Effect of Plasma Peening on Mechanical Properties and Fatigue life of AL-Alloys 6061-T6

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Abstract

An Investigation of estimated Mechanical Properties of AL-Alloys 6061-T6, which is one of the most commonly used in industrial applications, has been established experimentally. A new novel Plasma Peening techniques had been applied for the whole surfaces of the material by CNC-Plasma machine for 48 specimen, and then a new investigation were takeover to figure the amount of change in mechanical properties and estimated fatigue life. It was found that improvement was showing a nonlinear behavior according to peening duration time, speed, peening distance, peening number, and amount of effected power on the depth of the material thickness. The major improvement was at medium speed long duration time normal peening distance. Which shows up to 4 times improvements than the others cases. It was found that reducing in elongation of about 25% from references for 1x plasma peening for the most techniques used while a reduction in elongation of 31% for the two time plasma peening, on the other hand increment of 10% in elongation for 2x plasma peening and 5% of increment for peening with 5kW of plasma power. These results illustrated in both tables and figures. Farther study may established for other AL-Alloys to study the effects of plasma peening on it and to found the most effected one of them for the completely nine AL family.

Key words: Plasma Peening, Mechanical properties, Aluminum Alloy.

تأثير القذف بالبلازما على الخصائص الميكانيكية وعمر الكلال لسبيكة الألومنيوم 6061-T6

الخلاصة

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يدرس البحث تأثير تقنية جديدة لقذف السطوح عن طريق القذف بالبلازما على الخصائص الميكانيكية وكذلك عمر الكلل لسبيكة الألومنيوم 6061-T6 والتي تعد من أكثر سبائك الألومنيوم استخداماً والأكثر شيوعاً في عمليات انتاج هياكل الطائرات والمركبات والسفن لما تمتلكه من خصائص ممتازة. تم حساب الخصائص الميكانيكية للسبيكة المستخدمة في قسم التقييس والسيطرة النوعية – العراق وتم حساب عمر الكلل الأولي في مختبر مقاومة المواد – قسم الهندسة الكهروميكانيكية – الجامعة التكنولوجية لثمانية وأربعين عينة عملياً. تم تطبيق تقنية جديدة لقذف السطوح عن طريق القذف بالبلازما باستخدام ماكينة قطع بلازما مؤتمتة بعد تحويرها من عملية قطع الى عملية قذف فقط عن طريق تقليل القدرة وتغيير رأس القطع وكذلك مسافة رأس القطع عن العينة وكما سيتم شرح تفاصيل التقنية داخل البحث لاحقاً. تم تطبيق أكثر من تقنية كون العملية جديدة وغير مسبوقة ولا توجد مصادر معتمدة لكي يتم الاعتماد عليها في عملية القذف بالبلازما كما تم إعادة حساب الخصائص الميكانيكية وعمر الكلل بعد عملية القذف بالبلازما لمعرفة مقدار التغيير فيها. وجد ان هنالك تحسن غير نمطي في بعض الخصائص على حساب خصائص أخرى قد يصل احياناً الى اربعة اضعاف قيمته الأصلية وذلك بحسب التقنية المستخدمة وتم اجراء مقارنة بين تلك الخصائص وعمر الكلل قبل وبعد عملية القذف بالبلازما عن طريق جداول ومخططات مفصلة. وجد ان هنالك انخفاض في معدل الإستطالة يصل الى 25% في حالة القذف 1x كما انه يصل الى 31% في حالة القذف لمرتين في حين انه يزداد بنسبة 10% في حالة القذف x2 وكذلك بنسبة 5% في حالة القذف بطاقة 5كيلوواط. يمكن تجريب هذه التقنية على سبائك أخرى من الألومنيوم لمعرفة مقدار التغيير في خصائصها الميكانيكية وعمر الكلال لها.
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INTRODUCTION

A traditional surface treatment technique, shot peening (SP), has been effectively and widely applied in industry for over six decades. In traditional SP process, metal or ceramic balls acting as minuscule ball - peen hammers make a small indentation or dimple on the metal surface on impact **Fig.1**. A compacted volume of highly shocked and compressed material can produced below the dimple. Using different types or size of particles will made a different effect on the surface of the material **Fig.2**, **AL Alkawi H. J. M., 2012**.

Laser Shock peening is a cold work process, in which the metal part is struck by a high energy pulsed laser beam producing high amplitude stress waves. The surface material resists to stretching induced by the stress waves resulting in a formation of a compression stressed skin. Prior to laser peening the material surface plated with an opaque layer of black paint, metal foil or tape. The black layer then covered with a transparent overlay (commonly flowing water) **Fig.3**.

Plasma is a high-temperature, electrically conductive gas, comprised of positively and negatively charged particles as well as excited and neutral atoms and molecules. A dynamic balance exists between the dissociation, ionization and recombination processes that occur in the plasma state. Thus, the plasma behaves electrically neutral. In physics, plasma referred to as the fourth state of matter. Plasma naturally occurs in the interior of the sun and other stars due to the high temperatures. Lightning is also a natural form of plasma, caused by high electrical field strengths. To produce a technical plasma, a gas is either greatly heated using a heat source or subjected to a strong electrical field in order to transform it into an ionized state.

