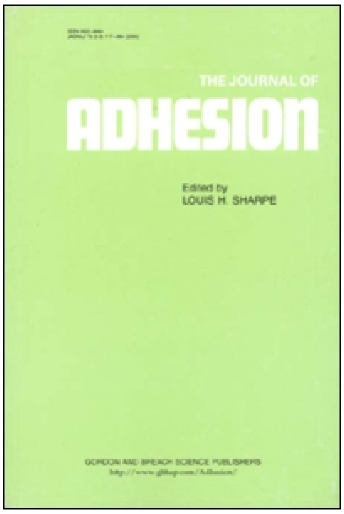

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Microstructure Characterization of Laser Treated Surfaces

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Excimer laser UV radiation presents a new technology for preadhesion surface treatment of various material adherends. The application of an ArF Excimer laser (193 nm) for surface pretreatment of polycarbonate, polyetherimide, PEEK composite, glass reinforced epoxy composite, aluminum, copper, magnesuim. PZT and fused silica was investigated. Experimental results indicated that UV laser surface treatment improved the adhesional strength significantly compared with conventionally-treated substrates for all the materials tested. The improved adhesion correlated with changes in morphology of the irradiated surface, chemical modification and removal of contaminants, which contributed to a strong and durable adhesive bond. This paper will concentrate only on the connection between the mechanical and morphological effect. The most common microstructure features on the surface after laser irradiation (examined by SEM and AFM) were small conical structures randomly distributed on the irradiated areas. Other features were periodic surface ridges or flat smoothened areas with spread arrays of microcracks. All these morphologies increase the roughness of the surface, enabling mechanical interlocking of the adhesive. It should be noted that the roughness is micron-sized, and uniformly spread on the surface, which presents an advantage over abrasive treatments. The distribution of the features and their size were dependent on the laser parameters (intensity and number of pulses). Some mechanisms are presented, and these interesting phenomena are discussed.

Keywords: Excimer laser; Microstructure; Adhesional strength; Surface treatment; Mechanism

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INTRODUCTION

Strength and durability of bonded joints are affected by various factors such as the nature of the substrate, its cleanliness, the nature of the adhesive, its curing cycle and stresses in the joint and mainly by interfacial interactions (physical and chemical). In order to improve adhesion, the common methods used are mechanical roughening, chemical modification, removal of weak boundary layers and moderation of stresses, and proper wetting. Applying proper surface treatment to the adherend is among the decisive factors with respect to the final quality and durability of an adhesive joint. Many treatments have been devised for preparing the surfaces of materials for adhesive bonding, coating and the like. The general purpose of these preparation procedures is to modify the original surface of the adherend material: (a) to promote development of interfacial bonds with adhesives and (b) to enhance the environmental resistance to moisture and humidity effects. Various materials (metals, plastics, composites and ceramics) require different surface treatments, some examples of which are detailed below.

Present processes for prebond surface preparation of thermoplastics, composites, ceramic adherends and metals involve the use of silicate "powders", acids (sulfuric, nitric, hydrochloric), strong bases or hexavalent chromium compounds. OSHA and EPA regulations ban such chemicals in industrial operations. In recent years, the intensified development of ultraviolet (UV) and infrared (IR) laser systems has led to an increasing tendency to use these devices in various process applications. The outstanding feature of UV laser radiation is its ability to break chemical bonds, to cause chemical reactions on the irradiated surface due to photochemical effects, and to build new microstructure morphology which modifies the surface and enlarges the surface area. The feature of IR laser radiation is its ability to ablate material surfaces, due to thermal effects. It was found that the effect of an excimer laser exceeds the effect of an IR laser in treating surfaces for adhesive bonding. Recently, an excimer laser was used for preadhesion surface treatment of metals, thermoplastics and ceramic [1] and an IR laser for treatment of reinforced plastics [2].

Laser treatment provides a clean and rather simple method of surface preparation and reduces the extent of damage to the treated surfaces.

In our present paper, the application of an ArF excimer laser (UV range at 193 nm) for surface treatment of thermoplastics, Ultem® and Lexan® and a carbon fiber reinforced thermoplastic (PEEK) composite [3], aluminum [4] and sealed anodized aluminum coating [5], copper, Invar®, magnesium [6], PZT and fused silica was investigated.

This paper concentrates on one aspect of the laser irradiation effect, mainly the change in morphology and the microstructure of the surface resulting from this treatment.

EXPERIMENTAL

Laser Treatment

The laser used during the course of this investigation was an ArF excimer laser model EMG 201 MSC (Lambda Physik, Germany). The laser parameters: repetition rate (5 – 30 Hz), energy density (0.9 – 4 J/P cm^2) and number of pulses (1 – 5000) were varied and optimized according to morphological appearance and adhesional strength. Optimization was achieved by conducting experiments over the total range of energy and number of pulses. At least thirty experiments with five duplicates for each experiment were conducted. All the adhesion strength tests of the laser-treated adherends resulted in optimum curves. The optimum point was chosen as the optimal laser condition. All experiments were conducted at ambient temperature and in an air environment. The investigated samples were irradiated by scanning the surface with the laser beam. The movement of the samples was governed by an X-Y computerized table.

Materials

Table 1 lists the adherends and adhesives tested during the course of the investigation. The various conventional surface treatments used for each material are described in Table 3.

