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World of Mechanics (2014)

(Wor.of.Mech 2014) Volume 2 Issue 2 (WOM: 04)

Research Received: May 05 2015 Accepted: July 30 2015 Published: August 3 2015

Mechanical Behavior Due to Innovative Processes on Light Alloys – A Review

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Citation: Dr. Sergio Baragetti (2015) “Mechanical Behavior Due to Innovative Processes on Light Alloys – A Review”

Abstract

Due to the continuous development of new technologic processes and surface treatments, new applications of high strength-to-mass ratio light alloys in the advanced aerospace, automotive and naval fields are becoming key factors in the mechanical design of innovative structural components. The recent advancements in the field of the Friction Stir Welding (FSW) technique, leading to improved weldability of high performance light alloys, are opening new horizons in the design of advanced machine parts. The surface characteristics of such alloys, which are traditionally an obstacle in the realization of components subjected to high contact forces, are nowadays improved by the adoption of low-temperature, hard and thin coating processes, such as the Physical Vapor Deposition (PVD) technique. A wide selection of coatings is applicable on different substrates, providing the material with an hard, low friction and wear resistant surface, often accompanied by a desirable compressive stresses pattern. However, due to the advanced nature of such processes, the actual effects of these treatments on the substrate are not always univocally defined in terms of mechanical properties. In the last decade, several studies have been produced on this subject, often analyzing a single effect on a single base material. The present work collects a review of the most recent analyses on the mechanical effects generated by innovative welding techniques such as FSW, as well as deposition PVD processes on light alloys for advanced application, thus giving to the mechanical designer a widespread view over possible new applications of these materials.

Keywords: PVD, Thin Coatings, FSW, Light Alloys, 7075-T6, Ti-6Al-4V

1) Introduction

The global thirst for fossil fuels is constantly increasing, due to the rising demand of the emerging markets, caused by a general growth of the production rate of developing and industrializing countries. The rise in public and private road vehicles demand is driving environmental and energetic concerns in the automotive sector. In the last decades, car designers have been striving to reach higher efficiencies and to reduce fuel consumption, minimizing the energetic impact of the automotive products, urged also by political regulations(1).

In order to increment the vehicles efficiency, the effort to design lightweight structures by substituting steel components has become an established tendency in the sector. The reduction of weight is critical to improve the fuel economy of road vehicles, since it produces both a direct reduction of the fuel consumption, and a ripple effect on the engine and power train size, which leads to further weight reductions(2). The global effect of the adoption of lightweight materials is hence more effective with respect to the simple redesign limited to the component geometry and to the increase of the power train efficiency alone. According to *Miller et al.*(2), the direct effect of a 10% weight reduction leads to a 5.5% fuel saving effect, which rises up to an 8-10% if considering the ripple effect.

Alternatives to steel have hence increased in the last decades, with a substantial predilection for aluminum alloys. The European automotive market, which has been more sensible to fuel economy problems due to higher prices, showed indeed a sensible trend in the last decades towards the adoption of aluminum alloys in cars mass production. The previsions presented at the beginning of the new millennium (2,3), which depicted a rise from a 50-60 kg average aluminum weight share in European-made vehicles by 1990 to a content of above 150 kg by 2010, have been fully confirmed by the market. The average share of aluminum parts in European cars has indeed risen from 60 kg per vehicle in 1988 to 160 kg in 2010(4,5), with a steady increase rate, only slightly affected by the economic crisis(5). The main usage of aluminum light alloys in car design, according to(2,5), has been directed to aluminum castings of engines blocks and power trains, chassis applications such as wheels, brakes(6), suspensions(7) and steering components. The most promising increase in terms of efficiency is still held by the body-in-white components, where mostly AA 5000, 6000 series are adopted, the 7000 series being limited to high strength applications due to poor weldability(2,5,8). However, 7000 series have the highest potential in substituting steels for high strength applications in the most critical BIW parts, such as the A and B-pillars and side impact beams(8). Their current usage in the automotive mass production is however limited by their poor weldability and limited surface properties, consisting in limited surface hardness, as well as Stress Corrosion Cracking (SCC) and corrosion fatigue sensitivity for the highest strength aluminum alloys(9-11).

Another key aspect in terms of weight reduction is the enhancement of lightweight components to replace steel in applications that have not been engaged by lightweight materials, due to specific limitations not affecting their steel counterparts. Some specific drawbacks of light alloys are typically linked to the surface performance of the alloys, to their resistance to corrosion in aggressive environments, to the difficulty of welding and other technological processes, which are typically well established in a steel-based manufacturing chain. In the present work, innovative methods to improve the surface properties and the welding processes of high performance light alloys, such as the AA 6000 and 7000 series, as well as the high strength Ti-6Al-4V titanium alloy, are briefly presented, their effects in terms of mechanical performances being discussed in extent. The aim of the review is to provide only a brief description of the technological and metallurgical aspects of such innovative methods, which are extensively described in the references, but to focus on the studies describing the effect of such processes on the material mechanical characteristics, and particularly on fatigue strength. Hence, precious information are collected for the structural designer involved in the drafting of innovative components exploiting such new techniques.