Plasma technique developed at the end of the 1950s for cutting high-alloy steels and aluminum. It designed to use on all metals that, due to their chemical composition, could not subjected to oxy-fuel cutting. Owing to its extremely high cutting speeds (especially with thin materials) and narrow heat-affected zone, the technique also used today for cutting non-alloy and low-alloy steels. Metal cutting today characterized by higher quality demands and increasing cost pressures. The edges of cut parts should not require any further processing and expected to exhibit maximum dimensional accuracy. As a result, the ability of traditional cutting techniques to meet these demands increasingly questioned. Plasma fusion cutting is in direct competition with other techniques such as oxy-fuel cutting, laser cutting and water jet cutting. However, it can also be an alternative to the mechanical processing techniques such as nibbling, punching, drilling, see **Fig.4-5, Linde, 2013**.

Recently Plasma arc surface hardening is an alternative selective surface hardening method that is effective, economical and a promising technology in heat treatment industries, many studies for anther application of the plasma technique established to investigate the ability to improve materials both properties and fatigue life by using plasma-peening see. **S.V.Petrov, 2007. Mohd Idris, 2012.**

Applications:

Alloy 6061-T6 sheet and plate products have application throughout excellent joining characteristics, good acceptance of applied coatings. Combines relatively high strength, good workability, and high resistance to corrosion also construction of aircraft structures, such as wings and fuselages, more commonly in homebuilt aircraft than commercial or military aircraft. Other AL-Alloys like 2024 alloy is somewhat stronger, but 6061 is more easily worked and remains resistant to corrosion even when the surface is abraded, which is not the case for 2024, which is usually used with a thin Alclad coating for corrosion resistance, the chemical properties of the 6061-T6 is as shown as in **Table 1**, **ASTM standards, 2012**.

Experimental Work:

In this, study a standard (ASTM D412 Type A) tensile test specimen used standard dimension is as shown as in Fig.6. Where the gauge length (60 mm), shoulder length (75 mm), (R = 40 mm) for plane sheet spacemen and overall length (165 mm). The tests were taken at the COSQC-Baghdad (Central Organization for Standardization and Quality Control) according to the ISQ (Iraqis Specification Quality) 1473/1989, the tests was included general properties such as hardness, strength, toughness …etc. the results is as shown as in **Table 2**. **,Samer Jasim Mahmood, 2013.**

Usually most of CNC-Plasma Machine are used for cutting materials but the novelty in this study is to use this machine (AJAN CNC-Standard Plasma Cutting Machine) **Fig.7**, to shoot the whole surfaces of the AL-Alloys used with plasma by:

1. Changing the nozzle head type **Fig.8**. (The machine came with three types of heads one for steel with plasma arc diameter of 5 micron the second for other nonferrous materials of diameter 1 millimeter and the third one is for nonmaterial of diameter 2.5 millimeter so we used the third one).
2. Reducing the power of the plasma arc to quarter of the initial power. (To reduce the heat generation of the plasma arc).
3. Using only three bottles instead of five (Oxygen, Argonne and Nitrogen to reduce the temperature of the plasma arc).
4. Increasing the speed of head movement twice of the usual speed. (To decrease the effective time of plasma on the surface).
5. Increasing the distance between the materials sheet and the head of the plasma machine twice to three times the usual distance. (To reduce the effects of plasma arc on the surface).

According to above we took the 48 spacemen and divided them into three groups of 16 specimen each, 8 spacemen were shot peened by plasma for one time, while the other 8 shot peened twice, then we take the next 16 spacemen and divided them into two groups, 8 shot peened by 2x plasma head distance while the other 8 spacemen was shot peened by 3x plasma head distance, finally we take the last group and divided them into two groups 8 were shot peened by 2.5 kW of plasma power and the other 8 were shot peened by 5 kW of plasma power as you can see in the block diagram **Fig.9**. A completely grand new technique there is not any guide or reference or know how, so the results is according to this sequences and any one could take different sequences and cheek if the results were similar or not. For the CNC-Plasma machine specification, the AJAN CNC-Plasma machine usually used for cutting application and the technique used changed in its specification as in **Table 3**.

Results and Discussion:

The results, which calculated after plasma peening for the mechanical properties is as shown as in, **Table 4**. For Hardness it has been noticed that the major value was for the 5kW of plasma peening of 28 point higher than **COSQC** (Central Organization for Standardization and Quality Control) reference while the miner value is for two time PSP of 5 point higher than reference which is clearly due to the amount of plasma effected at the specimen surface, for both the ultimate and yield tensile strength the enhancement was observe in set No.1 for two time PSP, while for set No.2 at 1x head distance shows reduction in those value, this is also indicated that the alloys hardness is increased due to the excessive heat from the plasma for two times which might made some changes in phases of the alloys surfaces leads the gran size to decrease. The extension of the alloys is decreased generally from references for all types due to the same reasons above but the major increment is as expected for two times plasma peening about 50% less than reference, while a little change in the modulus of elasticity for all sets, the major decrement in fatigue strength was also for 5kW of plasma peening power of about 19 MPa.

