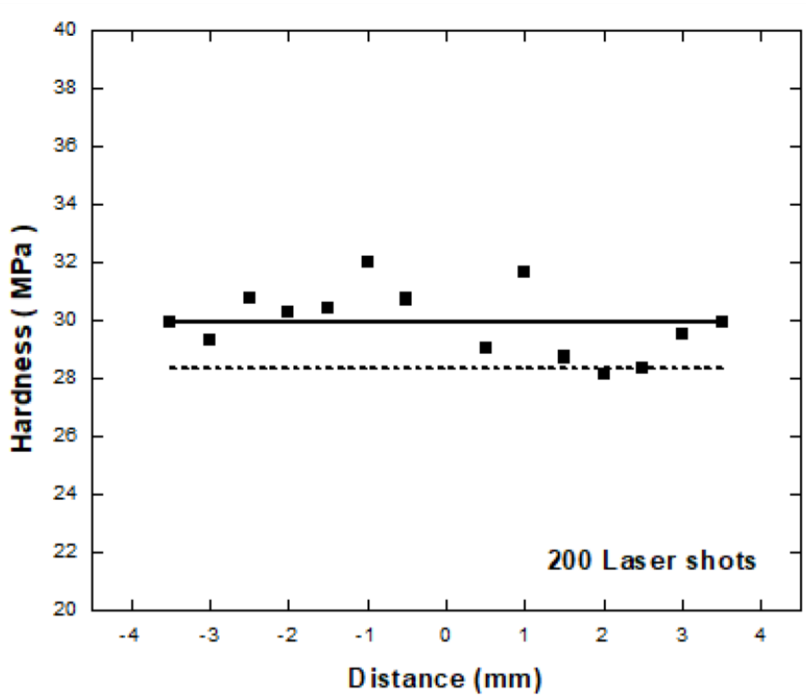

Fig. 9: Surface profile of Al alloy irradiated with 200 Laser shots

300 Laser Shots

The surface profile of laser irradiated Al with 300 laser shots is shown in Figure 10. The average surface hardness after laser irradiation with 300 shots has increased from 29.35 MPa to 30.1782 MPa which is 2.92 % higher than the hardness of un-irradiated specimen. But if we compare the hardness value of specimen irradiated with 300 laser shots to the hardness value of 100 and 200 shots irradiated specimen then it can be observed that hardness has decreased by 4.35% and 2.51% respectively. This decrease in hardness indicates that with increase in laser shots up to 300, the process of annealing is dominating and defects have started reducing. The decrease in the hardness is due to large scale atomic disorder-ness at different orientations. The dislocation enhances repulsive forces and results in deformation of irradiated material. At 300 laser shots the mechanism of dislocation leads to material energy localization and softening of the target material. At boundaries of crater, as represented in figure 14, diffusion due to refilling of the crater is observed, this process is responsible for reduction of hardness and softening of material.