Testing

The various substrates were treated with an excimer UV laser at different values of parameters such as intensity, repetition rate and

TABLE 1 Adherends and adhesives tested

Adherend	*Commercial (Producer)*	*Adhesive (Producer) Curing Conditions*
Polycarbonate	Lexan® 9023-112 (GE)	Two-Component Polyurethane, (Hexcel, USA), RT*, 48 Hrs
Polyetherimide	Ultem1000® (GE)	Two-Component Polyurethane, (Hexcel, USA), RT, 48 Hrs
Composite PEEK (Polyaryl-ether-ether-ketone) Reinforced with Continuous Carbon Fibers	APC-2/AS-4(ICI)	Structural Epoxy Adhesive -FM 300 2K (American Cyanamid) 2 Hrs, 120°C, 40 psi -AF 163-2 OST, (3M), 1 Hr, 120°C, 35psi
Aluminum	2024-T3 (Alcoa)	-Rubber Modified Epoxy Adhesive (Rafael), RT, 48 Hrs -Structural Epoxy Adhesive FM 73 (American Cyanamid) 2 Hrs, 127°C, $1.8 \cdot 10^3$ torr
Sealed Anodized Aluminum	2024-T3 (Alcoa), -Chromic acid anodization -Sulfuric Acid anodization	Rubber Modified Epoxy Adhesive (Rafael), RT, 48 Hrs
Copper	Electrolytic copper (Alfa)	-Rubber Modified Epoxy (Rafael), RT, 48 Hrs -EA9394 (HYSOL), RT, 5 days
Fiberglass Epoxy/Copper	F-4 (Sefan, Il)	-Rubber Modified Epoxy (Rafael), RT, 48 Hrs -Acrylic Adhesive F0011 (3M) 110°C, 20 min. 15psi
Copper Coated fiberglass Epoxy/Polyimide	F-4/Kapton® (DuPont)	-Rubber Modified Epoxy, (RAFAEL), RT, 48 Hrs -Acrylic Adhesive F0011 (3M) 110°C, 20 min. 15psi
Magnesium	AZ 91, AM 50, (Ortal, Il.)	-Modified Epoxy (3M), RT, 48 Hrs
PZT (Piezoelectric wafer—Pb,Zr,Ti)	5A (Morgan Matroc Inc.)	-LaRC—SI (IMITEC), 320°C, 35psi, 20min.
Invar/Fused Silica	(Alfa/Rafael)	-RTV159 (GE), RT, 24 Hrs.

*RT—Room Temperature.

number of pulses (Table 2). The adherends were bonded 2–4 days after laser treatment (maximum shelf life of the laser treatment was found to be 14 days without aging). The optimal laser treatment for each material was defined by achieving the maximal shear strength of the corresponding bonded joint. Joint properties were determined using

TABLE 2 Optimal laser parameters for the various adherends treatment

Adherend	*Laser Fluence* $J/P\cdot cm^2$	*Repetition Rate* *Hz*	*No. of Pulses*
Polycarbonate	0.08	10	12
Polyetherimide	0.08	10	200
Composite PEEK	0.19	5	100
(APC2/AS4)	1	5	10
Aluminum Alloy	0.19	30	2000
Sealed Anodized	0.8	30	1000
Aluminum Alloy	1.9		100
Copper	2.7	10	50
Fiberglass Epoxy/	0.18 (F4)	30	100
Copper	2.1 (Cu)	30	50
Copper/	0.18 (Cu)	30	1000
Polyimide	0.18 (Kapton)	30	100
Magnesium	0.4	20	100
PZT	2.2	10	10
Invar/Fused Silica	2.2	30	10

the Single Lap Shear (SLS) test according to ASTM D-1002-72. Specimens were tested, 4 days after preparation, in an Instron machine, model 1185, at a cross-head speed of 2 mm/min. The mode of failure was determined visually.

Two types of surface-treated reference samples were used for each set of experiments (see Table 3). For the thermoplastics and composites, the references were untreated and/or abraded with SiC (36 mesh). For the aluminum and sealed anodized aluminum adherends the references used were untreated aluminum and unsealed chromic acid anodized aluminum according to MIL-B-8625, respectively. For the copper the references were samples with a conventional black oxide treatment (Ebonol®) or sand blasting, for the glass-epoxy composite the reference was a sand-blasted sample and for the Invar®, magnesium and aluminum the references were samples abraded with alumina (80 mesh).

The morphology of the UV-laser-treated adherends was studied by SEM (Scanning Electron Microscopy) and AFM (Atomic Force Microscopy). AFM's advantage over the SEM is the fact that it allows atomic resolution of non-conductive-surface materials without further coating or treating of the examined surface.

