Effect of Plasma Shot Peening on Mechanical Properties and Fatigue life of AL-Alloys 2024-T3

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ABSTRACT

An Investigation of estimated Mechanical Properties of AL-Alloys 2024-T3, which is the most commonly used in industrial applications, been established experimentally. A new novel Plasma Peening techniques had applied for the whole surfaces of the material by CNC-Plasma machine for 48 specimen, and then a new investigation were toke over to figure the amount of change in mechanical properties and estimated fatigue life. It 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 5 times improvements than the others cases. It was found that reducing in elongation of about 32% from references for 1x plasma peening for the most techniques used while a reduction in elongation of 56% for the 2x plasma peening. 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.
سبائك الألمنيوم , الخصائص الميكانيكية , القذف بالبلازما

تأثير القذف بالبلازما على الخصائص الميكانيكية وعمر الكلال لسبيكة الألومنيوم 2024-T3

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الخلاصة

يدرس البحث تأثير تقنية جديدة لقذف السطوح عن طريق القذف بالبلازما على الخصائص الميكانيكية وكذلك عمر الكلل لسبيكة الألومنيوم 2024-T3 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 تكنيك 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 خمسة اضعاف قيمته الأصلية وذلك بحسب التكنيك المستخدم 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 32% في حالة القذف لمرة واحدة في حين انه يصل الى 56% في حالة القذف لمرتين. يمكن تجريب هذه التقنية على سبائك أخرى من الألومنيوم لمعرفة مقدار التغيير في خصائصها الميكانيكية وعمر الكلال لها.

1. 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**.

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 high 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, **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 **, Petrov, 2007** and **Mohd , 2012.**

2. APPLICATIONS:

This is the most common of the high-strength alloys. Aircraft quality. AL 2024-T3 aluminum sheet is the best choice for the aircraft alloy because of its strength. It has excellent fatigue resistance. Welding generally not recommended. Typical uses for 2024-T3 aluminum sheet are aircraft fittings, gears and shafts, bolts, clock parts, computer parts, couplings, fuse parts, hydraulic valve bodies, missile parts, munitions, nuts, pistons, rectifier parts, worm gears, fastening devices, veterinary and orthopedic equipment, structures aircraft skins, cowls, aircraft structures, and for restoration like airstreams because of its shiny finish. The chemical properties of the AL-Alloys 2024-T3 is as shown in **Table 1 , ASTM standards, 2012.**

3. EXPERIMENTAL WORK:

In this, study a standard tensile test specimen used of standard dimension is as shown 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.**

Usually most of CNC-Plasma Machine 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 type of nozzle head **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 toke the 48 spacemen and divided them into three groups of 16 specimen each, 8 spacemen were shouted by plasma for one time, while the other 8 shouted twice, then we take the next 16 spacemen and divided them into two groups, 8 shouted by 2x plasma head distance while the other 8 spacemen was shouted by 3x plasma head distance, finally we take the last group and divided them into two groups 8 were shouted by 2.5 kW of plasma power and the other 8 were shouted by 5 kW of plasma power as you can see in the block diagram below **Fig.9**. This a completely grand new technique there is not any guide or reference to as, so the results is according to this sequences and any one could take different sequences and cheek if the results were similar to as 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.**

4. 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 two time plasma shoot peening of 16 degree higher than (COSQC) reference while the miner value is for 3x head distance of 4 degree 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 wasn't much higher than references but a major increment were noticed for the two time plasma shoot peening this is also indicated that the alloys brittleness 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 shoot peening about 50% less than reference, while not noticed change in the modulus of elasticity for all sets the major decrement in fatigue strength was also for two times plasma shoot peening of about 9 MPa. **Fig.10** shows the effect of plasma peening for one time and two times plasma peening, **Fig.11** shows the effect of plasma peening power changing, while **Fig.12** illustrates the effect of head distance changing all with the standard P-S diagram the. **Fig.13** shows the changes in grain size due to SP 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 shot peening of AL 2024-T3 for set one time peening, 1x head distance with 2.5KW 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 2.22E+05 cycles for ASTM S-N standard and 3.37E+05 cycles for modified plasma shot 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 ($\sigma_a = \sigma_f\left(N_f\right)^b$) for calculating fatigue life to get ($\sigma_a = 154(5.25E + 05)^{-0.0335}$) with ($\sigma_a = 99.06\ MPa$).

7. CONCLUSION

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. 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. Then, when the surface cooled, its grin cells became smaller in size with respect to the internal grin 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 25%-50% 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.