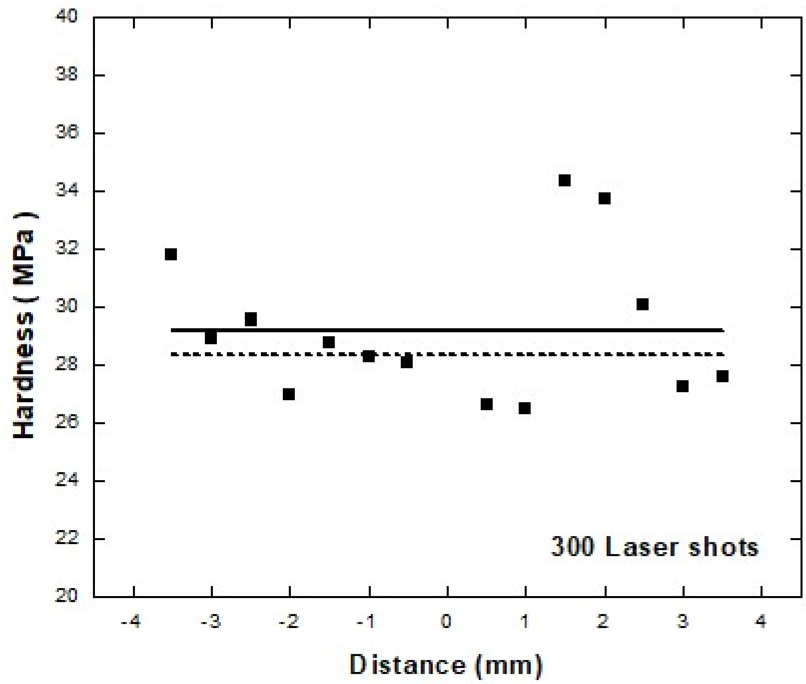

Fig. 10: Surface profile of Al alloy irradiated at 300 Laser shots

400 Laser Shots

Surface profile of laser irradiated Al alloy specimen with 400 laser shots is shown in Figure 11. As we can see that value of hardness of specimen irradiated with 400 laser shots is almost at the same level as for the un-irradiated specimen. It can be due to processes of defects generation and annealing are in equilibrium. The hardness value for un-irradiated specimen is 29.45 MPa while for irradiated with 400 shots is 29.31 MPa. The decrease in residual stresses and crystalline size with increasing laser shots is observed. This decrease in hardness is due to enhanced compressive and residual with higher diffusion. The results are compatible with optical microscopy analysis of laser irradiated Al samples as shown in figure 14.

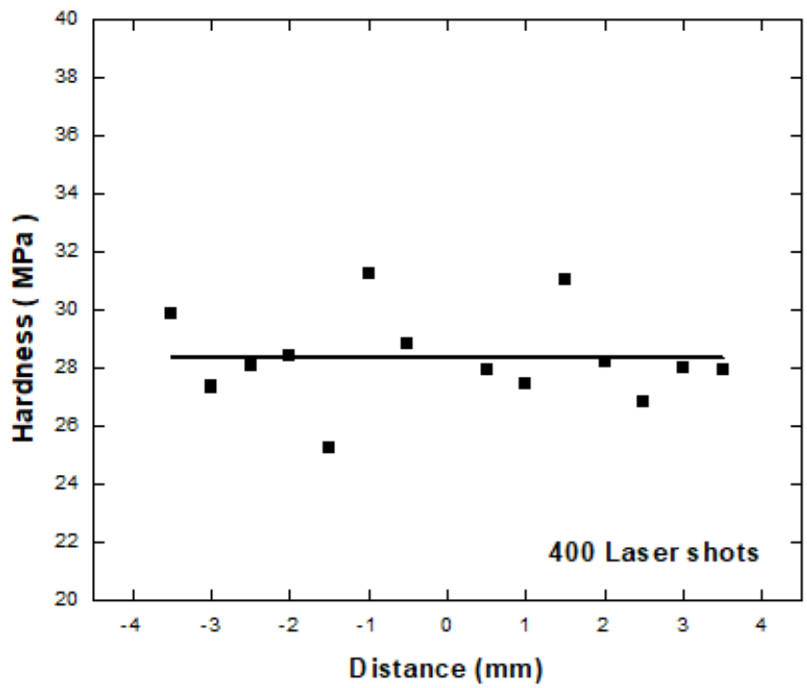

Fig. 11**:** Surface profile of Al alloy irradiated with 400 Laser shots

500 Laser Shots

The surface profile of Al alloy after 500 laser shots is shown in Figure 12. At 500 laser shots value of hardness again increases thus increasing defects in the specimen. The value of hardness has increased from 29.45 MPa to 30.94 MPa which is 2.08% higher.

The results of hardness are also compatible with variation in peak intensities and d-spacing of different laser pulses. The change in d-spacing is observed due to variation in lattice distortion and residual stresses. The lattice distortion is observed due to variation in the inter atomic distances, cooling conditions in the layers of irradiated surface, interstitial diffusion, thermal expansion coefficient, and heating in lattice planes. At 100 shots the peak intensity (200) increased due to crystal growth and the atomic diffusion across the boundaries of crater. With further increase in the laser shots the decrease in peak intensity is observed due to recrystallization, re-solidification, and laser induced melting. The decrease in plane intensity at (200) shows disintegration of large size grains on target surface into the smaller size and results in attenuation. With further increase in laser shots crystalline size decreases due to higher energy deposition on the surface that produces lattice strains due to interstitial diffusion of the target Al. At higher number of laser pulses, laser induced defects are generated that reduces crystalline size and act as barrier for the dislocation motion. The energy absorbed in the target material is utilized to generate new dislocation defects due to vibration or distortion and increases the mobility of already existing dislocation defects. At higher number of laser shots, the shock waves and lattice distortion is generated. In the irradiated Al higher tensile and compressive stresses are generated, the heating and cooling process generates great temperature gradients and produces localized heating along with plasma dynamic flow. These are the main reasons for the development of residual stresses in the surface of irradiated Al targets.