TABLE 3 Adhesive strengths and failure modes of the various bonded joints studied

	Surface Treatments		
Adherends/Adhesives	*Untreated SLS (Failure Mode) [MPa]*	*Conventional SLS (Failure Mode) [MPa]*	*Laser Treated SLS (Failure Mode) [MPa]*
Polycarbonate/PU	3.5 (A)[a]	5.0 (M) SiC	7.5 (C)
Polyetherimide/PU	2.5 (A)	5.0 (M) SiC	5.5 (C)
Composite PEEK (APC2/AS4)/			
Structural epoxy FM 3002K	6.1 (A)	14.7 (M) SiC	27.8 (M)
Structural Epoxy AF 163-2	21.7 (A)	34.0 (M) SiC	45.4 (C)
Aluminum alloy/ Rubber Modified epoxy	2.0 (A)	10.2 (C) Unsealed anodization	14.3 (C)
Sealed anodized Aluminum alloy/ Modified epoxy	4.5 (A)	10.2(C) Unsealed anodization	11.0 (C)
Copper/modified epoxy	6.1 (A)	14.9 (C), Sand	14.3 (C)
Magnesium (AZ 91)/ mod. Epoxy	15.6 (A)	21.8 (M/C), Alumina	24.3 (C)
Invar/fused silica/RTV	—	3.6 (A) Alumina	5.6 (C)

± 5% standard derivation (five samples for each test).
[a]A - interfacial; M - mixed; C - cohesive mode of failure.

SEM was performed with a JSM-840 (JEOL, Japan) model. Surfaces were Au/Pd sputtered prior to analysis to avoid charging.

AFM analysis was performed on a Nanoscope II SPM (Digital Instruments, Inc., Santa Barbara, CA, USA) operating in the contact mode with a silicon nitride cantilever tip in air and at room temperature. The scan size was 5000 nm^2 and the reference force was 2 pN. The AFM worked in a contact mode; a cantilever tip (SiN tip, atomically sharp) of known natural resonance was brought in contact with the examined surface and pushed against it to a predetermined force (reference force). The change in the tip resonance determined the forces on the surface. A laser-photodiode system with a piezoelectric feed-back loop kept this force constant on the surface, as the tip was rastered across the sample. The change in voltage in the piezoelectric device with the raster gave rise to a 3-D plot of the specimen surface [7]. The minimum, maximum and average roughness were plotted to determine the uniformity of the surface microstructure.

RESULTS AND DISCUSSION

Mechanical Results

Table 2 summarizes the optimal laser treatment parameters for each of the materials tested. As can be seen from the results, different conditions are required for the different adherends tested. Pure polymers, which are easy to activate, require the least intensity for laser treatment (~ 0.1 J/P·cm^2). Composites, which are more inert, require higher energy ($\sim 0.2-1$ J/P·cm^2) and metals and ceramics which have strong chemical bonds require very high energy (> 2 J/P·cm^2).

Table 3 summarizes the maximal lap shear strength achieved for the various bonded adherends when applying the optimal laser parameters (Table 2), compared with either nontreated or conventionally-treated ones. The results indicate that ArF excimer laser treatment is effective for all the different adherends treated and bonded, and it has an advantage over the conventional treatments.

Visual inspection of the failure surfaces clearly shows that the laser treatment causes the mode of failure to change from interfacial in non-laser treated adherends to mixed or cohesive at optimal laser operation conditions, indicating that the interfacial adhesion was significantly improved.

SEM Results

SEM micrographs of laser-treated adherends revealed morphological changes depending on the adherend material, laser energy and the number of pulses. The surfaces of the thermoplastic (polycarbonate and polyetherimide) adherends exhibited conic and rounded granules spread all over the surface (Figs. 1a and b). The carbon-fiber-reinforced PEEK composite exhibited the same characteristic granules accompanied by partial exposure of the fibers (Fig. 1c), at laser intensities of $0.1-0.2$ J/P·cm^2, while at higher laser intensities (above 1 J/P·cm^2) the laser-irradiated surface was smooth with randomly spread cracks (Fig. 1d) caused by mild ablation.

SEM micrographs of the Al adherends after laser treatment showed no morphological changes at low laser intensities ($0.18-0.2$ J/P·cm^2). Increasing laser intensity (0.7 J/P·cm^2) reveals a fine microstructure on