2) PVD Effects on the Mechanical Properties of Light Alloys

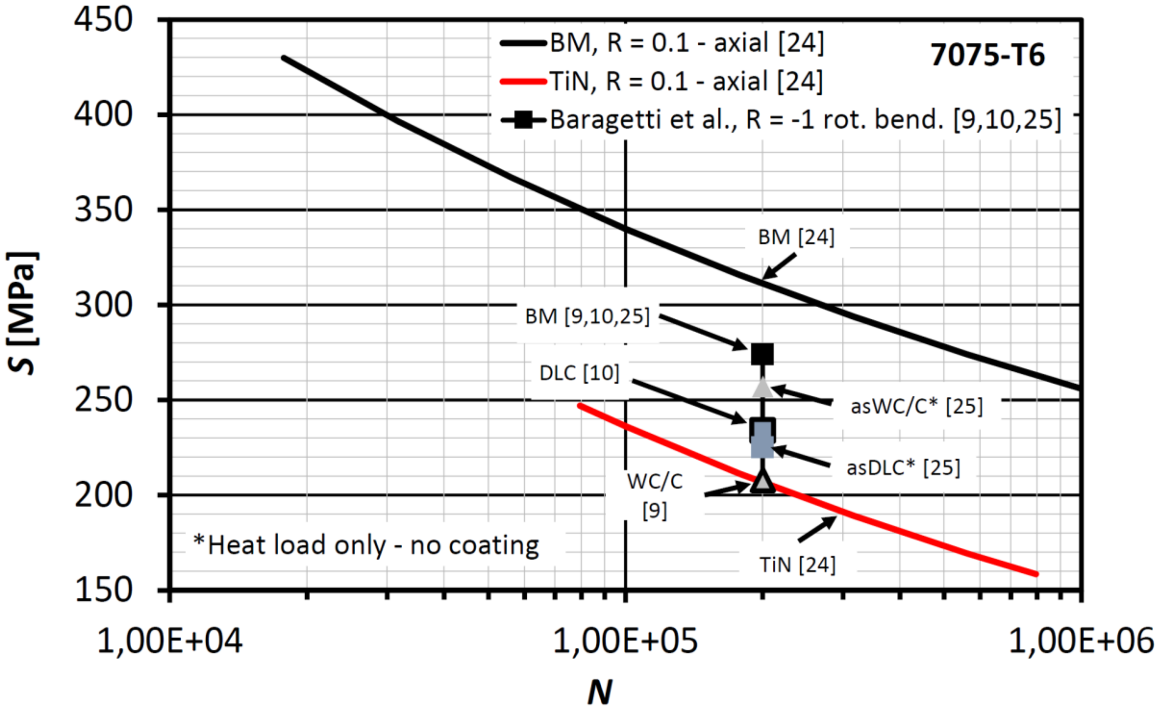
2.1. PVD techniques: In terms of surface enhancement, involving wear and oxidation/corrosion resistance, a proposed innovative technological process for light alloys is the Physical Vapor Deposition (PVD), which consists in the deposition of an inert thin hard layer on metallic substrates, composed by metal nitrides, metal oxides, carbides or a combination of them. Thin layer deposition by PVD has been extensively adopted in the cutting tools, automotive and aeronautic sectors, to improve the surface characteristic of crucial components subject to wear or corrosion, both for steels and light alloys, improving the surface hardness, wear and corrosion resistance(12-14). Its application to light alloy high performance spur gear components has been proposed, to reduce wear and rolling contact fatigue(15). In contrast with Chemical Vapor Deposition (CVD) techniques, which exploit a gaseous medium to deposit the substrate, PVD techniques involve solid evaporation and electrochemical processes in vacuum or inert gas to create a thin hard layer on the metallic substrate(13,16,17). Their adoption is preferred to CVD when high temperatures are not desired, since a CVD process typically reaches activation temperatures between 600 and 1200°C(16), PVD processes are preferred when low deposition temperatures are required, their typical maximum process temperature being included in the 200-500°C range(18). Another significant advantage of the PVD process is the reduced environmental cost, due to the absence of chemical by-products in gaseous or liquid form, granting increased industrial competitiveness if compared to CVD or electroplating techniques(19). Different physical processes are adopted for the evaporation of the solid coating components that will release ions to form the deposited layer. The most commonly adopted PVD processes are the cathodic arc evaporation and the magnetron sputtering technique. The first process evaporates the layer components with the help of an electric arc, creating a large number of ions, which are deposited on the target surface, usually kept at high negative voltage bias. However, the cathodic arc technique produces macro particles, which can pollute the deposited layer creating a non-uniform pattern with droplets or other inclusions. On the other hand, the magnetron sputtering technique releases a limited number of ion particles, while granting a homogeneous deposition of the PVD layer. In order to improve the ionization rate of magnetron sputtering PVD, Plasma Enhancement (PE) techniques are adopted in combination with magnetron sputtering(13).

2.2. Mechanical effects of PVD thin hard coatings on metallic substrates: Thin hard coatings have several mechanical effects when deposited in a metallic substrate. They generally increase the surface hardness of the substrate and its wear performances(13,14), and usually introduce a compressive stress pattern. The compressive residual stresses, associated with the deposition process, typically produce a highly beneficial contribution on fatigue life on PVD coated components(12,20,21), although they may reduce the coating adhesion to the substrate(22). The fatigue effect of the PVD layer may be however drastically be compromised by the onset of premature cracking in the coating, due to local defects and to high deflections of the hard coating at high applied stress levels, low fatigue life number of cycles(12,20,21). This aspect must be seriously taken into account concerning PVD coated light alloys at high applied stresses, where high deflections may induce premature cracking of the thin hard layer. The adhesion behavior of the layer on light alloy substrates, which for aluminum alloys presents reduced hardness with respect to a steel substrate, may introduce critical effects.

Another factor which has to be taken into account, when discussing of mechanical properties generated by thin hard coatings, is the substrate modification induced by the PVD deposition temperatures. Even if PVD treatments usually show reduced deposition temperatures, their contribution can be not negligible when considering light alloys with low melting and aging temperatures.