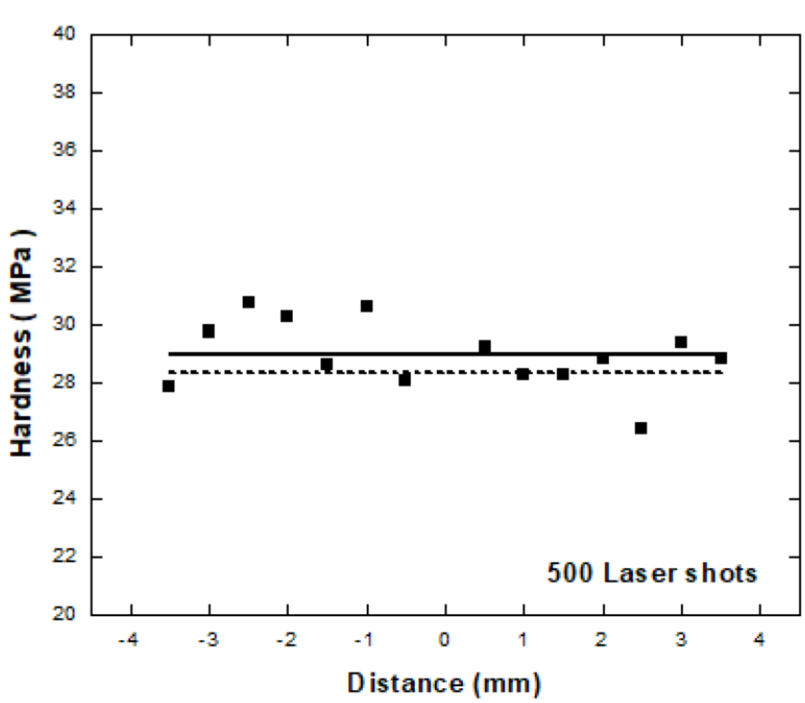

Fig. 12**:** Surface profile of Al alloy irradiated with 500 laser shots

Number of Laser Shots and Average Surface Hardness

The average value of surface hardness of un-irradiated specimens at different points on the surface was found to be 29.4591 MPa. The data for ave. surface hardness of un-irradiated and the specimens irradiated with various no. of laser shots has been tabulated in given below table.

Table 3: Average surface hardness (MPa) of Al under successive laser shots

Laser Shots	Ave. Surface Hardness (MPa)
0	29.4591
100	31.45
200	29.9115
300	30.1782
400	29.3157
500	30.9472

The data in the Table 3 shows that average surface hardness value for 100 laser shots has increased from 29.4591 MPa to 31.448 MPa. This is because laser irradiation has produced defects in the specimen which in turn increase hardness [5, 23].Then the value of average surface hardness decreases and becomes approximately equal to the un-irradiated level, as the laser shots are increased to 400 indicating that laser irradiation may have caused enough heating for the defects to be annealed out. Afterwards increase in average surface hardness value was observed with increasing laser shots up to 500. A plot of ave. surface hardness values of Al alloy verses laser shots is shown in Figure 13.

