

A review of inducing compressive residual stress – shot peening; on structural metal and welded connection

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Abstract Shot peening treatment (SPT) is a significant mechanical method to enhance the surface of the material by inducing compressive residual stress on the layer. This study provides a review of prominent improvement in fatigue life on high strength aluminium alloy, steel and welded connection by SPT. Compressive residual stress measurement and its factors data are extracted from assorted literature, optimized peening process commented in this paper, also different types of mechanical peening methods and its effectiveness are mentioned. Fatigue life improvement is focused commented to welded structural connections. The extracted results shows significant changes in the surface layer of metals, aluminium alloy 15 – 250% of fatigue life improvement, steel plain members 6-200% of fatigue life improvement, welded connections 50-75% of fatigue life improvement and significant improvement in mechanical properties like roughness reduction, wear, hardness, tensile strength, corrosion and scuffing.

Keywords: Shot peening, fatigue performance, weld, stress concentration, residual stress.

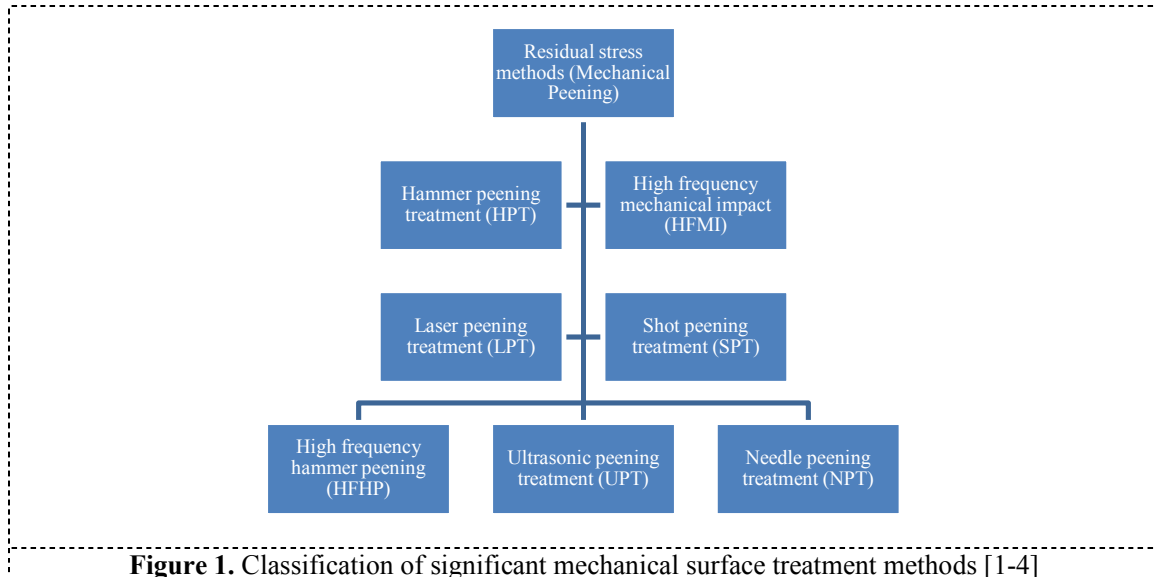
1. Introduction

Inducing residual stresses to the material will provide certain kind of resistance to the material against fatigue, impact, creep etc., in the case of fatigue life improvement many mechanical methods are available [1]. Improving fatigue strength in welded and non-welded structures is influenced by mode of fracture failure; making the delay of crack initiation and propagation can be done by inducing compressive residual stress in the steel. Residual compressive stress has a great influence on fatigue strength of metallic materials, but the tensile residual stress will reduce the fatigue performance [5]. Figure 1 shows the different notable types of residual stress methods discussed for welded structures.