From this work it can be re-discovered the great benefits of plasma techniques in industrial application ,by using a unique novel technique by the use a CNC-Plasma Cutting Machine to perform plasma peening on AL 2024-T3 and it was found that this technique changes it's mechanical properties in deferent levels ,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.

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Table 1. Chemical properties of al-alloys 2024-T3.

Component	**% Si**	**% Fe**	**% Cu**	**% Mn**	**% Mg**
Standard	≤ 0.5	≤ 0.5	3.8-4.9	0.3-0.9	1.2-1.8
Actual	0.25	0.09	4.53	0.81	1.51
Component	% Cr	% Zn	% Ti	% other	% Al
Standard	≤ 0.1	≤ 0.25	≤ 0.15	≤ 0.2	Reminder
Actual	0.014	0.13	0.014	0.065	Reminder

Table 2. Mechanical properties of al-alloys 2024-T3 as taken from the COSQC.

Mechanical Properties	**Value**
Hardness , Rockwell B	72 Converted from Brinell Hardness Value
Ultimate Tensile Strength	482 MPa
Tensile Yield Strength	340 MPa
Elongation at Break	16.5%
Modulus of Elasticity	71.5 GPa
Poisson's Ratio	0.32
Fatigue Strength	135 MPa
Shear Modulus of Elasticity	27.35 GPa
Shear Strength	281 MPa
Specific Heat Capacity	0.875 J/g-°C
Thermal Conductivity	121 W/m-K

Table 3. Both standard and the new technique machine specification.

Specification	**Original Specification**	**New Specification**
X, Y, Z axis feed rate	600 mm/min	1200 mm/min
Plasma head distance	25 mm	50 mm,75 mm
power	11 KW	2.5 KW, 5 KW
Gases used	5	3
Positioning increment	10 micron	10 micron
Max air volume	1200 m^3 / hour	1600 m^3 / hour
Plasma gas consumption	52 liter/min	29 liter/min

Table 4. Experimental results of mechanical properties of al-alloys 2024-T3, The yellow refers to highest while the red to lowest changes green for standard.

Properties	**One time Shoot**	**Two time shooting**	**2x head Distance**	**3x head distance**	**2.5KW Power**	**5KW power**	**Standard**
Hardness, Rockwell B	80	88	78	76	80	83	72
Ultimate tensile Strength (σ_{ut}) MPa	440	412	447	435	445	461	482
Tensile yield strength (σ_{yt}) MPa	348	305	345	325	356	333	340
Elongation at break %	12.7%	8.8%	5.9%	11.4%	11.7%	12%	16.5%
Modulus of elasticity (E) GPa	70.3	69.8	70.8	70.05	70.5	71.1	71.5
Poisson's ratio υ	0.32	0.32	0.32	0.32	0.32	0.32	0.32
Fatigue strength (σ_f) MPa	131	127	135	140	137	125	135

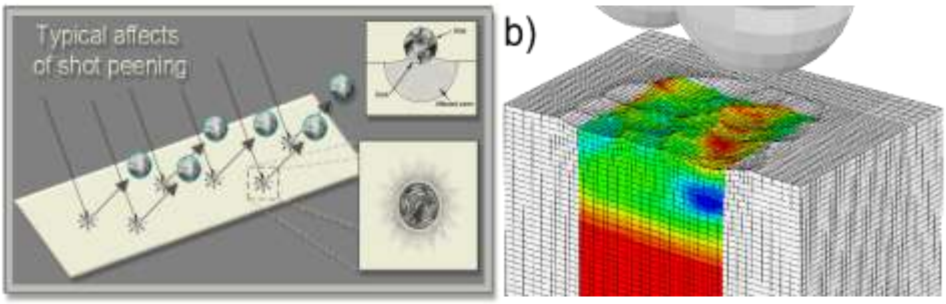


Figure 1. a) Typical effects of SP, **b**) finite model of SP at spacemen surface.