Generally all sets of the experimentally results used in this research leads to decreases in extension but with different levels. **Fig.10** shows the effect of plasma peening for one time and two times plasma peening, it shows that for one time plasma peening the decrement in extension was 5% with increments in both ultimate and yielding stresses from standards, this means that as much as the surface supplies to plasma peening for this set as much as the improvement in ultimate and yielding stress is. **Fig.11** illustrate the effect of head distance changing all with the standard P-S diagram, it seems that the effect of plasma peening for this set is little for ultimate and yielding stress, still the decrement in extension is clearly observed with 5% for 2x head distance and about 20% for 1x head distance this might due to the amount of plasma affected the surface of the alloy. Finally **Fig.12** shows the effect of plasma peening power changing on the properties of the alloy surface, her it could be observe the huge decrements in extension with 15% for 2.2 kW of plasma peening power and more that 50% for 5 kW as it's shown from the figure of plasma peening power and as far as our information there is no other shot peening technique gives such decrement, still there were increment in both ultimate and yielding stresses which indicates that the alloys is behave or approaching hardenability due to the excessive amount of plasma peening applied to its surface. **Fig.13** shows the changes in grain size by metallurgical microscopic images up to 250x due to plasma peening treatments,

where DT (dislocation tangles), DW (dislocation wall) and DDW (dense dislocation wall).
Finally, **Fig.14** shows the improvement in S-N curve from standard ASTM and that calculated from plasma peening of AL 2024-T3 for set No.1 with one time peening, 0.5x head distance with 1KW power. The S-N carve for this set of this technique shows a god improvement with the ASTM Standard for low stresses and high cycles as we can see that for the same load say 100 MPa we get 5E+04 cycles for ASTM S-N standard and 1.75E+05 cycles for modified plasma peening S-N diagram which is a major improvement, this might be according due to decrement in dislocation as in slip and diffusion as in grain boundary sliding or both for the same reason above knowing that we used (High Cyclic Fatigue) test and Basquin equation ($\sigma_a = \sigma_f (N_f)^b$) for calculating fatigue life to get ($\sigma_a = 93(5.01E + 05)^{-0.0111}$) with ($\sigma_a = 80.39\ MPa$).

Conclusion:

1. For set No.1 (0.5x, 1kW and One time Two time plasma peening) of testing 16 spacemen, the technique shows a little effects in the extension percentage with major increment in mechanical properties for both the ultimate and yielding points.
2. For set No.2 (one time PSP, 1kW and 1x, 2x plasma head distance form spacemen) for also 16 spacemen, both yielding and ultimate points were little decreased respectively with decrement in extension percentage also.
3. For set No.3 (one time PSP, 0.5x and 2.5 ~ 5 kW of plasma power) shows the major decrements effect in extension percentage especially for the 5kW condition of plasma peening power with increment for both ultimate and yielding stresses.
4. Its well-known that the yielding dependent upon nature of the material or alloy, also known that if the yielding increased this leads the materials to became more brittle which decreases the extension percentage at the tensile test and verse versa. Inscrutably this technique decreases the yielding with decrement in extension percentage too for set No.2. The explanation of this criterion is that the heat produces from plasma hardened the surface of the alloy only, while the center of the alloy still the same. And when the surface cooled its grain cells became smaller in size with respect to the internal grain cells which remains at its original size because it cooled slower, so when we test the alloy for tensile test and check the result it was found that an increment of about 20%-40% according to the technique used in both yielding and extensions percentage both, this is only can be done by this technique while other treatments does not give such condition.
5. The S-N carve for Set No.1 (One time peening, 0.5x head distance with 1KW power) in comparison with the ASTM Standard showing a god improvement especially for the low stresses and low cycles, this might be according also due to the excessive amount of plasma applied at the surface of the ally and for different types of applied stresses at the fatigue application from the stresses applied in the tensile tests were the stresses is axially effects, while at the fatigue condition the load is pure bending.
6. From this work it can be re-discovered the great benefits of plasma techniques in industrial application ,by using and improving a CNC-Plasma Cutting Machine to perform plasma peening on (AL 6061-T6) and it was found that this technique changes it's mechanical properties in deferent levels for different test sets ,this change depends upon the parameters applied from changing the nozzle head distance of the

plasma arc to change the power of the plasma applied and number of plasma peened the amount of mechanical properties that changed even if it was not huge but clearly noticed especially if we know that this technique is kind of cheap with respect to other shoot peening applications gives this technique privilege as the other applications not doesn't optimize the material beater, so for those how need quick not expensive easily handled this technique is the best choice for them.

7. This is a totally new technique there is no how in this procedures used and the sets type were taken by diligence of the researchers so for further studies a new sets might applied to enhances this technique by studying its effects on the mechanical properties of this alloy or other materials.