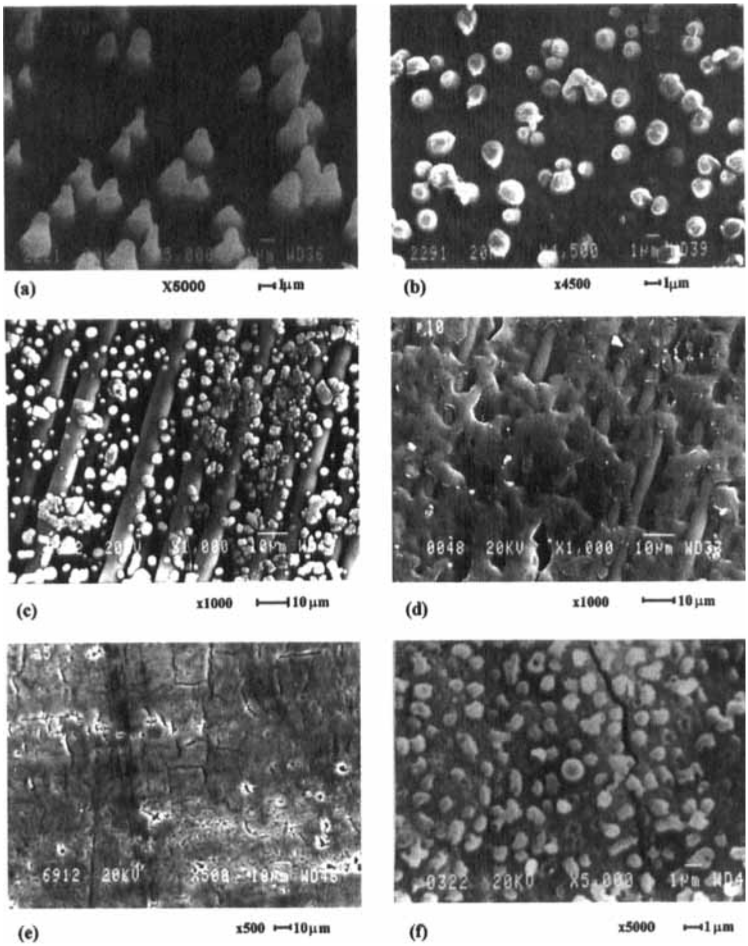

FIGURE 1 SEM micrographs of a) Polycarbonate treated with excimer laser (0.085 $J/P\cdot cm^2$, 12 pulses), b) Polyetherimide treated with excimer laser radiation (0.085 $J/P\cdot cm^2$, 200 pulses), c) Composite PEEK treated with excimer laser (0.18 $J/P\cdot cm^2$, 100 pulses), d) Composite PEEK treated with excimer laser (1 $J/P\cdot cm^2$, 10 pulses), e) Aluminum 2024-T3 treated with excimer laser (0.7 $J/P\cdot cm^2$, 200 pulses), f) Sealed anodized Aluminum 2024-T3 treated with excimer laser (0.7 $J/P\cdot cm^2$, 200 pulses).

the treated surface demonstrating arrays of cracks about 1 μm wide and small holes (Fig. 1e).

Irradiation of the sealed anodized specimens at low laser intensities (0.2 $J/P\cdot cm^2$) showed no change in surface morphology even after 1000 pulses. At 0.7 $J/P\cdot cm^2$ changes in morphology include open bubbles, resulting probably from evaporated water. Some spherical droplets of Al_2O_3 due to redeposition from plasma (caused by laser ablation of Al_2O_3) and surface cracks can be observed (Fig. 1f).

Irradiation of copper at low energy showed only color changes due to oxidation. At higher energies morphological changes were observed showing interconnected round spheres (elongated welts) spread evenly on the entire surface (Fig. 2a).

Irradiated glass-fiber-reinforced composites showed the same morphology as composite PEEK only the globes were surrounded by round circles which seemed like diffraction patterns (Fig. 2b).

Kapton at low energy showed features similar to cones sticking out from the surface (Fig. 2c), at high energy (Fig. 2d) the features are round globes similar to those observed for the thermoplastic adherends but of larger diameter (Fig. 1a,b).

Irradiated Invar® showed at low energies a change of color and at higher energy changes in morphology appearing as "moon-like" ridges and canals (Fig. 2e). At very high intensities (2.2 J/P.cm^2, 1000 pulses) the ridges formed into smooth shapes.

The fused silica showed no morphology change at low intensities but showed a morphology similar to sealed anodized Al at high intensity (Fig. 2f).

Laser-irradiated magnesium alloys showed a very uniform morphology of round "hills" and "valleys" surrounded by cracks and holes for AZ 91 alloy and square hills surrounded by cracks for AM 50 alloy (Fig. 3a,b). It should be noted that AZ 91 is more sensitive to laser treatment than AM 50 due to its chemical composition which contains Zn that is more active than Mn.

The same morphology as seen in fused silica was also observed on laser-treated PZT surfaces.

An additional interesting phenomenon was detected on the PZT when the treated surface became covered with a very thin coating of metal (Pb, about 30 Å) as observed by XPS. This metal results from breaking of the metal oxide bonds by the laser, leaving bare metal on the surface. A similar phenomenon was observed with irradiated AlN [7].

In our previous research on thermoplastics [4] it was found that the morphology depended on the laser energy and the number of pulses. The higher the energy supplied by the laser or the greater the number of