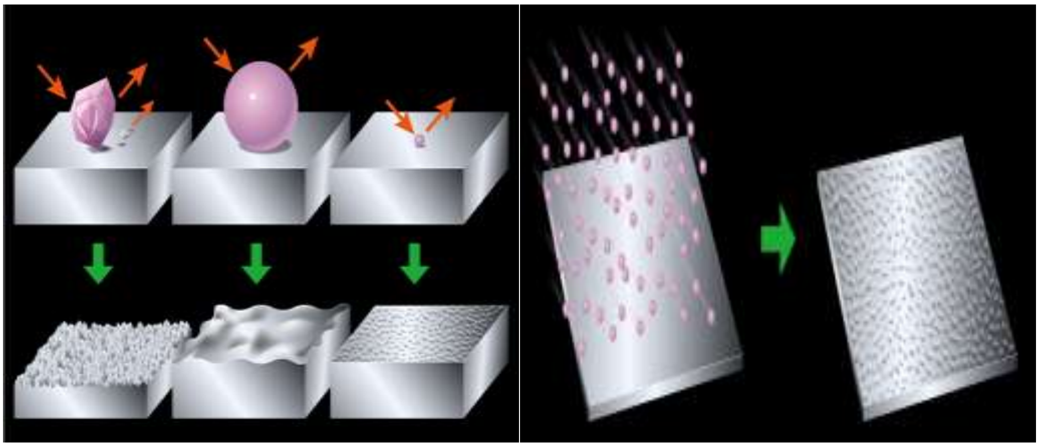


Figure 2. Effects of different types or size of particles on SP.

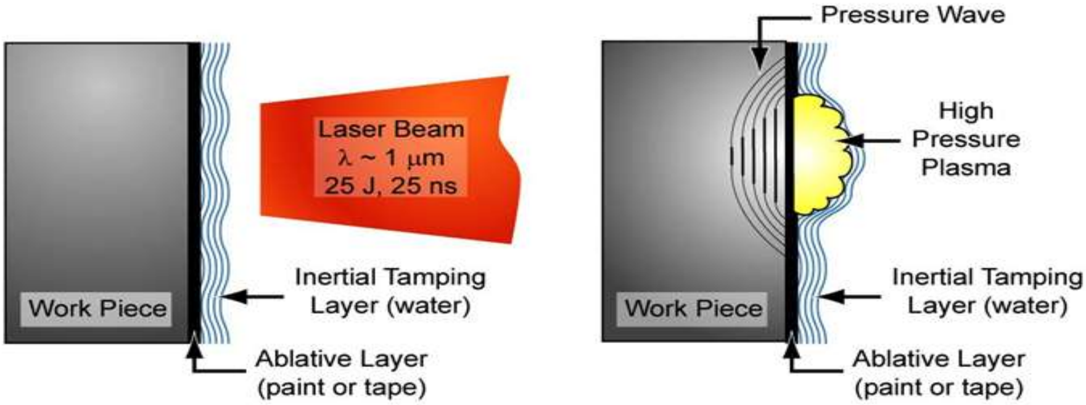


Figure 3. Schematic configuration of laser shock peening LSP.