2.3. PVD effects on fatigue behavior of 7075-T6 aluminum alloy: When applying PVD thin hard coatings on high performance structural aluminum alloys, such as the 7075 alloy in the T6 temper, particular care has to be appointed on the temperatures reached during the deposition process. The aging temperatures of such materials are typically very low, *i.e.* 121°C for the 7075-T6(23), while the PVD process temperatures, even if lower than other deposition treatments, can be above 400°C for certain coating depositions, such as the TiN layer(18,24). The effects of a PVD coating process can hence be detrimental for the fatigue properties of light alloys, due to the microstructural modifications induced in the light alloy aluminum substrate. In Figure. 1, the effects on R = 0.1 fatigue behavior of high temperature TiN PVD coating are reported(24), along with data from rotating bending (R = -1) fatigue testing at 200’000 cycles for low temperature (180°C) WC/C and DLC carbon PVD coatings(9,10,25). In the latter case(25), the effects on fatigue life given from the heat loads have been decoupled from the overall contribution of the PVD coating, highlighting the contribution of the micro structural modifications.

Figure 1– *S-N* fatigue strength comparison between uncoated and coated 7075-T6 specimens for different load ratios and applied coatings(9,10,24,25).

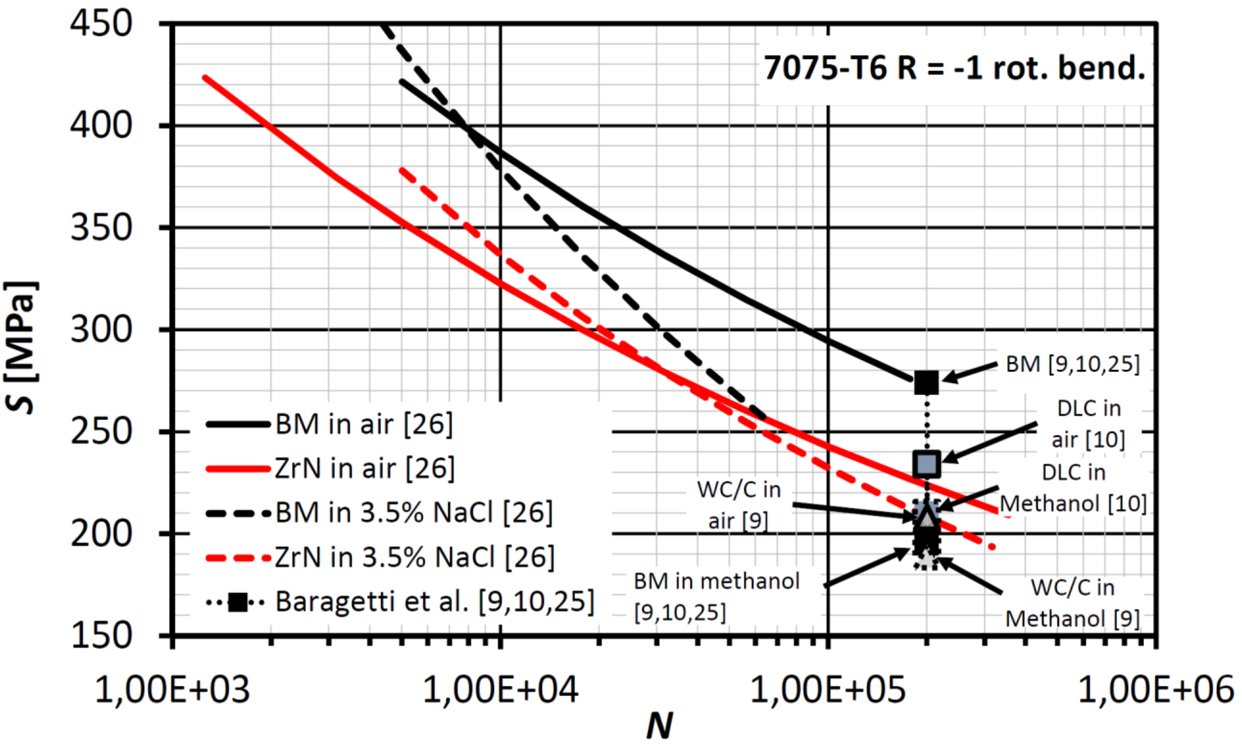


From the collected data(24), it can be seen that the high temperature associated with the TiN deposition process has a dramatic effect on the fatigue strength of the material. The average drop of the limiting stress S_{lim} at 200’000 cycles is around -35%, for an R = 0.1 load ratio. For rotating bending, R = -1 step loading fatigue tests on low temperature PVD coatings(9,10,25), a drop of -24% S_{lim} and -15% S_{lim} is found for WC/C and DLC coating processes on diamond polished surfaces, respectively. By testing uncoated specimens, which have been subjected to the same thermal loads of the PVD processes, a S_{lim} drop of -6% is found for the WC/C and of -18% for the DLC process. These results suggest that the microstructural modification due to thermal loads has a significant contribution for the DLC coating, where the loss caused by the thermal effects alone is more severe than the overall loss experienced by the coated component, suggesting some beneficial mechanical interactions between the DLC layer and the substrate. On the other hand, the WC/C deposition behavior has been influenced negatively by the mechanical interaction between the coating and the substrate, with only a small contribution of the drop caused by thermal effects, as can be seen in Figure 1.

The results of rotating bending fatigue tests in air and aggressive environments are reported in Figure. 2, based on the rotating bending fatigue data (R = -1) obtainedfrom literature(9,10,26).