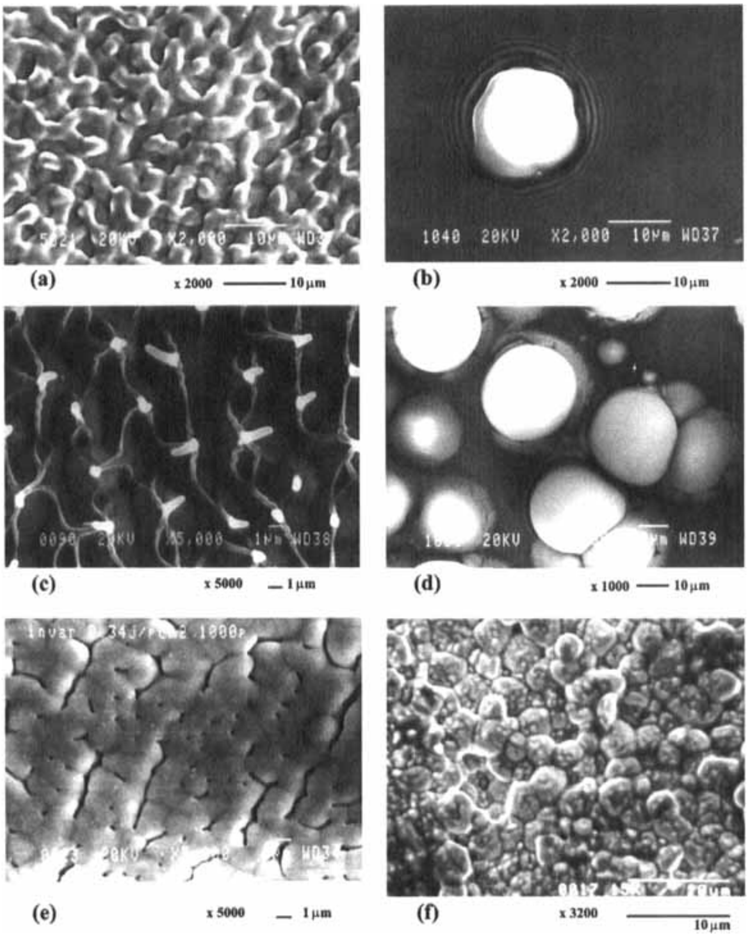

FIGURE 2 SEM micrographs of a) Electrolytic Copper treated with excimer laser (2.7 J/P·cm^2, 50 pulses), b) Epoxy Fiberglass treated with excimer laser (0.28 J/P·cm^2, 100 pulses), c) Kapton® treated with excimer laser (0.18 J/P·cm^2, 500 pulses), d) Kapton® treated with excimer laser (1 J/P·cm^2, 100 pulses), e) Invar® treated with excimer laser (0.34 J/P·cm^2, 1000 pulses), f) Fused Silica treated with excimer laser (2.2 J/P·cm^2, 1000 pulses).

pulses, the denser was the concentration of the granules on the surface and the smaller their size or the more agglomerated they became.

At high laser intensity or number of pulses, a weakening of the treated layer of the adherend was observed due to ablation. This is shown by loosely-connected granules at the thermoplastic surface,

(a)

(b)

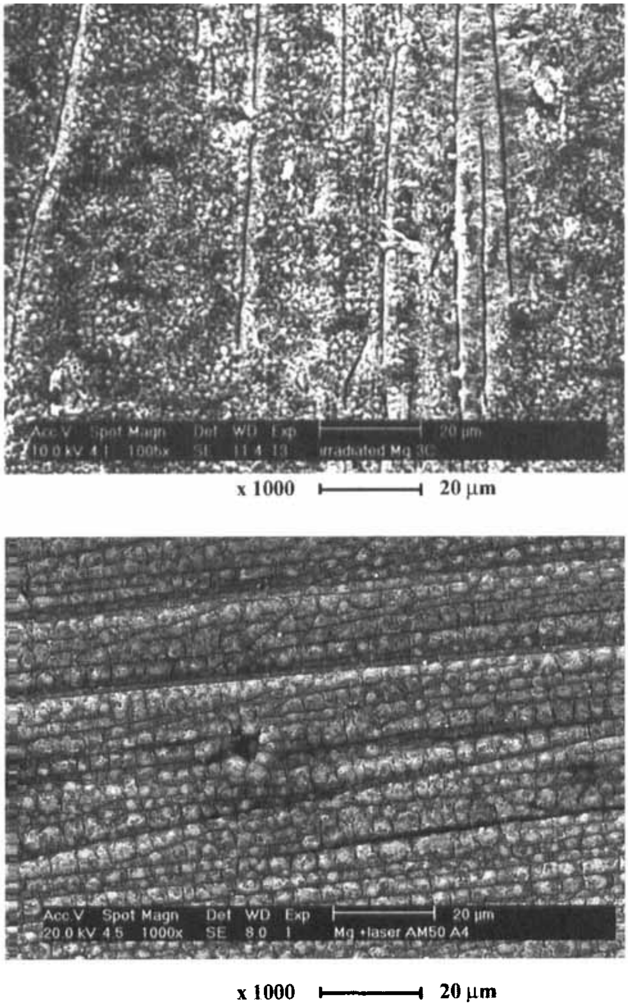

FIGURE 3 SEM micrograph of Magnesium alloys treated with excimer laser, a) AZ 91 (0.4 J/P·cm^2, 100 pulses), b) AM 50 (1 J/P·cm^2, 20 pulses).

deformed and exposed fibers of the composite, molten dendritic areas of the Al, magnesium, and anodized Al surface, loose spheres on the Cu surface, and molten areas in the irradiated areas of the fused silica and PZT.

All these morphologies increased the roughness of the surface, enabling mechanical interlocking of the adhesive. It should be noted that the roughness is very uniform and evenly spread on the surface, which presents an advantage over abrasive treatments.

The enhanced adhesion and cohesive type of failure due to mechanical interlocking was clearly revealed in the SEM micrographs at nearly all laser treatments and for all adherends tested. The cohesive mode of the failure (Table 3 and Figs. 4a and 4b) was indicated by an adhesive layer attached to each adherend showing a replica of the granules or bubbles formed during laser treatment. This far better