1.1 Mechanism to induce residual stress

The material can be stressed either at the stage of the manufacturing process or by an external application, during manufacturing stage the material plastically deform to bring perfect shape and it's happened by means of rolling, bending, forging, drawing and





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The material can be stressed either at the stage of the manufacturing process or by an external application, during manufacturing stage the material plastically deform to bring perfect shape and it's happened by means of rolling, bending, forging, drawing and extrusion. Also, some surface modification did during manufacturing like grinding, machining, peening and carburizing [6], due to an external application like welding, casting, quenching and phase transformation major part in inducing residual stress. Figure 2 shows the parabolic curve of tensile residual stress induced by means of tensile force.

Nomenclature			
σ_y	Yield stress	USPT	Ultra sonic peening treatment
MPa			
$E_L, \%$	Elongation	LCF	Low cycle Fatigue
API	Almen Peening Intensity	Al	Aluminium Alloy
P_a	Air pressure	Ts	Tensile strength increment
S_r	Stress Ratio	SS	Stainless steel
FLI	Fatigue life increment	d_s	Mean diameter of Shot size
e_A	Strain Amplitude factor in range	MMA	manual metal arc
CSP	controlled shot peening	MIG	metal inert gas
WAl	Wrought aluminium alloy	TIG	tungsten inert gas
SCC	surface corrosion crack	ADI	Austempered ductile iron
HESP	high energy shot peening		

1.3 Residual stress measurement methods

Residual stress evaluation is quite complicated because of its degree of independency of stress to plot load versus deformation curves. Considering the energy release rate by relaxation method or in Griffith's analysis it is possible to find, many relaxation methods have been developed both general and specific types of specimen namely [6]

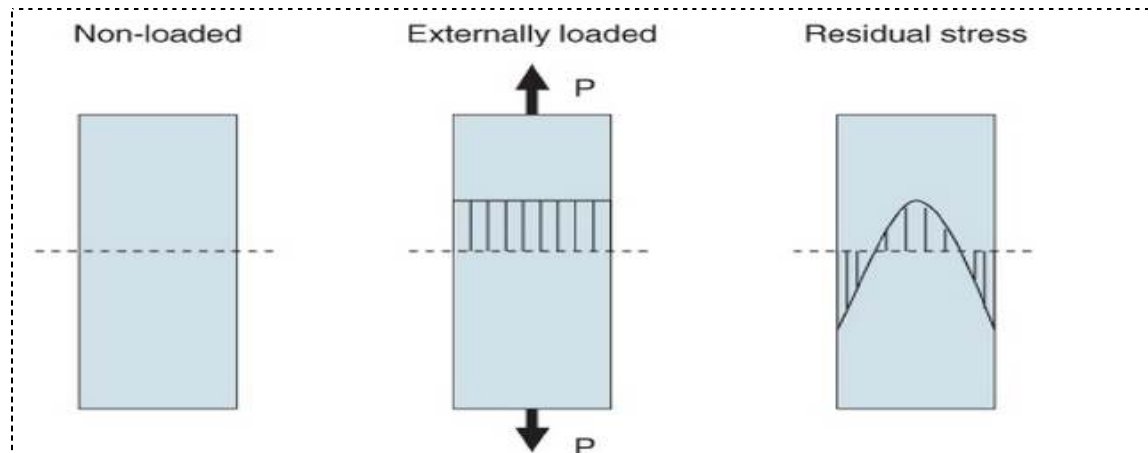


Figure 2. Schematic diagram of residual stress existence (toughened glass sheet) [6]

Relaxation methods are [7-8]	Diffraction methods are	Some other methods are
i. Splitting method	i. X- ray diffraction method	i. Magnetic residual stress measurement method
ii. Sectioning method	ii. Synchrotron X-ray method	ii. Ultrasonic method
iii. Layer removal method	iii. Radiation diffraction method	iii. Thermo elastic method
iv. Hole drilling method	iv. Neutron diffraction method	iv. Photo elastic method
v. Slitting method		v. Indentation method
vi. Contour method		