From the work by *Puchi-Cabrera et al.*(26), concerning 7075-T6 AA coated with a ZrN coating, it is found that a fatigue drop due to the coating in air is around -24% at 2e5 cycles. The loss is similar, although inferior, to the drop experienced by R = *0.1* testing of TiN coating on the same substrate(24), in laboratory air environment, reported in Figure. 1. When the 7075-T6 alloy, which is particularly sensible to SCC and corrosion fatigue in salt water environments(11,27), is put into a 3.5 wt.% *NaCl* solution, a remarkable drop in the fatigue behavior is found for the uncoated specimens, with a downward shift of the *S-N* curve along with an increase in its slope. The ZrN coated specimens however show only slight modifications with respect to testing in laboratory air, highlighting a significant contribution of the coating in the retardation of the initiation phase of the corrosion fatigue phenomenon, being competitive with the uncoated specimens at low applied stresses.

Figure 2: *S-N* rotating bending (*R* = -1) fatigue strength for PVD coated and uncoated 7075-T6 specimens in air, 3.5 wt.%NaCl solution and Methanol aggressive environments(9,10,25,26).

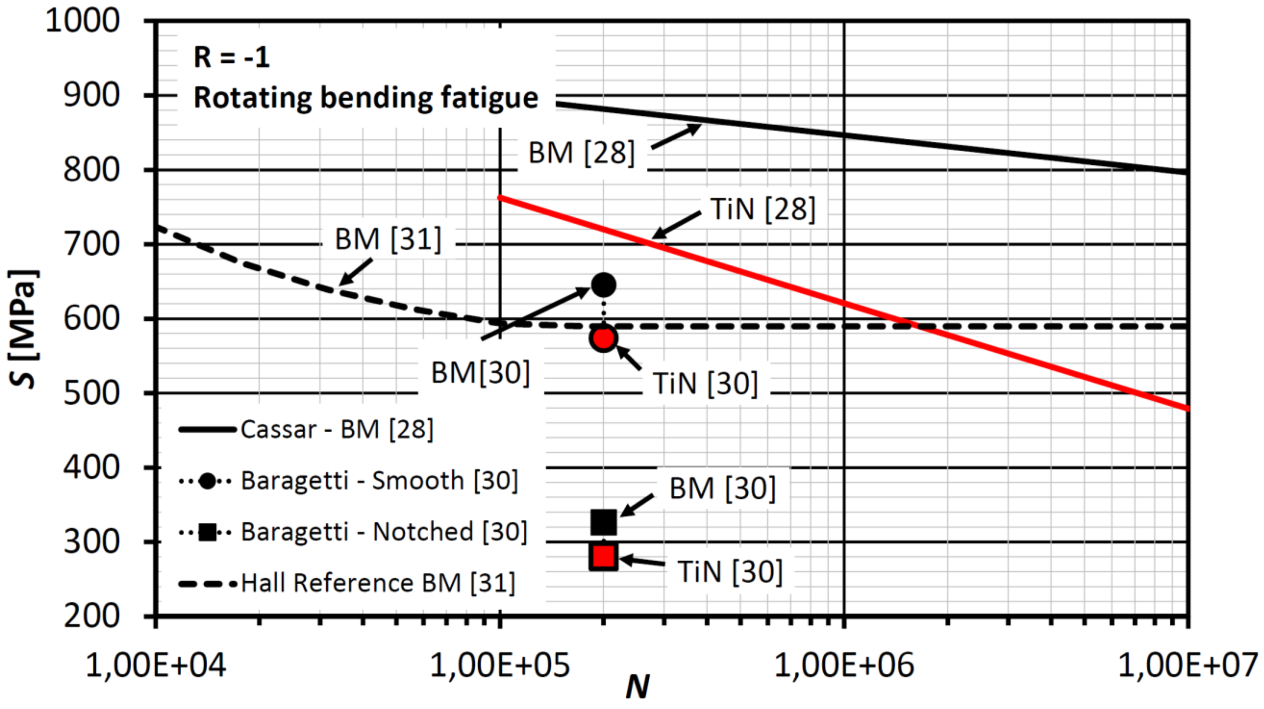


If considering the adoption of WC/C(9) and DLC(10) PVD coatings for corrosion fatigue protection in a methanol environment, the fatigue behavior at 200’000 cycles, *R* = -1 on a 7075-T6 AA substrate is investigated. In the aggressive environment, WC/C does not influence positively the corrosion fatigue behavior, with a $S_{\lim}$ drop of -9% with respect to the uncoated specimens in environment. The reduced drop, with respect to the -24% $S_{\lim}$ fall measured between coated and uncoated specimens in laboratory air, suggest however a certain protection capability. As for the DLC coated specimens, a rise of +10% $S_{\lim}$ with respect to the uncoated samples in methanol assures a good corrosion fatigue behavior for 7075-T6 specimens coated with this substrate, although the coating does not fully recover the fatigue properties of the uncoated specimens in air.

2.4. PVD effects on fatigue behavior of Ti-6Al-4V titanium alloy: The effect of PVD coatings on the fatigue behavior of high strength Ti-6Al-4V titanium alloys have not been yet extensively analyzed in literature. However, some researchers have started to investigate the effects of PVD coatings on the Ti-6Al-4V fatigue strength, since such treatments are desired to improve the poor surface and wear characteristics of this high resistance alloy, often employed for light-weight, dynamic loaded high performances structural components(15,28,29). PVD are sought for as possible substitutes of the currently adopted nitriding treatments, which are used to improve the sliding wear performances for Ti-6Al-4V(29) and the surface characteristics, and to reduce the high environmental costs associated to electroplating and electrochemical bath processes(19).