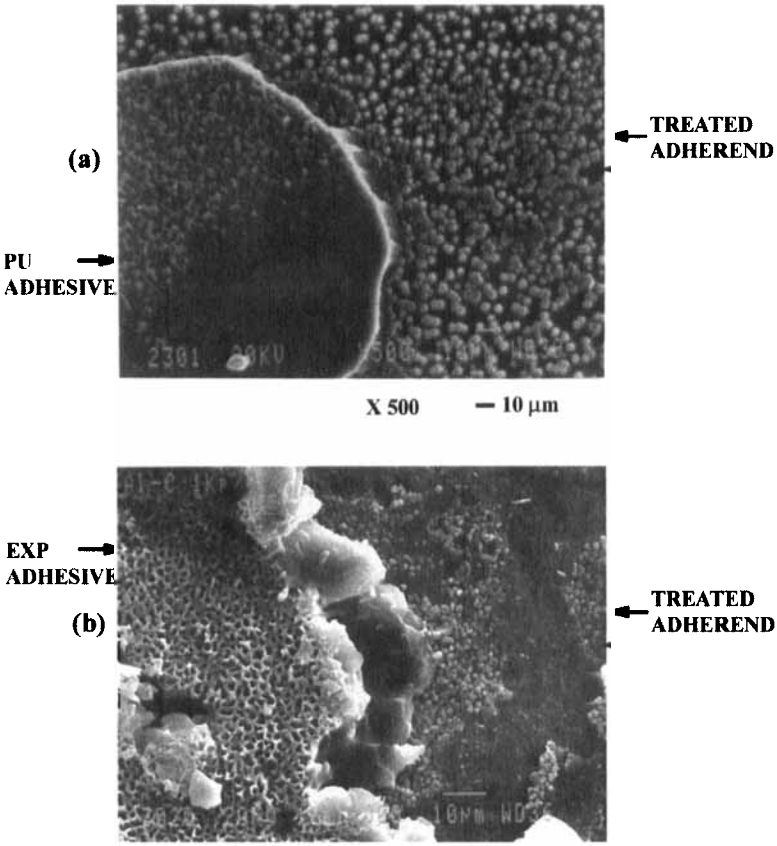

FIGURE 4 SEM micrograph of fractured joint surfaces (cohesive failure) of a) Polyurethane/Polyetherimide treated with excimer laser radiation (0.085 J/P·cm^2, 200 pulses), b) Sealed Anodized Al-Epoxy Adhesive treated with excimer laser radiation (0.8 J/P·cm^2, 100 pulses).

adhesion (partly cohesive failure) could be observed compared with the interfacial failure of the untreated adherend. Figures 4a and 4b represent the surface failure micrographs showing the replica formed during the cohesive failure of a thermoplastic joint and an anodized Al joint. The same phenomenon was also observed in the PEEK composite, Cu, glass fiber composite, Invar, magnesium and fused silica.

It should be noted that even if visually the failure seemed partly interfacial, high magnification showed that a thin layer of adhesive was always present on the laser-treated adherend.

AFM Results

The morphological modification was also investigated using an AFM/STM Nanoscope II microscope, which provides a high nanometer resolution, 3-D imaging of the surface and quantification of surface roughness at sub-nanometer reolution [8]. In order to analyze the results, polished surfaces were compared with non-polished ones before and after laser treatment. Table 4 summarizes semi-quantitative roughness measurements of the surfaces tested.

Table 4 shows that no matter what the original roughness of the Al and Cu adherend had been (polished or non-polished), the resulting roughnesses after laser treatment were roughly the same. The smoothening of the non-polished ceramic adherend by the laser was also emphasized.

The AFM results show that the carbon-fiber-reinforced PEEK exhibits increased roughness after low-energy laser irradiation (180 mJ/100P) (Figure 5a) and became very smooth at high energy (1J/P, 10P) (Figure 5b). A ridge-like pattern is clearly seen by the AFM/STM nanoscope, which is attributed to the periodic erosion of the surface of the same order as the wavelength of the laser (193 mm).

TABLE 4 Roughness measurements (in nm) of polished and non-polished surfaces

	Polished		*Non-Polished*	
Material	*Non-Treated*	*Laser Treated**	*Non-Treated*	*Laser Treated**
Al 2024	19.2 ± 3	39.1 ± 3	103.5 ± 8	23.6 ± 3
PEEK/C	—	—	33.2 ± 3	70.2 ± 5
Cu	19.3 ± 4	37.7 ± 5	148 ± 9	19.2 ± 3
Ceramic	—	—	178 ± 13	4.8 ± 3

*Optimal laser parameters (Table 2).