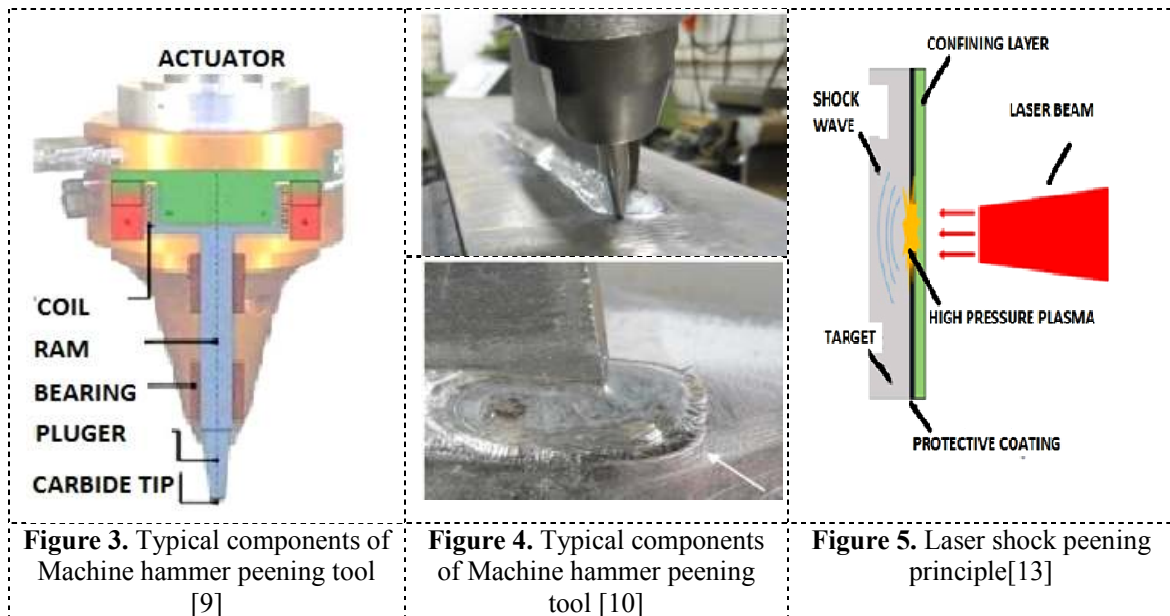
1.3.1 Classification of inducing compressive residual stress methods. Residual stress methods are discussed below

a) Hammer peening (HP)

HP is one of the most reliable methods by working in cold region operation speed can adjust based on machine availability. Operation done either Manual or machine by engines, electrical and pneumatic system is used, all tools have some curved nose or blunt nose to produce even local plastic flow. This is usually judged by eye. Frequently, special tools are made for special purposes, figure 3 shows the typical graphic diagram of the machine hammer peening tool component, spherical carbide tip has been used to produce the peening on the welded surface. This actuator controlled by CAM software and rate of peening is given by repeated frequency of the plunger movement [9].

b).High frequency hammer peening (HFHP)

Sometimes high-frequency hammer peening required to improving fatigue strength for welded and non-welded structures having high yield strength steel like 960 N/mm^2 , 1100 N/mm^2 and 1300 N/mm^2 . High frequency will make the modification of residual stress locally on high strength steel, greater fatigue resistance can achieve using HFHP and Figure 4 shows HFHP the typical model of peening application resulting plastic deformation [10]. HFHP produced high compressive residual stresses and the hardness increase in the upper surface layer resulting from the reduction of surface roughness like glazed surfaces [11]



c) Laser peening (LPT)

Deep compressive residual stress induced by higher level controller process by LPT, figure 5 shows the typical application principle of LPT [13]. Here high power laser beam nearly 20 N.m enables irradiances between 20 MW/mm² and 100 20 MW / mm². Laser spot generally 3mm to 10mm provided with plasma force builds to 10-30 kbar force in nanosecond time [12]. Laser peening improves surface quality and fatigue performance more effectively [14]. Another way using diode laser, re-melting of weld toe also improves fatigue performance in the welded structures [15]. Fatigue resistance evaluates in the hook shank application for aircraft results shows notable increment in crack initiation time by LPT [16].