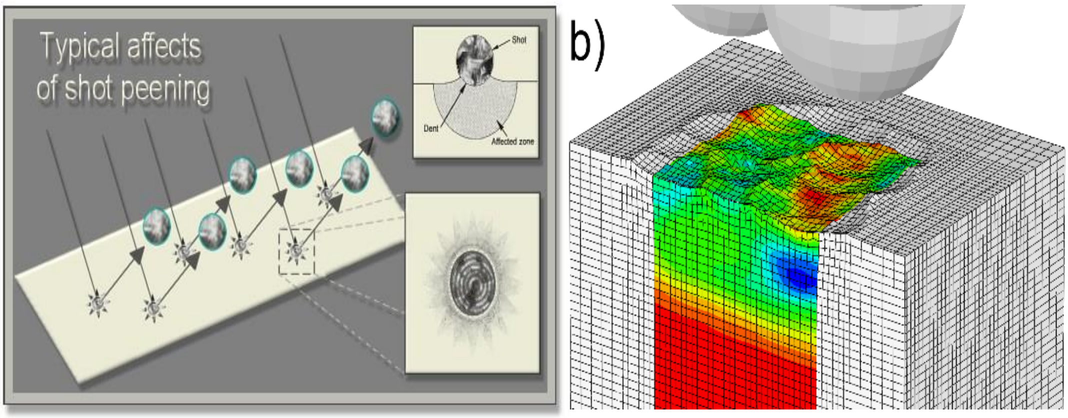


Figure (1). a) Typical effects of SP, b) Finite Model of SP at Spacemen Surface [Alexandre Gariépy]

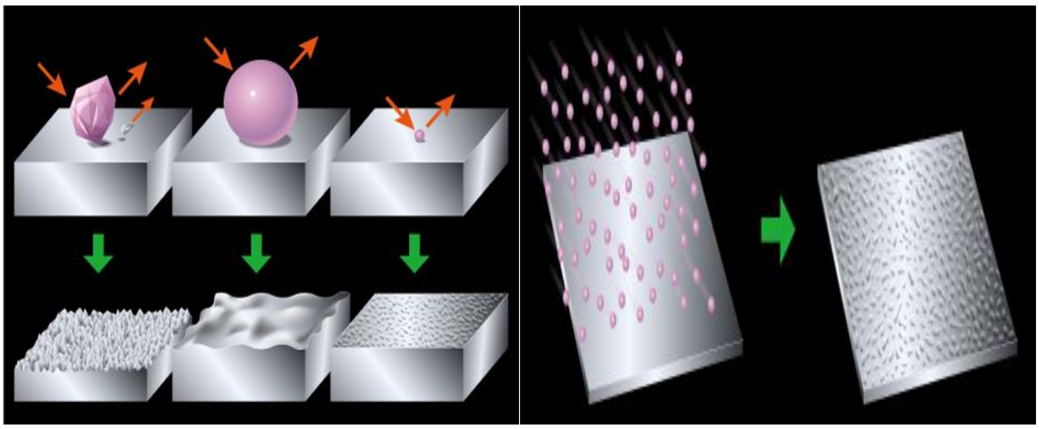


Figure (2). Effects of different types or size of particles on SP [Shot Peening (JapaneseClass.jp)]

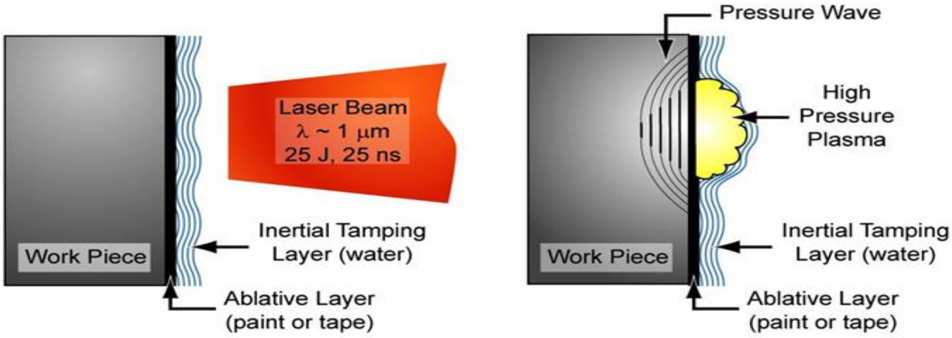


Figure (3). Schematic configuration of laser shock peening LSP [Metal Improvement Company - Laser Peening (Job Shop.com)].