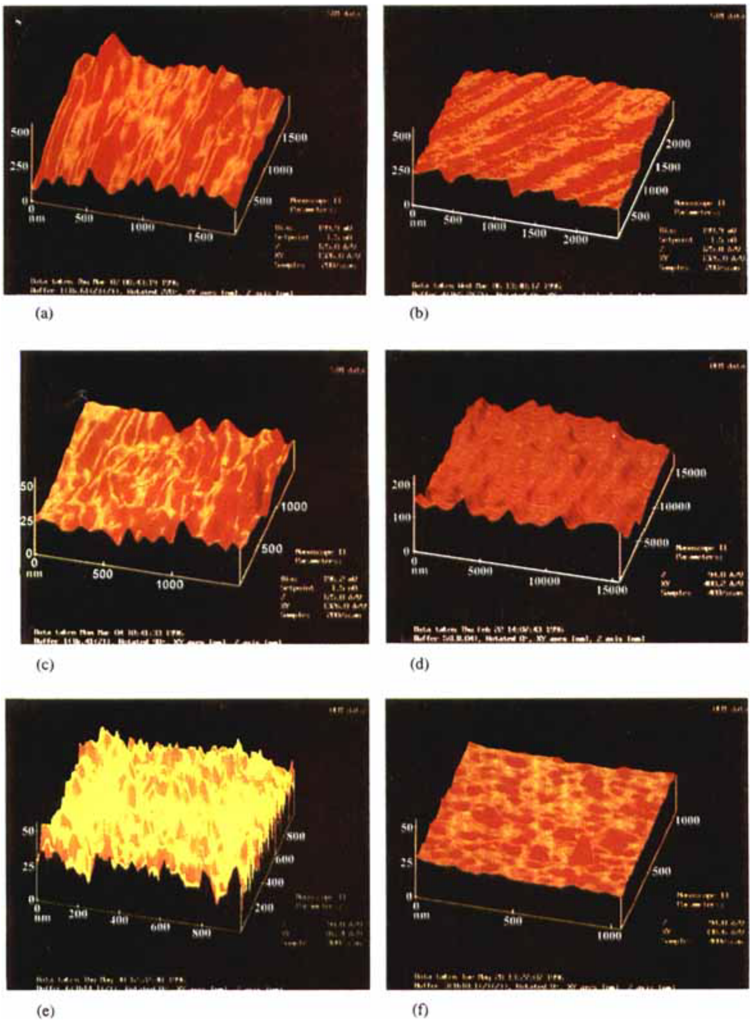

FIGURE 5 AFM contact mode image of a) Composite PEEK treated with excimer laser (0.18 J/P·cm^2, 100 pulses), b) Composite PEEK treated with excimer laser (1 J/P·cm^2, 10 pulses), c) Polished Aluminum 2024-T3 treated with excimer laser (0.7 J/P·cm^2, 200 pulses), d) Unpolished Aluminum 2024-T3 treated with excimer laser (0.7 J/P·cm^2, 200 pulses), e) Polished Copper treated with excimer laser (2.2 J/P·cm^2, 50 pulses), f) Unpolished Copper treated with excimer laser (2.2 J/P·cm^2, 50 pulses).

Al 2024 showed, as stated before, that no matter what the starting surface roughness was, after laser treatment all surfaces (polished or non-polished) showed the same roughened morphology (Fig. 5c and 5d).

Cu shows very rigid sharp features at low laser energy and round globules at high energy (Fig. 5e and 5f). These features were similar to the ones observed by SEM (Fig. 2a). The ceramic shows very uniform smoothening of the surface after laser treatment (Fig. 6).

Proposed Mechanisms

Some mechanisms were described in the literature [9] to explain the typical and common features created by laser treatment on most materials. Cones and globules were formed through shielding of the

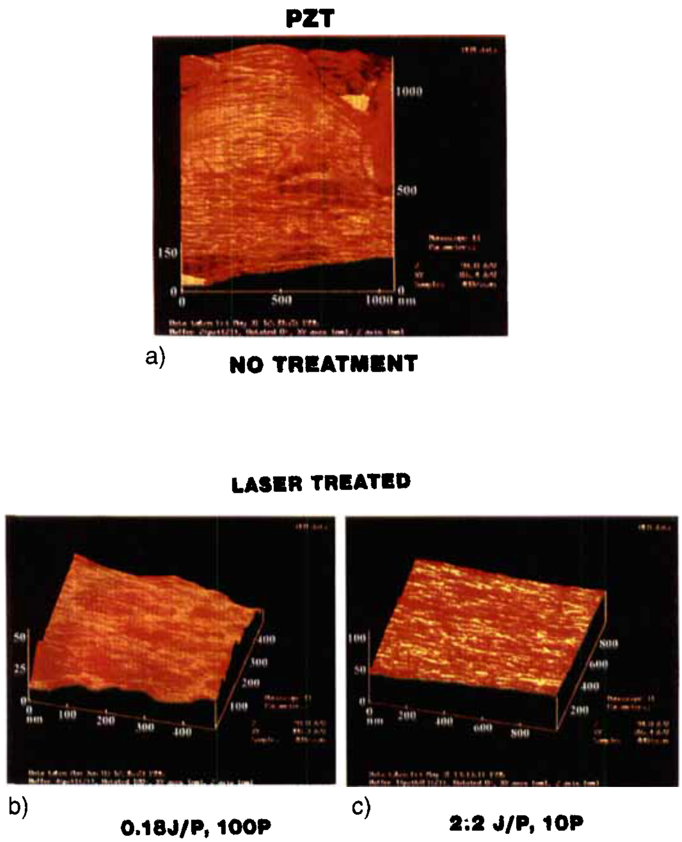

FIGURE 6 AFM contact mode image of PZT wafer treated with excimer laser (2.2 J/ $P \cdot cm^2$, 10 pulses).

target by focal defects at the polymer surface. The ablation-resistant defects (usually inorganic) prevented etching of the underlying polymer causing tiny raised areas surrounded by removable material. The walls of the raised features were sloped as observed by SEM and AFM. Eventually, the entire surface was covered with these conical features (for example see Figs. 1 – 3). The cones shielded the radiation and ablation stopped so that only the upper surface was affected by the laser and not the entire bulk. A schematic description of this mechanism is shown in Fig 7. The diameter of the cones at optimal conditions was about 2 μ. At higher laser energy the concentration of the cones increased and their size diminished. This observation supports the suggested mechanism where laser irradiation acts on the surface like a nucleation phenomenon.