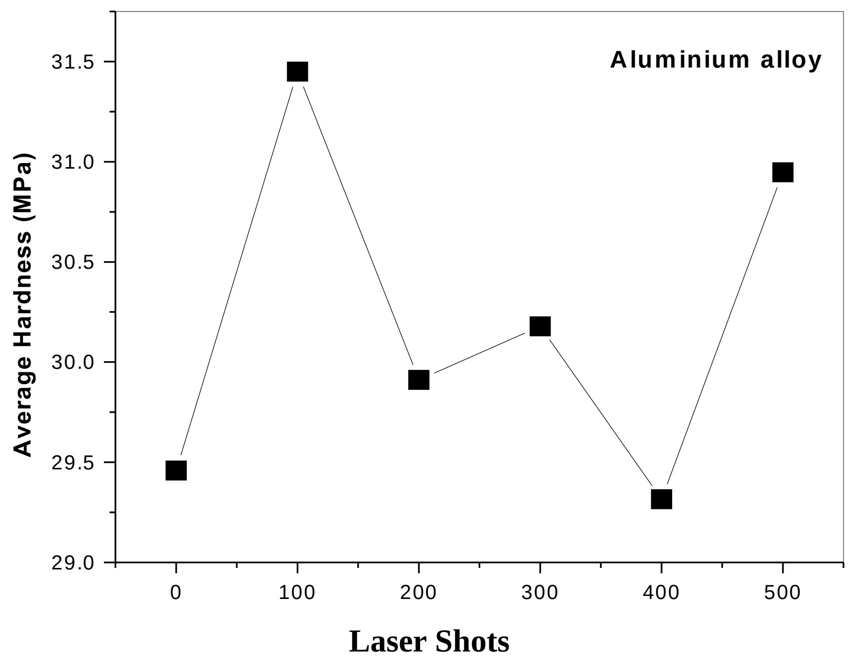

Fig. 13: Average surface hardness of laser irradiated Al surface verses laser shots

Optical Microscopy

The surface of the optical micrograph of laser irradiated Aluminum alloy samples were taken with a reflection mode optical microscope (produced by Olympus) with an amplification of 10x. Figure 14. (a, b, c, d and e) shows the area affected by the temperature, together with the area heated by the laser due to irradiation with 100, 200, 300, 400 and 500 shots respectively. Figure 14 shows that the surface of the non-irradiated Aluminum alloy samples is relatively smooth comparative to the exposed sample. The shape of the area exposed by the laser is not expected due to the changing heat conduction around the area of the molten laser.

In the laser produced crater major and minor half-axis of the ellipse of the values of different parameters are drawn around the area affected by the heat radiated by the laser and also its depth, perimeters and the area enclosed by it are shown in Table 4. The crater size depicts value of the semi-major axis and the minor half-axis increases by increasing number of laser shots. The relationship between the number of laser shots and depth of each specimen as shown graphically in figure 17. The depth of irradiated area is increasing gradually increase in number of laser shots.

The relationship between the perimeters of high temperature pretentious region and amount of laser shots is explicitly as shown in figure 15. The perimeters go on growing with growing amount of laser shots.

The major semi axis and the minor semi axis of ellipse are drained round the temperature exaggerated area as shown in figure 14 (a, b, c, d and e) and figure 15 depicts the relation between the number of laser shots and beam affected area as shown in figure 15. The beam affected area goes on gradually increasing as the laser shot increases.