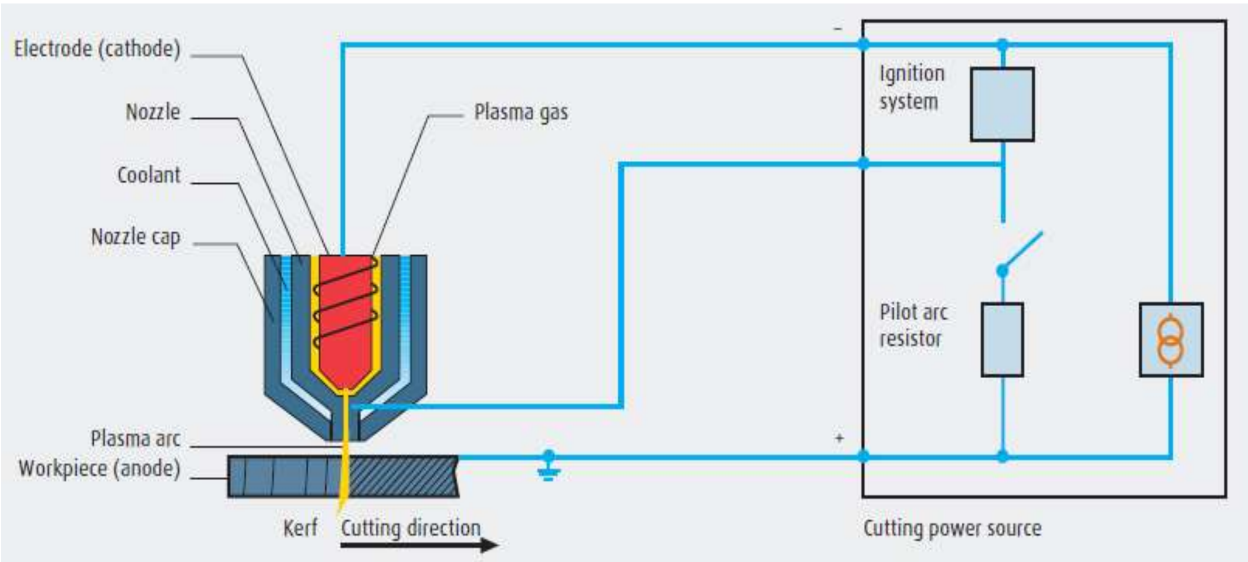


Figure 4. Principle of plasma technique, **Linde Group, 2013.**

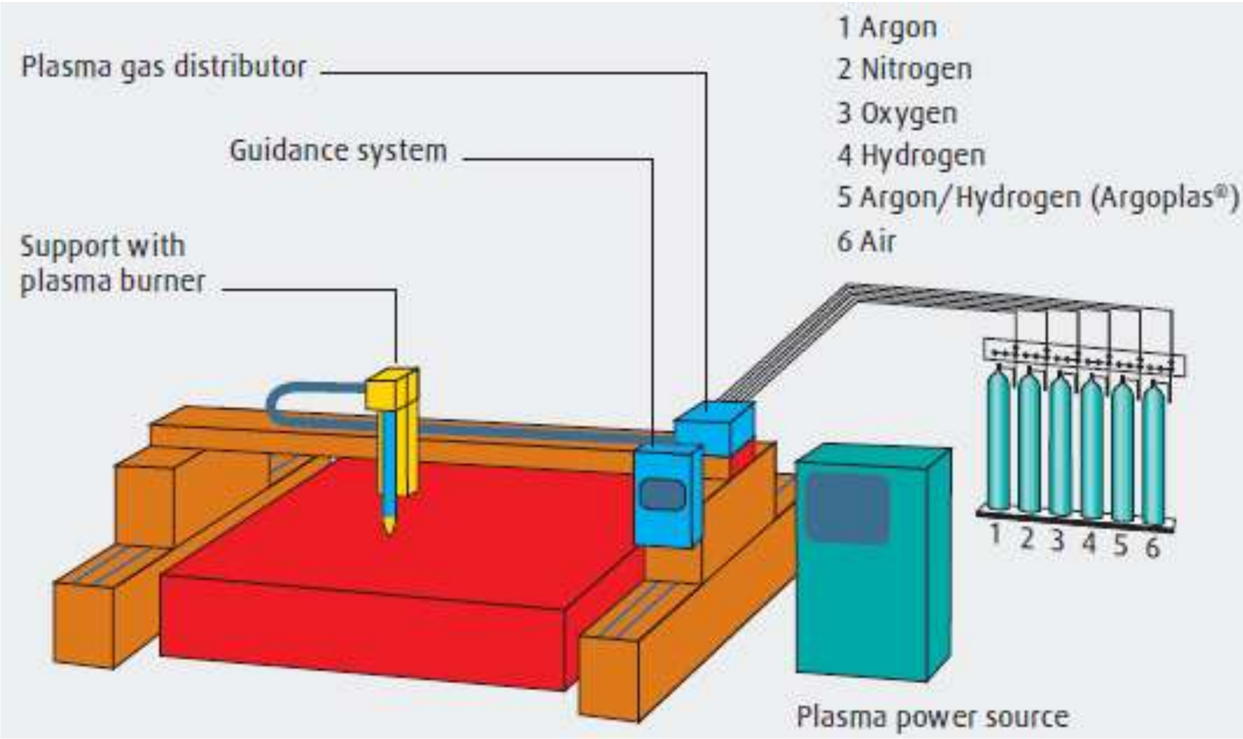
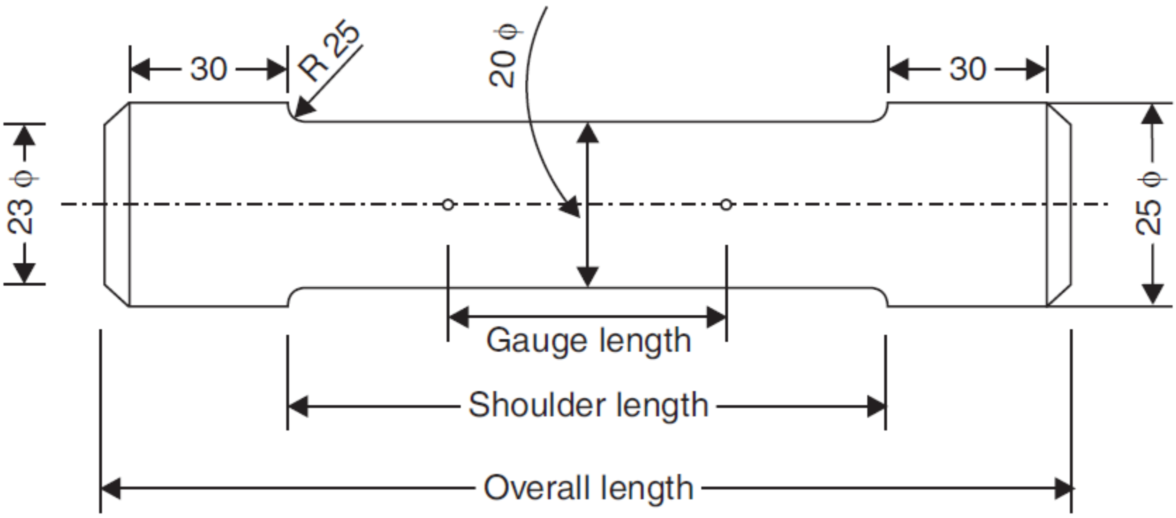