d).Ultra sonic peening (UPT)

Inducing plastic deformation by means of compressive residual stress method UPT is a most promising method for enhancing fatigue life and strength, corrosion resistance and increase surface micro-hardness. The UPT process cylindrical rods or pins used for surface finishes of metallic materials [17]. UPT provides ultra long life in fatigue performance for post welded structures [19]. Ultrasonic impact treatment (UIT) gives significant improvement in the fatigue strength of highly stressed spokes of cast aluminum wheels [20]. Figure6. Shows UPT equipment components.

e).High frequency mechanical impact (HFMI)/(HiFiT)

Operating HFMI provides minimized spacing between alternate impacts, finer surface finishes and user-friendly, also HFMI device can lead in ultrasonic and pneumatic operations [21]. HFMI treatment can improve up to 26% fatigue strength and 353 N/mm² welded fatigue strength [22]. Figure7. Shows the device commonly used for HFMI, UPT and needle peening. In lightweight design, the fatigue strength improvement is successfully implemented by HFMI treatment of longitudinal stiffeners [24][25][26].

f).Needle peening treatment (NPT)

NPT also notable treatment for welded connections, Peening process is done by rounded headed needles to prepare a surface. [27]

2. Shot Peening (SPT)

SPT is the process to produce high compressive stress at very near surfaces with very limited surface roughness reduction. It is similar like sand blasting instead garnet is replaced by steel balls, figure 8. Showing SPT process which is involved impact at high speed creates a dimple, compressive stress development and residual stress concentration area. Normally the steel ball used as 0.8mm – 0.05mm diameter size [28]. Area coverage and creation of surface nano-layer is the major advantage in SPT, also it requires less time to finish the treatment process and testing [28-29].

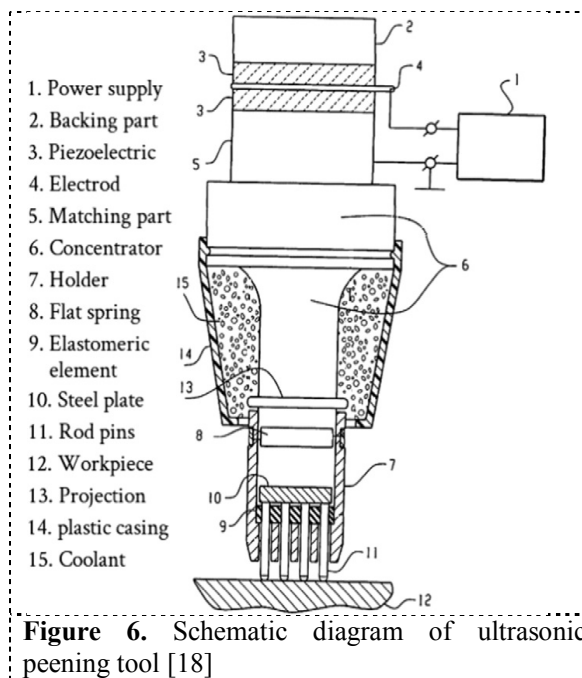


Figure 6. Schematic diagram of ultrasonic peening tool [18]



Figure7. HFMI device and its indenter [23].

Vaibhav Pandey et.al was studied about low cycle fatigue (LCF) behavior on aluminum alloy AA7075 and W.C.lie et.al was investigated about high cycle (HCF) fatigue behavior of the magnesium alloy Mg–10Gd–3Y with four different condition as - cast, cast- T6, as-extruded and extruded-T5 both experimentation shows maximum beneficial effects due to LCF and HCF[30][31]. SPT enhance the corrosion resistance property which is dealt with welded connections, 75% of corrosion can be decreased after 1000 hours of salt mist exposure [33].