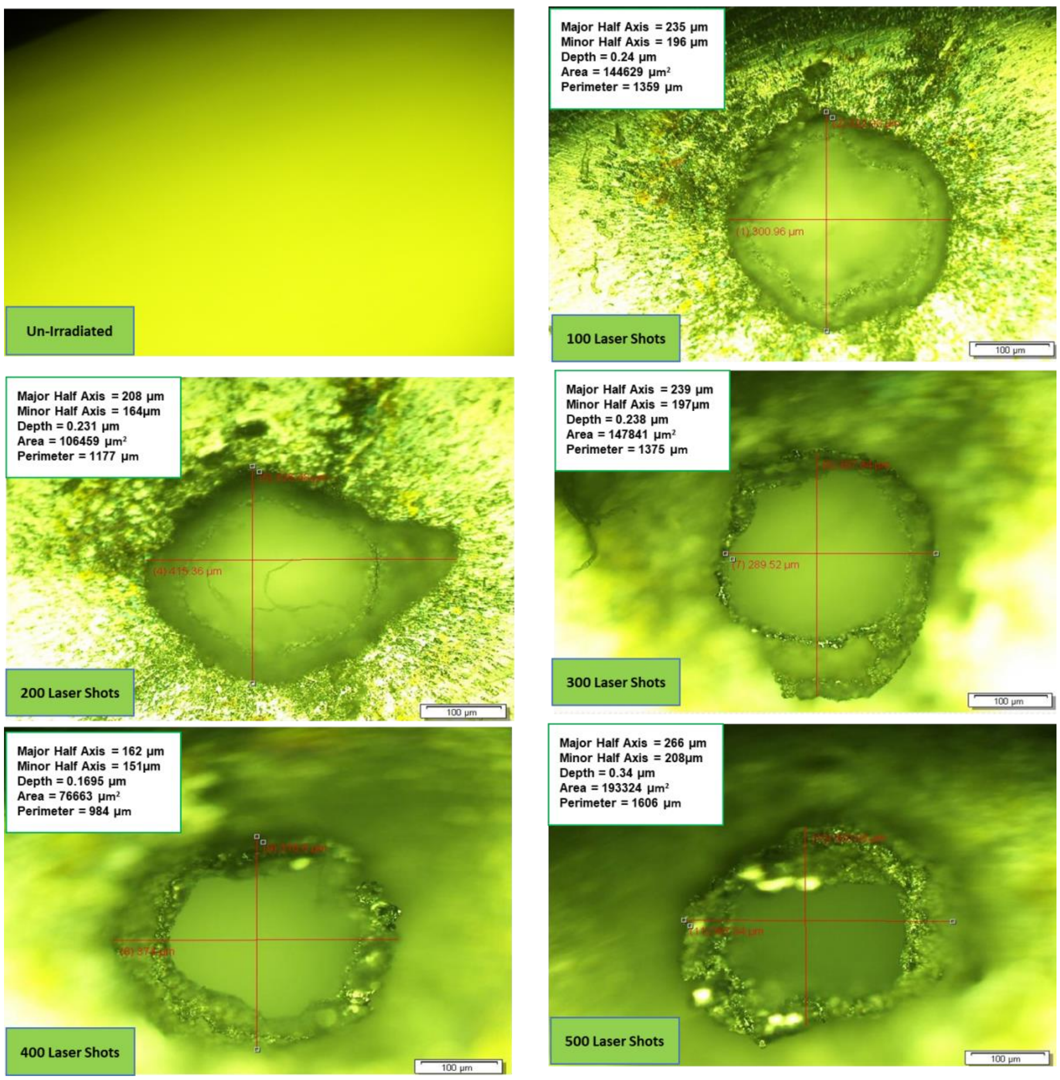

Fig. 14: Optical micrograph of Al alloy surface of un-irradiated and laser irradiated Al (Alloy) after increasing number of shots 100,200,300,400, and 500 as shown in (a, b, c, d and e)