Figure 5. Example setup for standard plasma machine **,Linde Group, 2013.**



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

Figure 6. ASTM 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.

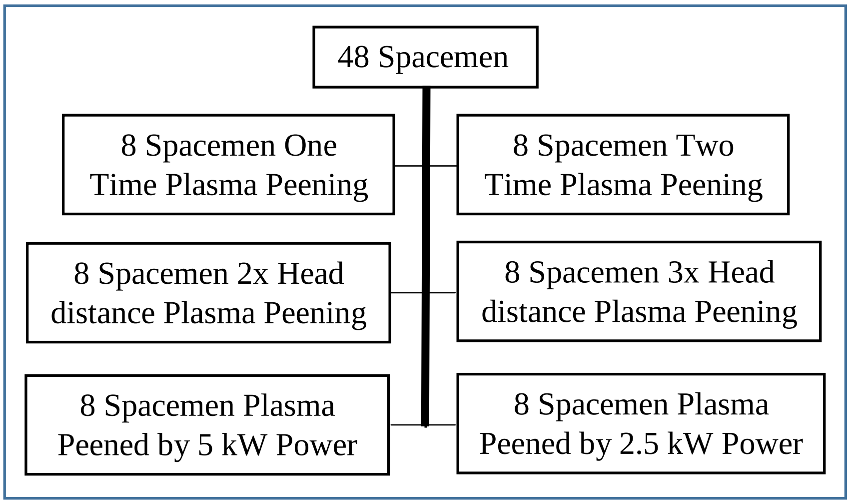


Figure 9. Block diagram of the technique procedure.