Residual Stress Distribution:- With various experimental data Jinxiang Liu and Ming Pang analyzed to predict fatigue life by calculating distribution of residual stress, existing approach is to find fatigue strength is theory of critical distances[34]

$$\Delta\sigma_{av} |(\text{Area}, r = a_0) = \Delta\sigma_{\max} / \{1 - (4/3\pi) a_0 \beta\} \quad (1)$$

Here, $\Delta\sigma_{av}$ = $\Delta\sigma$ averaged over a semi-circular area of radius $r = a_0$

$\Delta\sigma_{\max}$ = Cyclic stress at notch root ('hotspot' stress)

a_0 = ElHaddad constant

β = normalized stress gradient $\{1/\sigma_{\max} \times (d\sigma/dr)\}$.

inducing residual compressive make surface harder and reduction in grain size results high corrosion resistance to the metal [35]

3. Experimentation Results

Residual stress are induced by SPT to Wrought aluminium alloy specimens results in Table 1,2 and 3. High strength aluminium alloys is the predominant material, normal alloy metals are magnesium, manganese, silicon, copper, zinc and tin. Normally used in machineries, vehicles, aircraft and engineering structures component. WAl 2000 series are alloyed with copper, 5000 series are alloyed with magnesium, 6000 series are alloyed with magnesium and silicon and 7000 series are alloyed with zinc. T3 represents solution heat treated and cold worked, T6 represents solution heat treated and artificially aged, T8 represent solution heat treated, cold worked and artificially aged and H1 represents strain hardened without thermal treatment. Table 4 shows the fatigue life improvement in structural materials such as carbon steel, alloys, stainless steel and Austempered ductile iron. Table 5 and 6 shows improvement of mechanical behavior like roughness, hardness, tensile strength, wear and Scuffing resistance with considering API, P_a , d_s and S_r .

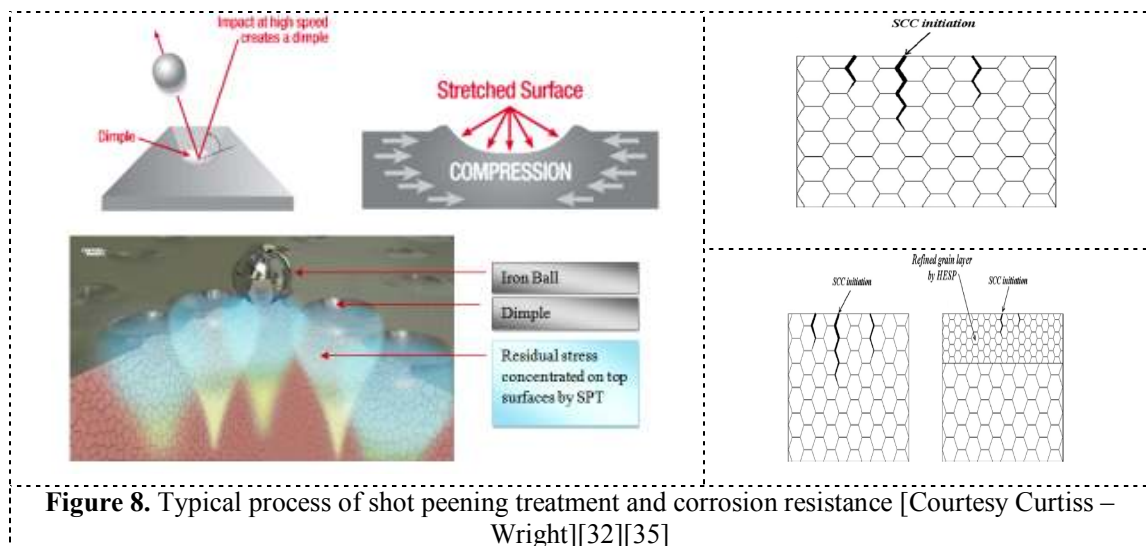


Figure 8. Typical process of shot peening treatment and corrosion resistance [Courtesy Curtiss – Wright][32][35]