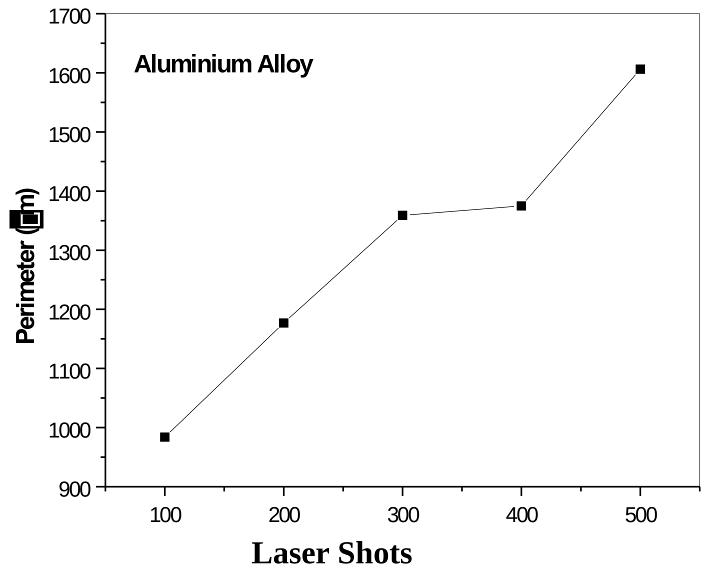

Fig. 15**:** Ellipse perimeters of laser irradiated Al alloy

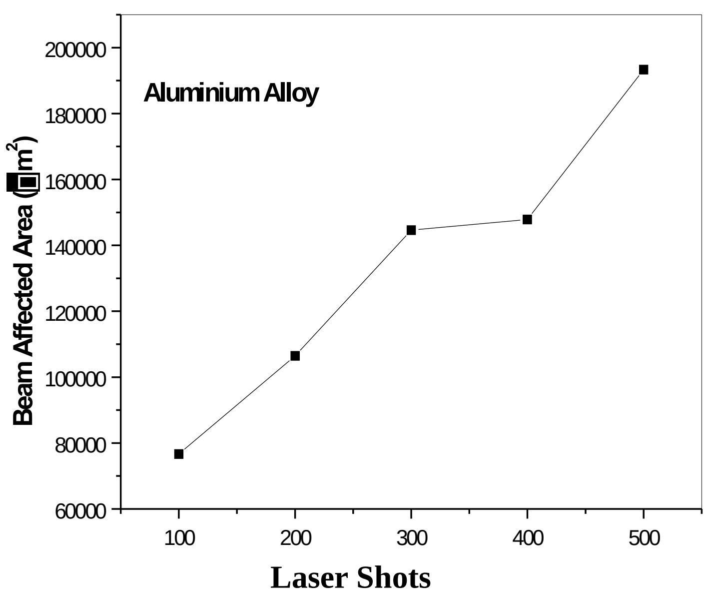

Fig. 16: Beam affected area verses laser shots

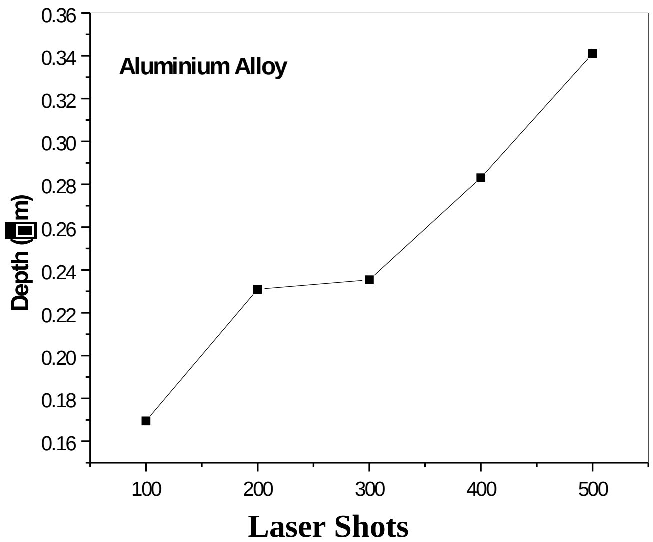

Fig. 17: Depth Vs number of laser shots of Al alloy

Table 4: Values of different parameters of laser irradiated Al alloy

Laser Shots	Major Half Axis (µm)	Minor Half Axis (µm)	Depth (µm)	Perimeters (µm)	Area (μm^2)
100	162	151	0.1695	984	76663
200	208	163	0.231	1177	106459
300	235	196	0.254	1359	144629
400	239	197	0.283	1375	147841
500	296	208	0.34	1606	193324

Tensile Test Results

Stress strain curves of Aluminium alloy specimens of un-irradiated and irradiated with Nd:YAG laser for 100, 200, 300, 400 and 500 laser shots are exhibited in figure 17. The comparison of all these curves reveals that the Ultimate Tensile Stress (UTS), Fracture Stress (FS) and maximum percentage elongation, almost same for 100 laser shots. When the laser shots increase to 200 then the FS and the UTS decreases this decreases trend shows that the material drop its ductility with rapid increase in laser shot. Through distortion the displacement changes along their slip planes under application of functional stress. The movement of dislocation is vulnerable due to the penetrating of disruption with the laser irradiation brought defects.

When the laser shots increased to 300 and 400 it produces sufficient heat due to which increases the UTS and FS. The improvement of the UTS and FS of un-irradiated and irradiated target are co-related with the dislocation line density and the crystallite size. When the UTS and FS decreases then the crystallite size increases and the dislocation line density decrease.