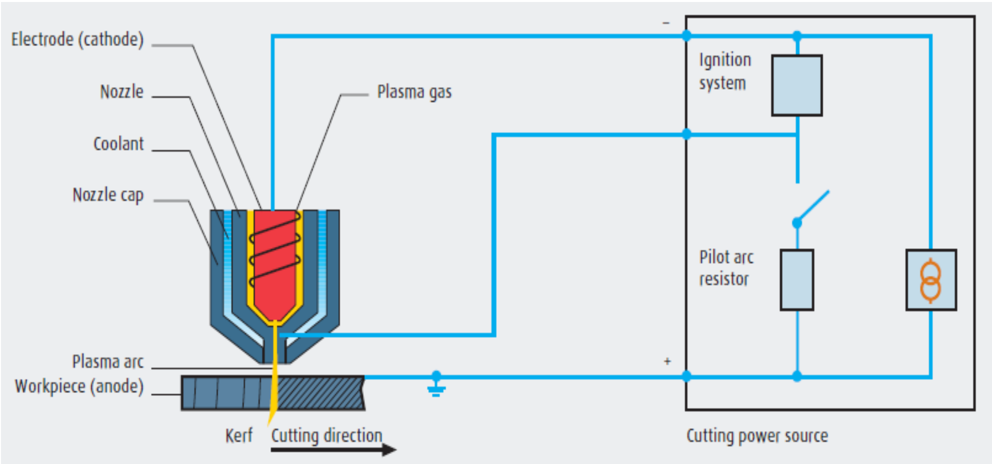


Figure (4). Principle of Plasma Technique, [Linde Group, 2013].

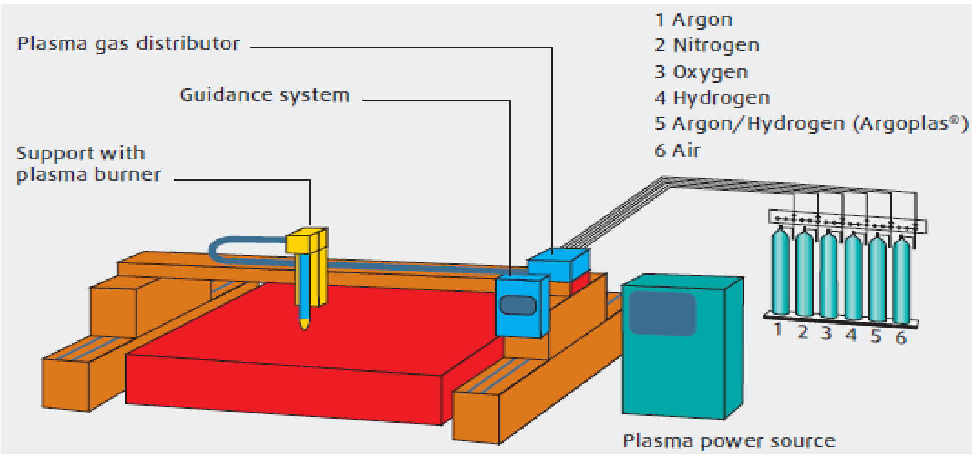
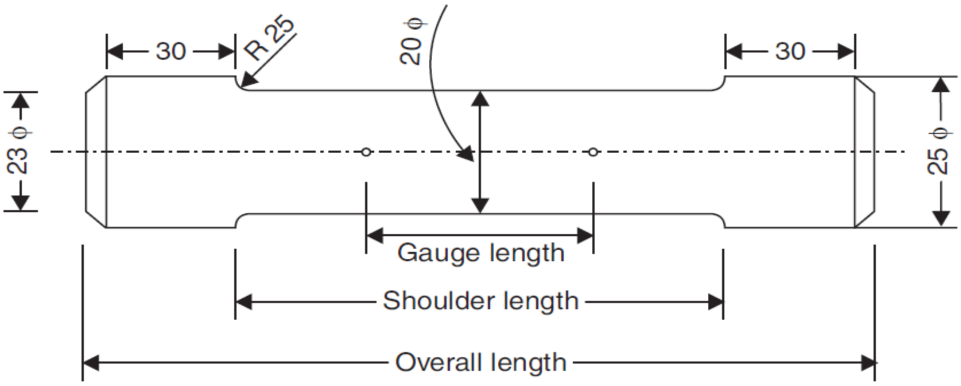


Figure (5). Example Setup for Standard Plasma Machine, [Linde Group, 2013].