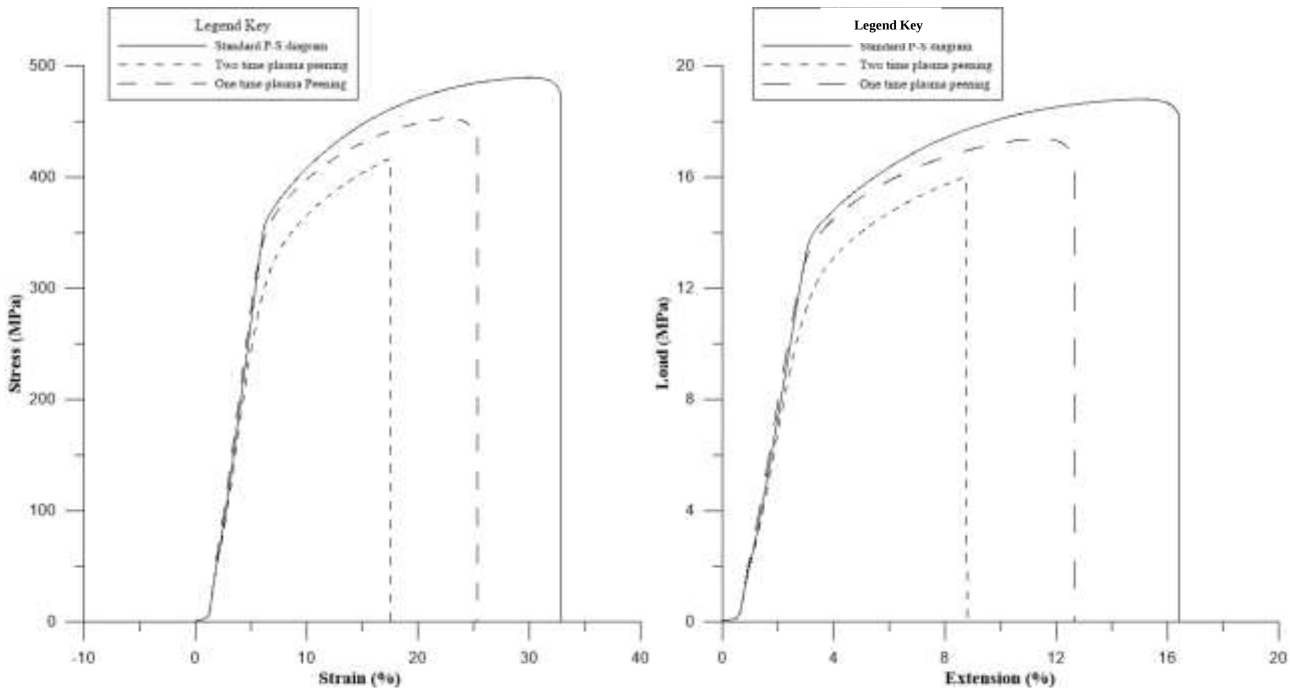


Figure 10. The effect of one time and two times plasma peening on P-S diagram of AL 2024-T3.

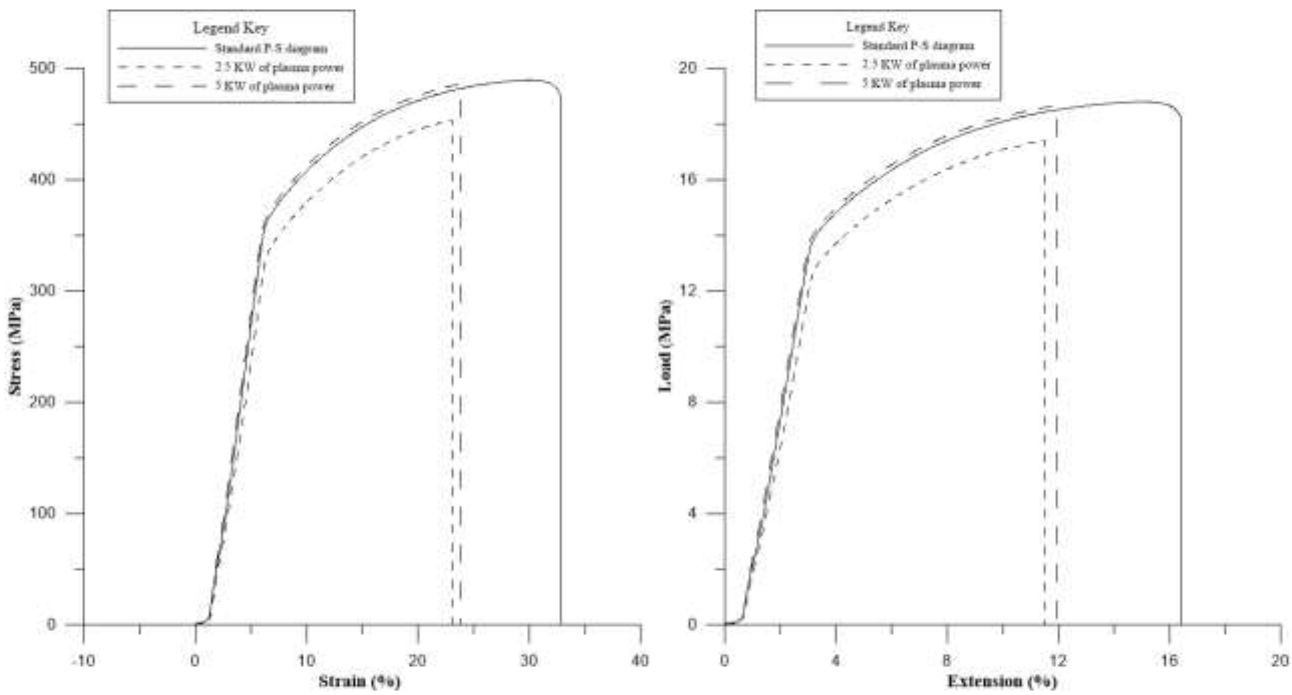


Figure 11. The effect of power changing of plasma peening arc on P-S diagram of AL 2024-T3.