The first study on the fatigue effects of a Titanium Nitride TiN deposition on Ti-6Al-4V has been performed by *Wilson et al.*(29), by means of rotating bending, R = -1 fatigue tests(29) on plasma assisted, electron beam PVD deposition. The results obtained indicate that the PVD deposition does not alter significantly the fatigue behavior with respect to the base material, obtaining an S-N diagram, which is very similar to the results obtained on uncoated Ti-6Al-4V specimens. In recent times, several authors have proposed the analysis of TiN PVD techniques in terms of their impact on the Ti-6Al-4V. *Baragetti et al.*(30). carried out a staircase campaign to identify the fatigue strength limit at 200’000 cycles for TiN coated Ti-6Al-4V ELI rotating bending R = -1 specimens, for smooth and notched geometries(30). The results, reported in Figure. 3, show a limited detrimental effect of the coating on the material fatigue strength at high-applied stresses, both for smooth and notched specimens. The fatigue strength reduction on notched geometry was however less influenced by the PVD process with respect to the smooth samples. *Cassar et al.*(28) carried on a rotating bending, $R = -1$ fatigue test campaign to determine the S-N behavior of different surface treatments on Ti-6Al-4V specimens, including TiN PVD coatings. The results, reconstructed in Figure. 3 from the statistical data presented in literature(28) in terms of maximum stress, show a reduction in fatigue strength due to TiN deposition extended for fatigue lives from 1e5 to 1e7 cycles, in agreement with the results obtained in(30). In Figure. 3, literature reference for the base material is reported from *Hall* tests regarding rotating bending fatigue(31). Other data are available from the works by *Peters et al.*(32), *Sadananda et al.*(33), and *Morrisey and Nicholas*(34) for axial, R = -1 fatigue.

Figure 3 – Fatigue strength of uncoated and TiN PVD coated Ti-6Al-4V specimens from rotating bending fatigue test, R = -1, N = 200’000, adapted from literature(30).



3) FSW Effects on the Mechanical Properties of Light Alloys

3.1. FSW technique: Another typical process issue, which often affects light alloys, is their poor and difficult weldability, due to highly resistant, passive external layers, typical of Aluminum and Titanium high performance light alloys. The development of the Friction Stir Welding technique has been proposed from 1991 by The Welding Institute(35,36), to overcome welding difficulties on light alloys. The technique is based on the thermo mechanical agitation of the material to be welded by means of a rotating and advancing pin tool, which is forced in the material, pressing it with a flat shoulder. The material is extruded around the pin, and forged by the pressure on the flat tool shoulder, thus forming a weld bead. The bead is subdivided in three regions: i.e. the Heat Affected Zone (HAZ), the Thermo mechanically Affected Zone (TMAZ) and the stirred zone(37). The advantages of the FSW method include the capability to weld low-conducting, hardly weldable light Aluminum and Titanium alloys at temperatures inferior to the material melting point, with reduced distortions and residual stresses(37).

A brilliant review on the mechanical performances in terms of fatigue life has been composed by *Lomolino, Tovo and dos Santos*(37), on several 2000, 5000 and 6000 series aluminum alloys. Data are subdivided in terms of process parameters, *i.e.* tool thread diameter, tool rotating speed and weld advancing speed. The results were statistically analyzed by the authors, to obtain *S*-*N* design curves, highlighting the satisfactory characteristics of the FSW procedure for several classes of aluminum alloys. The performances of the FSW-welded samples were further improved by machining the weld surface after the process, cleaning the specimen from the tool marks.

In the present review, further aspects of the FSW effects on the mechanical properties of aluminum alloys are considered, including the tensile and fatigue behavior of FSW on 7075-T6 high strength AA, the influence of the tool shape on the weld fatigue performances, and the comparison between FSW and other welding techniques. The effects of FSW on the high strength Ti-6Al-4V fatigue performances are also addressed.

3.2. FSW effects on aluminum alloys: In the work by *Di et al.*(38), the $R = 0.1$ axial fatigue effects of the FSW on a 7075-T6 alloy are analyzed, to investigate its capability to replace riveted joints. The results are compared with data obtained on the 7475 high fracture toughness aluminum alloy, taken from the work by *Magnusson et al.*(39), as cited by *Lomolino, Tovo and dos Santos*(37). The fatigue strength at 2e6 cycles is reduced for the 7075-T6 AA with respect to 7475: a value of 79 MPa against 131 MPa is found respectively, with a reduction of 40% in terms of efficiency. The cause of the drop is attributed to welding defects on the backside of the weld, which are only detectable by metallographic analysis. The slope between the two *S-N* curves is comparable, being 7.2 for 7075-T6 and 6.3 for 7475. The behavior of the welding is compatible with the Eurocode 3 55-6 category, with a 43% increment of the characteristic fatigue strength at 2e6 cycles for the 7075-T6 alloy, if compared with the Eurocode standards.

Moreira et al.(40) compared FSW butt-welding of 6082-T6 and 6061-T6 AA with the corresponding MIG welding procedure. Considering the tensile properties, the FSW procedure reduced the YS of both alloys if compared to the MIG welds, but it increased the UTS and the elongation of the material. R = 0.1 fatigue tests were carried out on both FSW and MIG welded specimens. The FSW samples exhibited a better fatigue behavior with respect to their MIG counterparts, showing runouts above 1e7 cycles for a fatigue load of 60-65% of the YS and higher fatigue strengths at lower lives. The data scatter was indeed reduced for the FSW samples. The two considered alloys showed also differences between the two processes, the 6061-T6 presented in fact a reduced slope with respect to the 6082-T6 for MIG welding, while for the FSW procedure the behavior was opposite for the two alloys.