Table 1. Fatigue life prediction of SPT on Wrought aluminium alloy Al

References	Type	σ_y , MPa	E_L , %	API,	P_a , bar	d_s , mm	S_r	FLI, %
[36]	Al 2195	215	9	00.008–0.012mmA	-	0.59	0.1	increased
[37]	Al 7075	462	11	0.27mmA	0.7	0.19	0.1	70
[38]	5183 H11A1	143	26	16-20 A	-	0.8	(i) 0.1	135
[39]	Al 6082	200		0.15 – 0.2mmA	-	0.6	0.1	26
[40]	Al7075–T6	520	-	-	-	-	0.1	130

[41]	Al-7075-T6	534	11	4.5N	-	0.06-0.12	-1	20
[42]	Al-7075-T6	515	15	4.5N	-	0.06-0.12	0.05	15
[43]	Al-7075	480	-	0.25-0.14mm		0.21- 0.32	0	250
[44]	Al 2024-T3	347.4	15	14A	-	0.5842	0.1	significant improvement
[45]	Al 5083	196	-	0.5& 0.9mm		0.9906	-1	75%

Table 2. Deflection control and hardness of SPT on AA5A06 [42][46][55]

References	Type	σ_y , MPa	E_L , %	deflection reduction in %	hardness increment in %	mechanical property
[46]	Al5A06	124	27	92.3	10	considerably increased
[47]	2124-T851Al	453	10	reduced	13	3.92 Pa and 0.84 dia shot ball
[48]	Al2024	451	11	-	53.5	87nm-13nm size, 180sec

Table 3. Corrosion resistance and fatigue performance by SPT on Al

References	Type	σ_y , MPa	API,A	Corrosion density, (A/cm ²)		Fatigue performance	note
[49]	Al 7075	400	12	As-machined 2.1×10 ⁻⁶	Shot-peened 5.2×10 ⁻⁶	ability to retard crack propagation 87%	5% of NaCl

Table 4. Fatigue life prediction of SPT on steel plain member

References	Type	σ_y , MPa	E_L , %	API,	P_a , bar	d_s , mm	S_r	Ts, %	FLI, %	note
[50]	Carbon steel	770.57	-	0.3 mmA	6.8	0.36	0.1	6.04	6.18	Shot wire used
[51]	12CrNi Mo	868.1	-	8-12A		0.584	0.93	increase	Increase	Din No 1.493
[52]	ASTM A516 grade 70	262	17-21	14-16A		0.431	0.1	-	50 – 63	MMA, MIG, TIG by CSP
[53]	20CrMnTi.	-	-	0.56 mmA	-	0.8	0.1	-	38.87	
[54]	Q345 steel	391	30.5	0.3 mmA	3	0.56	0.1	95		
[57]	En 3 CS	386	29	0.008-0.01 mmA	-	0.584	-	-	22	

Table 5. Stainless steel roughness reduction, hardness, compressive yield strength, and wear resistance

References	Type	σ_y , MPa	P_a , bar	d_s , mm	Roughness reduction in %	Hardness increase in %	Ts, in %	Wear	Remarks
[55]	17-4 SS	914	3.79	0.07-0.14	70	16	3	much lower	-