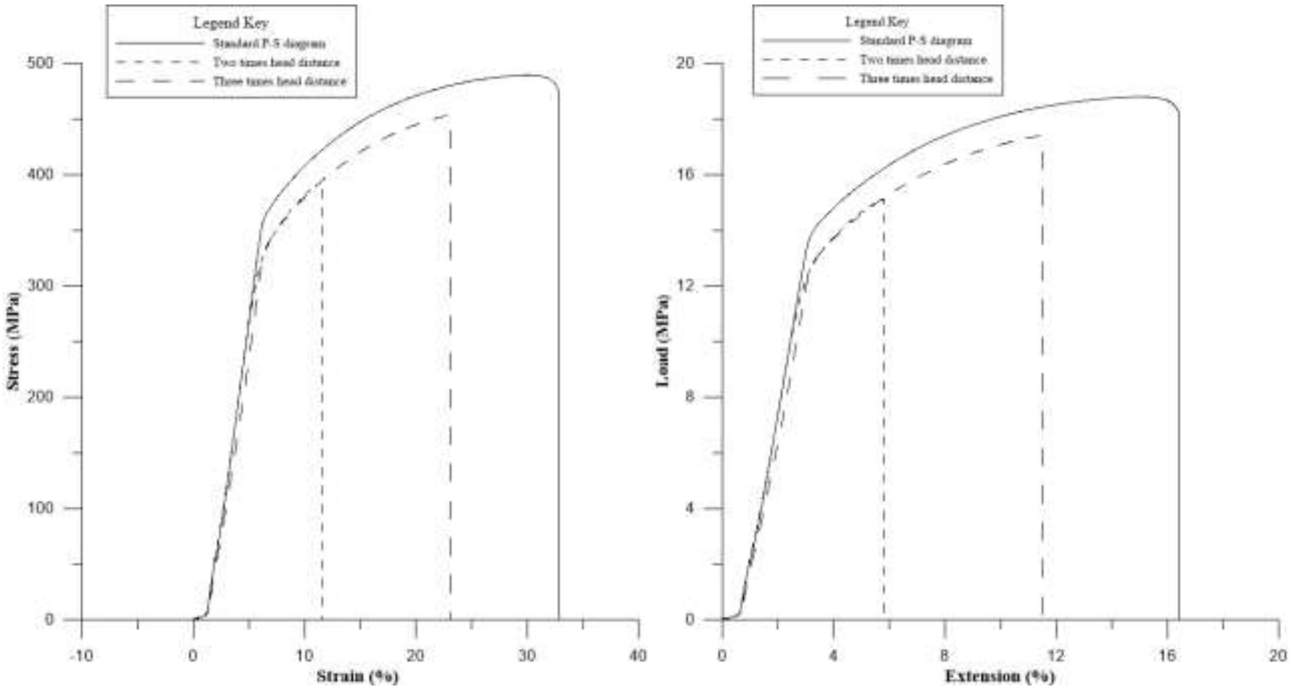


Figure 12. The effect of changing of plasma peening arc head distance on P-S diagram of AL 2024-T3.