Another mechanism was described for ripple formation [9]. At low energy, regularly-spaced parallel ripples were formed. These structures (Figs. 2a, e, f and Fig. 3) were attributed to interference between laser incident and scattered radiation to and from the surface. This interference led to ripple morphology. The minimum to maximum ripple size was a direct periodic function of the radiation wavelength (Fig. 8). The etched features were typically of the dimensions of the

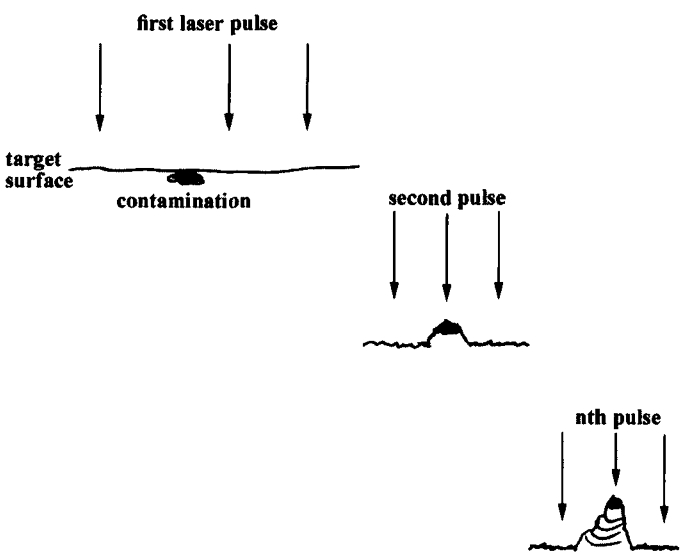

FIGURE 7 Schematic description of cone formation during laser irradiation.

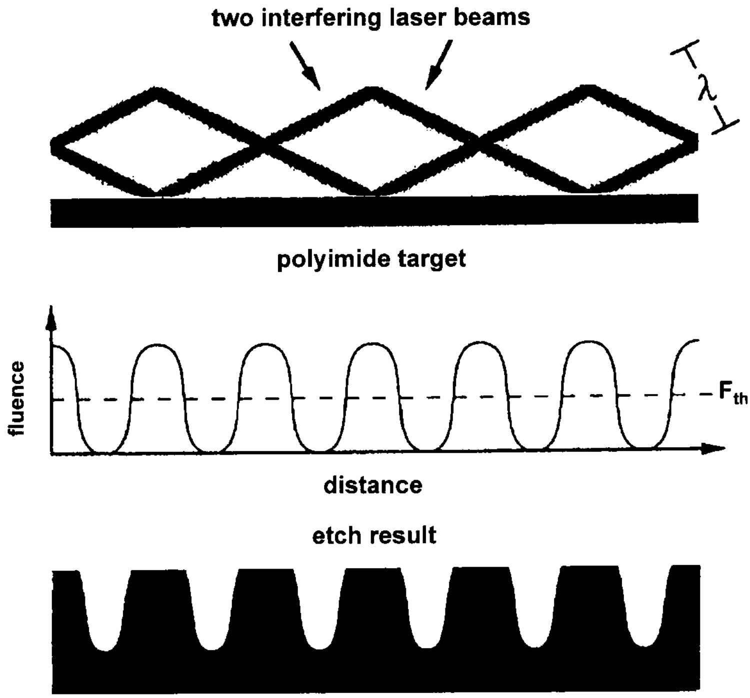

FIGURE 8 AFM contact mode topography (schematic) showing the ripple periodic size.

incident radiation. This result was clearly seen in the AFM features (Figs. 5a, c) where the ripples were about 200 nm wide, while the laser wavelength is 197 nm.

A third mechanism, typically found in metals irradiated by an excimer laser at high intensities, revealed flow lines and wide ridges usually concentrating to central points. These features might be a result of local re-solidification of the upper surface of the irradiated metal.

All these morphologies increased surface area and adhesive anchoring into the surface. The morphology is extremely uniform, which is essential for uniform bonding.

CONCLUSIONS

The use of an ArF excimer laser as a preadhesion treatment for various substrates (plastics, ceramic, composites and metals) was found to be most efficient. It presents an alternative to the use of ecology-unfriendly chemicals. Its mechanism involves changes in morphology, chemical modification and surface cleaning (indicated by FTIR and XPS [5]), which contribute to a strong and durable adhesive bond. The optimal laser treatment for each material for achieving the maximal shear strength was dependent on the material. Shifting from optimal laser conditions to higher energy and a greater number of pulses results, in most cases, in further decomposition, melting and ablation, which should be avoided [4, 5, 6].

Adhesional strength was improved compared with non-treated adherends and was similar to or higher when compared with conventional treatments. Changes in failure mode from interfacial to cohesive was due to increased mechanical roughness and uniformity resulting in the interlocking of the adhesive into the treated and roughened surface of the adherends.

The UV laser produced discrete microscopic etching on the treated adherends. The change of the surface morphology introduced uniform roughness which was observed by SEM and AFM. Three phenomena, cone formation, periodic surface rippling and re-solidification altered the smoothness of the etched surface. The resulting morphology exhibited a very uniform and micron-sized roughness, as observed by SEM and AFM, which contributed to the improved adhesion. These phenomena were described by the proposed mechanisms.

It can be concluded that UV laser treatment has many advantages, such as enhancing of adhesional strength and a limited surface effect without damage to the bulk properties of the adherend. The process is effective in air and at room temperature. It was proved to be a clean, environmentally-friendly, precise, and safe process.

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