In another work by *Moreira et al.*(41) the tensile and R = 0.1 fatigue behavior of FS welded, notched (0.5 mm radius) specimens was investigated on a 6063-T6 AA. The tensile properties, measured on smooth FSW samples, showed a YS reduction of 42% and a UTS reduction of 12% with respect to smooth, un-welded specimens. The fatigue strength of the notched, FS welded specimens was always higher than the un-welded notched samples, even at very low fatigue lives, where the YS of the FSW samples were exceeded. At the lower stress amplitude tested, *i.e.* 80 MPa, the fatigue life of the FSW samples was an order of magnitude higher with respect to the un-welded material. A study of the stress distribution was conducted by elasto-plastic finite element analysis to assess the notch effect on the mechanical behavior of the material, showing sharper peaks for the un-welded specimen configuration.

Finally, *Baragetti and D'Urso*(42) investigated the effect of pin geometry and feed rate on the R = 0.1 fatigue behavior of a FSW butt weld over a 6060-T6 AA. The pin shape, varying between a flat and a tri-flute threaded profile, did not affect significantly the tensile properties, while the feed rate varied slightly the behavior, with higher tensile properties obtained at the lower feed rate of 150 mm/min, and a drop of about 5 MPa for a feed rate of 600 mm/min. The fatigue strength at 1e4 and 1e5 was found by staircase testing, highlighting a reduced fatigue strength drop for the unthreaded pin process, while the fatigue behavior of the welding was worsened by the adoption of the threaded tool. The fatigue strengths obtained on the FS welded samples with an unthreaded tool showed little dependence from the feed rate, leading to an efficiency of 62.5% at 1e4 and 69.5% at 1e5 cycles, with respect to the base material. The slope of the FS-welded material was hence less steep than the base material.

In Table 1, the numerical results from the presented literature(38-42) are reported for tensile tests and chosen fatigue lives.

Table 1: Tensile properties and fatigue behavior of FSW AA alloys – *R* = 0.1, from (38-42).

Material	Ref.	Test conditions	YS (MPa)	UTS (MPa)	S_{lim} (MPa)	N cycles
7075-T6	(38)	FS welded	-	-	79	2e6
7475	(39)	FS welded	-	-	131	2e6
6082-T6	(40)	Not welded	276	323	-	-
		FS welded	141	226	115*	2e2
		Mig welded	177	210	80*	2e2
6061-T6	(40)	Not welded	306	342	-	-
		FS welded	159	242	100*	2e2
		Mig welded	156	221	90*	2e2
6063-T6	(41)	Not welded	192	218	108*	2e2
		FS welded	112	193	124*	2e2
6060-T6	(42)	Not welded	223	252	239	1e4
					202	1e5
		FSW, unthreaded@ 150 mm/min	-	155	149	1e4
					144	1e5
		FSW, unthreaded@ 600 mm/min		150	146	1e4
					138	1e5
		FSW, threaded @ 150 mm/min	-	156	134	1e4
					129	1e5
		FSW, threaded @ 600 mm/min		149	126	1e4
					90	1e5

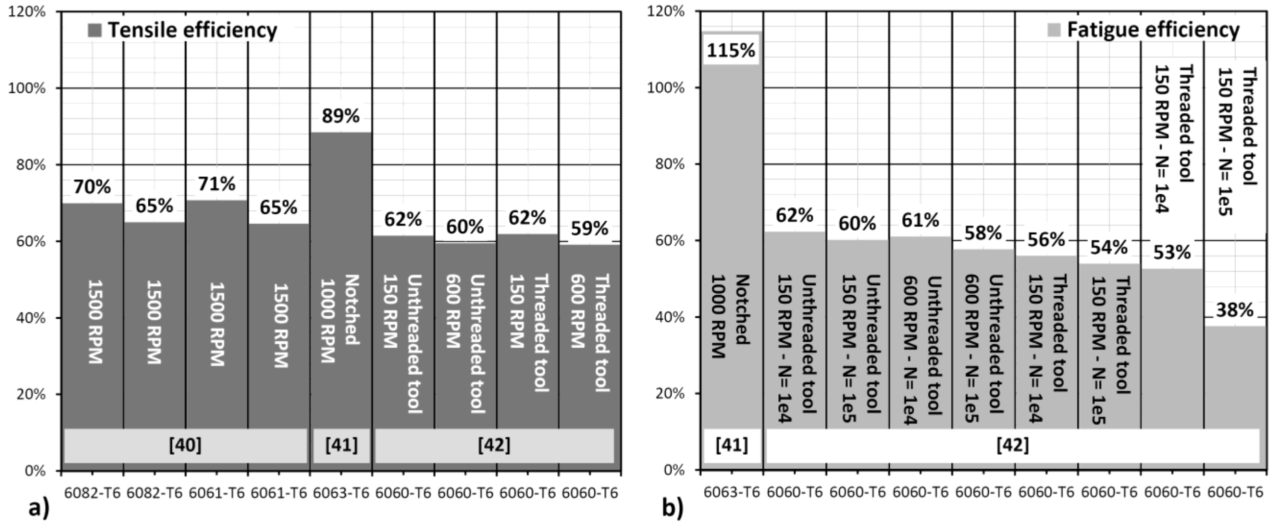
**Extrapolated from S-N curves*

By examining the data contained in Table 1, some significant facts can be highlighted. The FSW technique has proven to be sufficiently efficient for aluminum light alloys, especially concerning 6000 series aluminum alloys. The tensile and yielding strength loss is contained, if compared to classical MIG welding techniques(40). The main causes of such loss of tensile properties are to be found in the microstructural modification of the region affected by the FSW treatment(40,42), as well as by the presence of macroscopic defects in the weld seam in some cases(40).

Considering fatigue performances, significant fatigue drops were found for any tested material and configuration, due to the highly detrimental effects of local microstructure modification and macroscopic welding defects inside the specimens, as highlighted in (38). The fatigue cracks were started either from FSW defects(38) or from the surface of the samples(40-42). In some cases, the defects were determinant in the failure Mechanisms(38). In certain cases (41), defects in the FSW seam existed, but in the shape of internal voids, not affecting the surface(38). Their effects in fatigue crack initiation were not severe, as can be also assessed by looking at the results from Table 1.