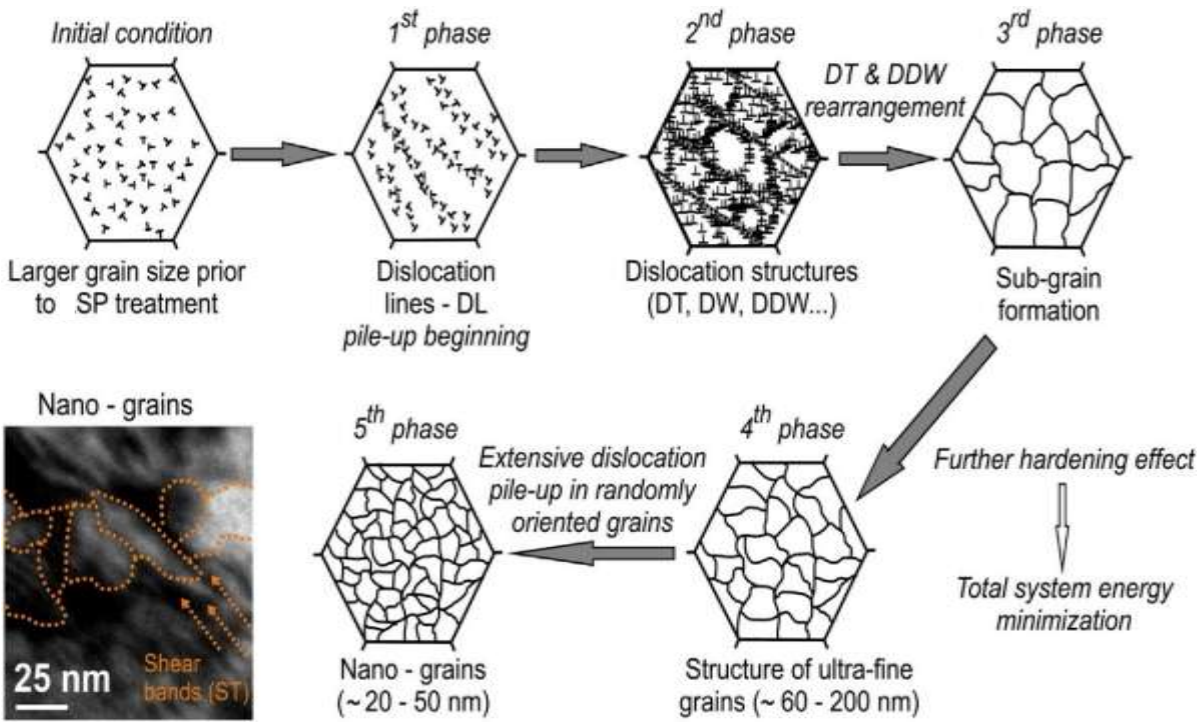


Figure 13. Schematic diagram shows the changes in grain size due to SP treatments.

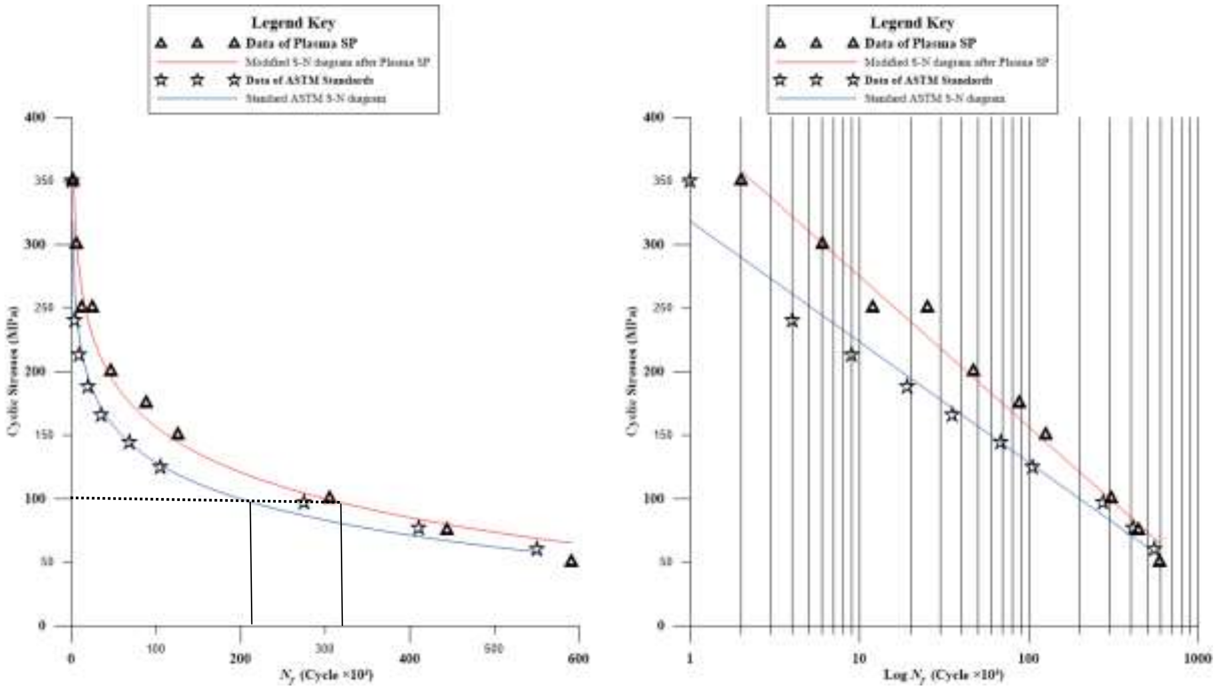


Figure 14. The improvement in both Liner and logarithmic S-N diagram of the AL 2024-T3 shot penning by plasma of the set (One time peening, 1x head distance with 2.5KW power) with the ASTM standard.