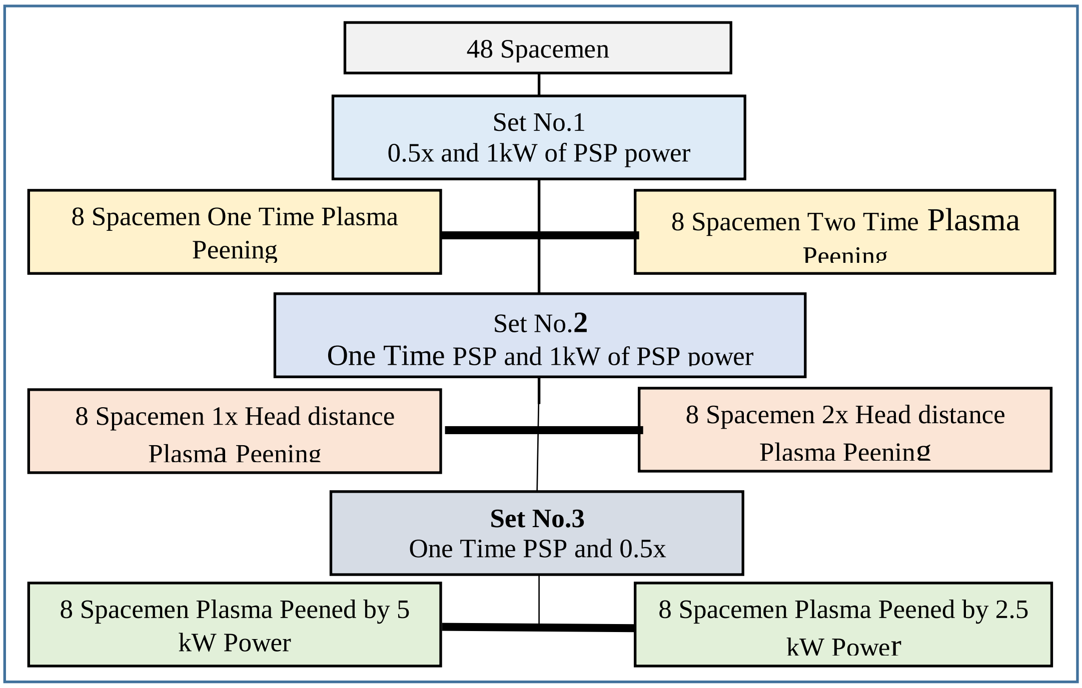


Note: Gauge, shoulder and overall lengths according to IS : 210-1978.

Figure (6). (ASTM D412 Type A) Standard Tensile Test Specimen for both shafts and plane spacemen with R = 40 for plane model, all dimension in (mm), ASTM Standards, 2012.

Figure (7). AJAN CNC-Plasma Machine

Figure (8). Machine Heads



Figure(9). Block diagram of the Technique Procedure

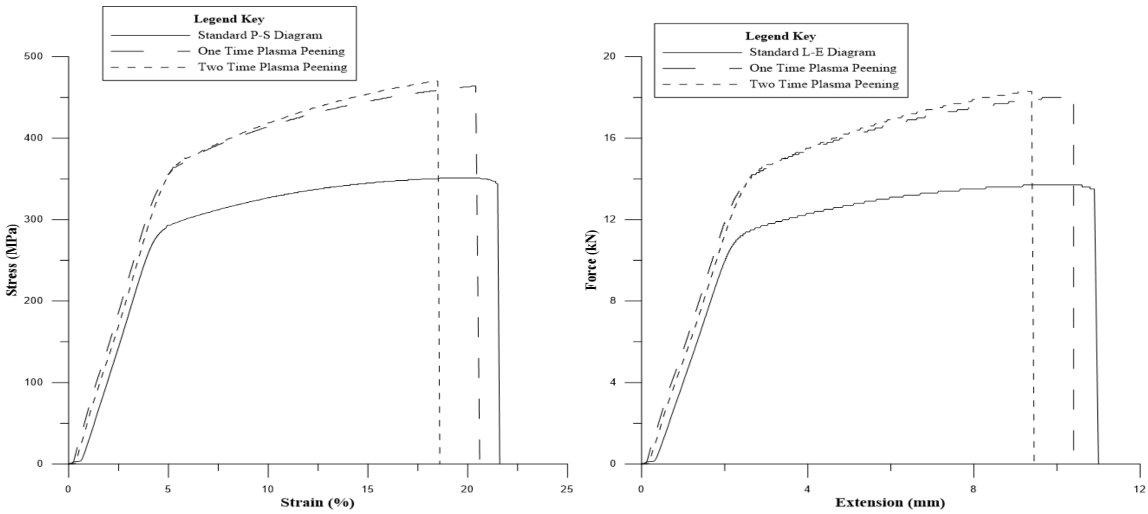


Figure (10). The effect of one time and two times Plasma peening on P-S diagram of AL 6061-T6

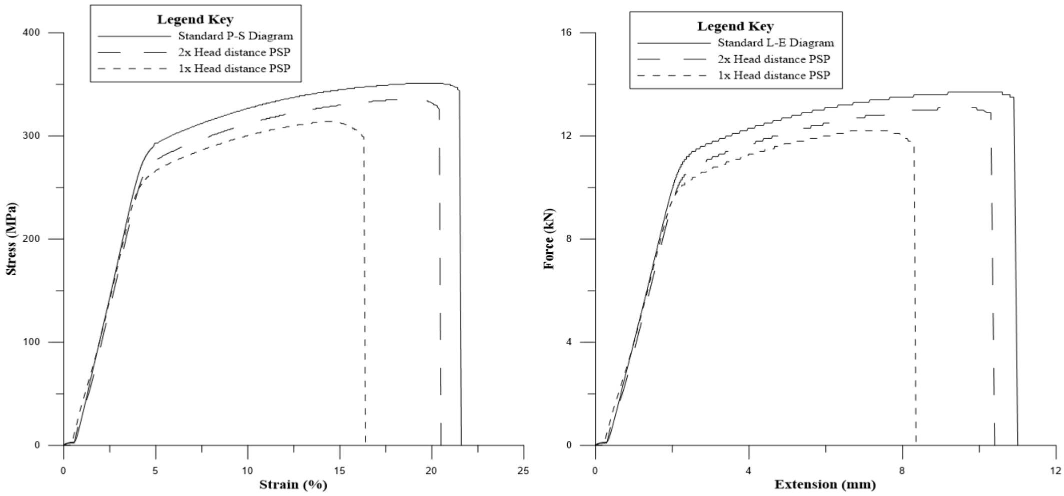


Figure (11). The effect of changing of Plasma peening arc head distance on P-S diagram of AL 6061-T6