To better investigate the overall performances of the welding procedures, the efficiencies in terms of UTS and fatigue strength ratios, concerning the data of Table 1, where extracted when available, and presented in Figure 4. Efficiencies were obtained comparing welded and not welded samples.

Figure 4–UTS tensile (a) and fatigue (b) strength efficiencies concerning FSW on aluminum light alloys, extrapolated from literature(40-42).



From Figure. 4, it can be seen that typical static efficiencies of FSW are roughly between 60 and 70 %, for aluminum alloys from the 6000 series. Concerning 6060-T6 samples, it has been found that such efficiency values were maintained for the fatigue strength, at least for unthreaded samples(42). Unfortunately, no values regarding un-welded samples for the comparison of fatigue strength were given by various authors(38-40). A specific mention must be made for the notched samples tested by *Moreira et al.* (41). The presence of the notch resulted in very high efficiencies for static and fatigue tests, particularly for low cycles fatigue loads. This fact highlights a reduced notch sensitivity of FSW junctions(41).

3.3. FSW effects on Ti-6Al-4V: A few literature works exist on the effect of the FSW technique on the fatigue behavior of the Ti-6Al-4V aluminum alloy, the first documented application being dated back in 2003 (43). Microstructural and tensile studies were available in the work by *Zhang et al.*(44), while the FSW fatigue behavior has been recently studied both for axial fatigue specimens tested at R = 0.1 and R = 0.6(44,45) and alternating fatigue of L shaped structures with R = -1(47).

In the work by *Zhang et al.*(44), tensile testing showed slight reduction of the YS and UTS of the material, which were further decreased by increasing the tool rotational speed. From a YS of 845 MPa, UTS of 940

MPa, related to the base material, a drop of about 1.5% UTS and 2.4% YS was found at 300 rpm. The strength reduction at 600 rpm was of 6.3% UTS, 7.1% YS. Shorter specimens, with the whole test section occupied by the stirred region up to the grips, showed however an increase in tensile properties, with an 11.7% UTS and 12.4% YS increase at 300 rpm. The increment was inferior for 600 rpm, being of plus 9.0% UTS and 11.2% YS. Concerning elongation, short specimens with extended FSW zone showed increased ductility.

The research carried on by *Sanders et al.*(45), investigated deeply the R = 0.1 fatigue behavior of a Ti-6Al-4V FSW process, by analyzing several process parameters and their influence on the fatigue strength of the material. The best fatigue limit, identified with the fatigue strength at around 1e6 cycles, was found when the FSW technique was accompanied by post treatment machining, stress relieving and low plasticity burning to introduce compressive stresses. In this case, the welding efficiency was around 91%, if compared to the base material, which presented a fatigue limit of 620MPa. The efficiency was lessened by another 13% if one between the machining and the low plasticity burning option was removed. The samples that did not present one of these two options, including not treaded and stress relieved only specimens, showed a much worse fatigue behavior, with dramatic fatigue limit drops.

In a paper by *Edwards and Ramulu*(46), tensile properties and R = 0.1 and 0.6 fatigue behavior of FSW Ti-6Al-4V samples of different thicknesses have been presented. The FSW specimen presented average UTS of 1025 MPa, and a YS of 974 MPa, comparable to the base material, even if with reduced elongation. The R = 0.1 fatigue results showed an S-N trend which was very close to the base material for the 3mm thickness samples. The R = 0.1, 6mm and the R = 0.3, 3mm and 6mm samples showed a higher dispersion and slightly inferior values of S_{lim}.

Finally, in another work by *Edwards and Ramulu*(47) performed R = -1 bending tests of L shaped, 6mm thick Ti-6Al-4V structural details, comparing the results obtained by FSW details with the fatigue behavior of the same details obtained from wrought and extruded material(47). The S-N results demonstrate an equivalent, if not better behavior of the FSW details. FSW on Ti-6Al-4V alloy is indeed proposed by the authors of reference cited (47) as an ideal candidate to assembly structural details for high fatigue resistant components for aerospace and other advanced engineering applications.

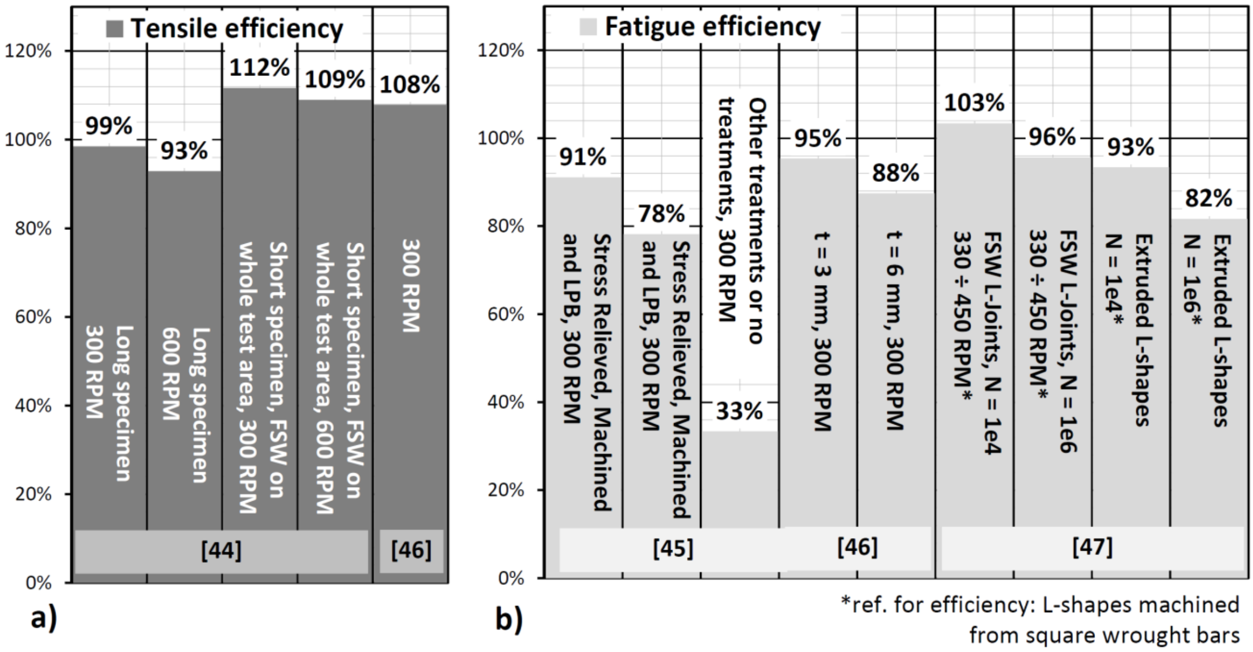
Table 2: Tensile properties and fatigue behavior of FSW Ti-6Al-4V alloy, extrapolated from experimental data (44-47).