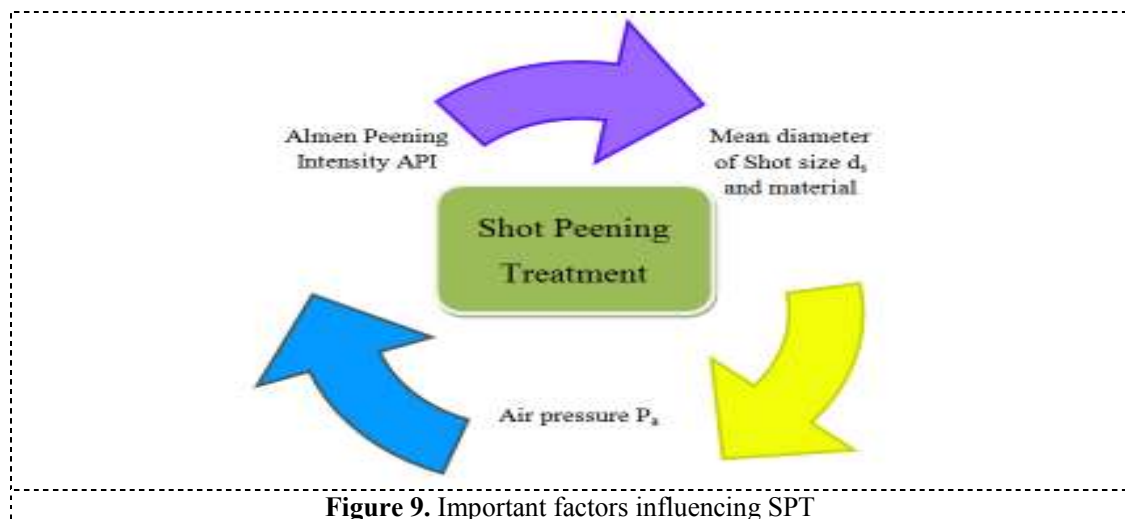
Table 6. Austempered ductile iron hardness, roughness reduction, wear and scuffing

References	Type	API, mmA	d_s , mm	Hardness increase, in %	Surface Roughness reduction in %	Wear resistance improvement, in %	Scuffing resistance
[56]	ADI	0.38	0.8382	30.84	93.5	30	higher

4. Discussion

In this section, mechanical properties such as yield strength, elongation index, hardness, tensile strength increment, surface roughness reduction, wear resistance; deflection control, corrosion and scuffing resistance are discussed for the following materials like carbon steel, stainless steel, austempered ductile iron and aluminium alloy.

From different literature, results of shot peening treated materials are collected. Basically, the data's categorized from following factors as shown in figure 9.



Almen strips are used to measure the intensity of shot peening, standard strips are almen A (cast shot), almen N (glass bead peen and ceramic bead peen) and almen C (thicker strip for higher intensity application). The different diameter of shot ball used for appropriate material based on this the property improvement identified. Peening pressure also involves surface variations. Omer et.al Al 2195 with the yield of 215 MPa SPT done 0.008 – 0.012 mmA almen intensity using 0.59mm dia d_s improves limited FLI but D.W. Hatamlan, N. Sihhoma et.al proves increasing almen intensity (0.27 to 0.3 mmA) at the same time d_s for Al7075 from 0.7 and 0.8mm provides increases FLI 70-135%. Ivo cerny et.al fix the almen intensity in a range of 0.25-0.14mmA and d_s 0.21-0.32mm for the same

Al7075 proves up to 250% of FLI hence the almen intensity and shot dia plays important role in the FLI. Some other mechanical property like hardness and deflection for the Al material gives significant improvement depends on the duration of the shot peening process [46][47][48]. Considerably thickening the surface layer will arrest the corrosion development in Al and gives the ability to stop crack propagation against fatigue loading Figure 8 shows the same [35][49]. In plain structural steel member considerably keeping API range of 0.56mmA and ds 0.8mm gives the greater value of FLI 38.87% [53]. Whereas the structural welded connection the API and ds limited in the range of 14-16A and 0.431mm to increase in the FLI 50-63%[52]. R.B. water house et.al proved the increases of hardness, surface roughness reduction, wear resistance and scuffing resistance using 0.38mmA API and 0.8382mm ds.

5. Conclusion and suggestion

The Wrought aluminium alloy (Al series) for fatigue life improvement is suggested to provide the range of 0.27 to 0.3 mmA API and 0.6-0.8mm shot peening cast steel ball will make constant improvement with 180 sec SPT. Structural plain member best API and ds is 0.38mmA – 0.56 and 0.8mm cast steel ball to improve for yield, fatigue strength, hardness, surface roughness reduction, wear resistance and scuffing resistance. In Structural welded connection 14-16A API and 0.431mm ds acquired the significant improvement in fatigue strength.

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