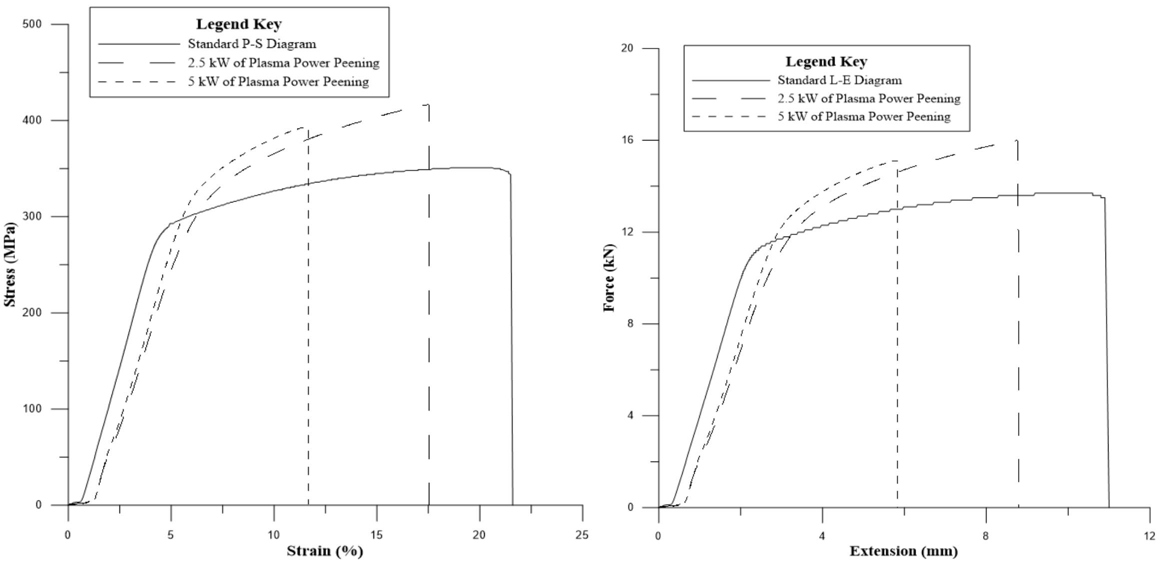
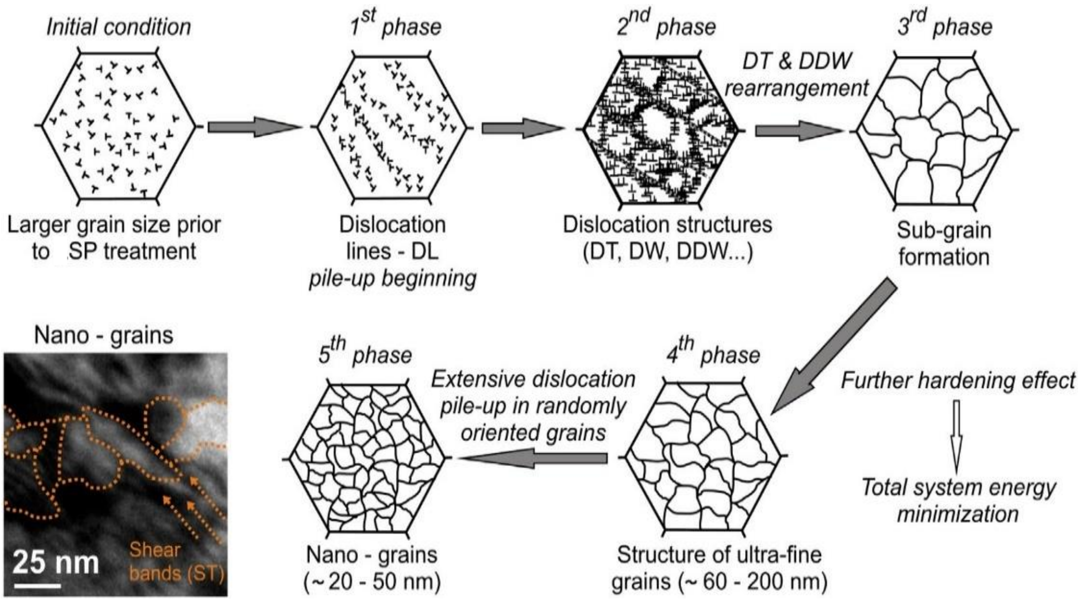


Figure (12). The effect of power changing of Plasma peening arc on P-S diagram of AL 6061-T6