When the laser shot increases to 500 then the crystallite size increases and dislocation line density decreases. This shows that the material loses its ductility with increase in laser shots and hence decrease the UTS and FS. The tensile characteristic of Al alloy shows the inconsistent conduct because of the variation in laser shots number.

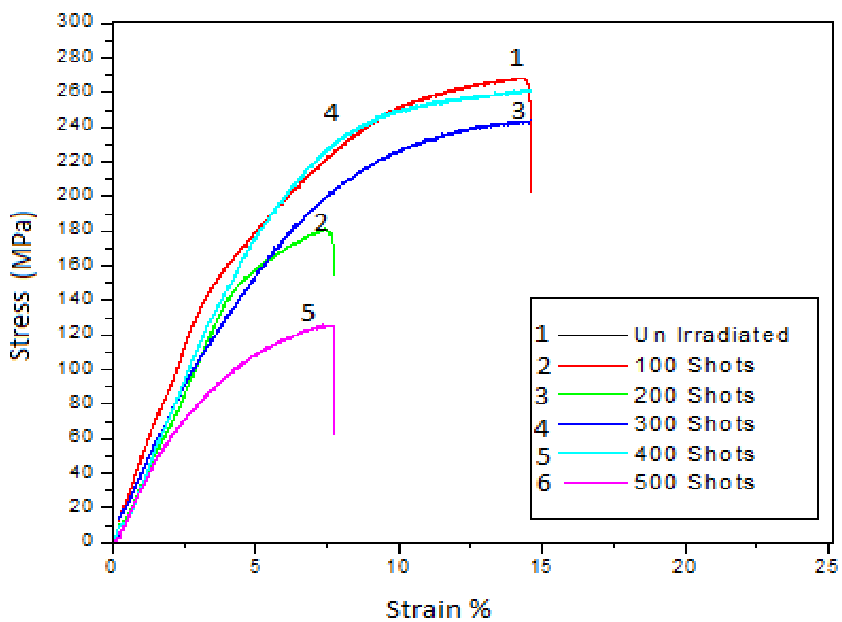

Fig. 18: Stress, Strain curve for irradiated & Un- irradiated Al alloy for (2) 100, (3)200, (3) 300, (4) 400, and (5) 500 shots.

Table 5**:** Results of Ultimate Tensile Strength (UTS) and Fracture Stress (FS) for irradiated &Un- irradiated Al alloy targets

Laser Shots	Ultimate Tensile Strength (MPa)	Fracture Stress (MPa)	Percentage Elongation Strain (%)
Un-irradiated	274.27	140.98	22.62
100	274.25	136.81	22.64
200	187.15	134.61	9.25
300	249	180.52	14.42
400	276.85	235	22.31
500	132	100.72	9.41

Conclusions

There is a difference in the diffracted peak intensity due to the defect formation. It is observed that there is no extra peak found by increasing no. of laser shots, and max. intensity is observed at (200) plane for all laser shots because of the domination of annealing process, and minimum intensity observed at (220) plane. The preferred orientation remains same for all the planes after laser irradiation. No significant change was observed in d-spacing of laser irradiated Al (Alloy) targets. By increasing laser shot the shape of the laser exposed heat affected area is un-expected due to the changeable heat conduction around the laser molten zone and depth of heat affected area also increases. Laser ablation of the specimen resulted in boiling, splashing and crater formation on its surface. The size of crater initially increases and then gradually decreases with increasing number of lasers shot. The tensile properties of Al alloy show the inconsistent behavior due to the variation of number of laser shots. The average value of surface hardness of un-irradiated specimens was found to be 29.4 MPa. Upon irradiation with 100 laser shots there is an increase of 7.4% in surface hardness. Then its value falls almost to the un-irradiated level, as the laser shots are increased from 100 to 400 indicating that further laser irradiation may have caused enough heating so that the lattice defects produced due to irradiation were annealed out. Afterwards 3.7% increase in average surface hardness is observed with an increase in laser shots up to 500.

Author's Contribution:

N.A[1] & I.M.G, Conceived the idea; M.Q & R.Z, Designed the simulated work and acquihired data; N.A[1]& N.A[3], executed simulated work, data analysis and interpretation of data and wrote the basic draft; S.R, & S.N, Did the language and grammatical edits or Critical revision

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