(44) Tensile	**YS (MPa)**	**UTS (MPa)**
Base material	845	940
Long 300 rpm	825	926
Long 600 rpm	792	873
Short 300 rpm	950	1050
Short 600 rpm	940	1025
(45) Fatigue, R = 0.1	***N***	***S* (MPa)**
Base Material	1e6	620
Stress Relieve + Machining and LPB	1e6	565
Stress Relieve + LPB or Machining	1e6	485

Othertreatments or no treatments	1e6	207
(46) Tensile	**YS (MPa)**	**UTS (MPa)**
Un-welded	880	950
FSW	975	1025
(46) Fatigue, R = 0.1	***N***	***S* (MPa)**
Base material	1e6	760
t= 3 mm	1e6	725
t= 6 mm	1e6	665
(47) Fatigue ,R = -1 - L-joints	***N***	***S* (MPa)**
FSW Joints	1e4	751
	1e6	328
Machining from square bars	1e4	727
	1e6	343
L-shape extrusion	1e4	679
	1e6	280

The overall static and fatigue mechanical properties analyzed in literature(44-47) are presented in Table 2. From the reported results, it is evident that FSW shows an optimal behavior on the Ti-6Al-4V alloy. The tensile properties are typically comparable, when not better, to the behavior of the un-welded samples. Concerning fatigue strength, it is possible to obtain very high efficiencies on Ti-6Al-4V FSW. However, proper process parameters, including weld surface machining, stress relieving and low plasticity burning have to be adopted, otherwise highly detrimental effects are found(45). Besides, correctly treated FSW assemblies of structural details can results in weld fatigue performances comparable, if not superior, to the base material (47). In order to quantify properly the FSW effects, the efficiencies over the base material have been summarized in Figure. 5.

Figure 5– UTS tensile (a) and fatigue (b) strength efficiencies concerning FSW on Ti-6Al-4V alloy, extrapolated from literature(44-47).



4) Summary

In the present review work, a survey on the effects of innovative processes on high strength-to-mass ratio aluminum and titanium alloys has been carried out. The impact of PVD coatings and FSW techniques on such alloys were investigated. Tensile and fatigue properties have been assessed by analyzing the most recent experimental research works available in literature. The following conclusions are reported, to give ready indications to mechanical designers:

Concerning the effect of PVD coatings on 7075-T6, high-strength aluminum alloy, fatigue strength drops must be expected. ZrN, WCC and DLC coatings on diamond polished surfaces shown respectively a -24%, -24% and -15% on fatigue strength at 2e5 cycles, for $R = -1$ rotating bending tests. TiN deposition resulted in the worst performances with a 35% drop at 2e5 cycles, $R = 0.1$.

PVD performances on 7075-T6 are improved when fatigue testing is performed in aggressive environments, due to improved corrosion resistance. Considering $R = -1$ fatigue strength at 2e5 cycles, encouraging effects have been found on ZrN, WCC and DLC coated specimens. ZrN coated samples in NaCl showed no difference with respect to the coated ones. WCC specimens in methanol resulted in a fatigue strength drop of -9%, while DLC showed a positive gain in fatigue strength of +10%, in the same environment.

TiN coated Ti-6Al-4V showed fatigue strength drops if compared to the base material. Variable magnitudes were identified by researchers, varying from null to -18% fatigue strength drop at 2e6 cycles. The fatigue drop was reduced in the presence of notches.

By examining the effects of FSW joints on 6000 series AA, tensile and fatigue efficiencies ranged between 58% and 71%. An exception was assessed for notched specimens, where 89% tensile and 115% fatigue strength efficiencies were achieved. Moreover, the adoption of threaded tools for FSW reduced the fatigue strength of the material well below the 60% threshold. Optimal FSW performances were obtained on Ti-6Al-4V samples and structural details. Tensile efficiencies ranging from 93% to 112% were found. Concerning fatigue strength, efficiencies from 78% up to 103% were found on FSW welded samples, at different fatigue lives. However, fatigue tests on specimens which were not properly machined, stress relieved or welded with low plasticity burning, resulted in a dramatic fatigue strength drop, with a weld efficiency of just 33%

5) Funding and Conflict of Interest

The authors state that the present work has been carried on by means of their own research funding. No conflicts of interest have been acknowledged by the authors.

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