Figure(13) Shows the changes in grain size due to SP treatments **[U.Trdan]**

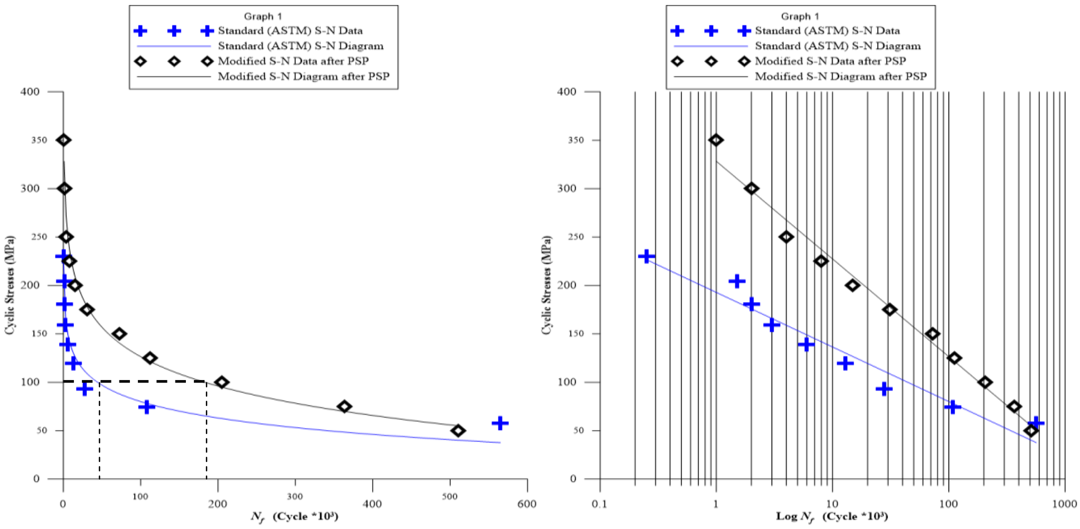


Figure (14). The improvement in S-N Diagram of the peened AL 6061-T6 by Plasma penning (One time peening, 1x head distance with 2.5KW power) with standard.

Table (1): Chemical Properties of AL-Alloys 6061-T6

Component	% Si	% Fe	% Cu	% Mn	% Mg
Standard	0.4-0.8	≤ 0.7	0.15-0.4	≤ 0.15	0.8-1.2
Actual	0.56	0.35	0.22	0.08	1.12
Component	% Cr	% Zn	% Ti	% other	% Al
Standard	0.04-0.35	≤ 0.25	≤ 0.15	≤ 0.15	Reminder
Actual	0.065	0.16	0.025	0.097	Reminder

Table (2): Mechanical Properties of AL-Alloys 6061-T6 as taken from the COSQC [Central Organization for Standardization and Quality Control / Iraq-Baghdad]

Mechanical Properties	Value
Hardness , Rockwell B	60 Converted from Brinell Hardness Value
Ultimate Tensile Strength	302 MPa
Tensile Yield Strength	296 MPa
Elongation at Break	21%
Modulus of Elasticity	69 GPa
Poisson's Ratio	0.33
Fatigue Strength	156 MPa
Shear Modulus of Elasticity	26.15 GPa
Shear Strength	201 MPa
Specific Heat Capacity	0.895 J/g-°C
Thermal Conductivity	165 W/m-K

Table (3): Both Original and the new technique Machine Specification

Specification	Original Specification	New Specification		
		Set No.1	Set No.2	Set No.3
X, Y, Z axis feed rate	600 mm/min	1200 mm/min	1200 mm/min	1200 mm/min
Plasma Head Distance	25 mm	50 mm	75 mm,100 mm	50 mm
power	11 KW (Cut)	1 KW	1 KW	2.5 KW, 5 KW
Gases used	5	3	3	3
Positioning increment	10 micron	10 micron	10 micron	10 micron
Max air volume	1200 m^3 / hour	1000 m^3 / hour	1000 m^3 / hour	1000 m^3 / hour
Plasma Gas Consumption	52 liter/min	25 liter/min	25 liter/min	40 liter/min

Table (4): Mechanical Properties experimental results of AL-Alloy 6061-T6, The yellow refers to highest while the red to lowest changes.

Set Number	Set No.1		Set No.2		Set No.3		Standard Without Treatment
Other Specification	0.5x and 1kW		1kW one time PSP		0.5x one time PSP		
Properties	One time Shoot	Two time shooting	1x head Distance	2x head Distance	2.5KW Power	5KW power	
Hardness, Rockwell B	72	65	77	71	82	88	60
Ultimate Tensile Strength (σ_{ut}) MPa	465	470	305	330	415	395	330
Tensile Yield Strength (σ_{yt}) MPa	370	375	251	265	260	305	296
Elongation at Break %	20.5%	18%	16%	20.25%	17.5%	12%	21%
Modulus of Elasticity (E) GPa	72	74.5	68.3	70	68.6	72	69
Poisson's Ratio υ	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Fatigue Strength (σ_f) MPa	152	158	142	150	160	175	156

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