Effect of shot peening conditions on fatigue strength of two alloys for turboengines disks

J.-Y. Guédou, SNECMA, Dept Matériaux et procédés- EVRY (France)

Introduction

Damage of operating highly loaded parts of turboengines, especially disks, is mainly due to flight cycles "take off-cruise-landing", which are cause of low cycle fatigue phenomena, with high stress-strain amplitude and low frequency. Therefore, it is very important to improve as much as possible the fatigue strength of those components, and surface conditioning is an outstanding parameter which greatly influences the fatigue life. A widely used industrial process for surface condition enhancement is shot peening (1), which is known to have effect both on mechanical properties and on surface microgeometry. Thus in order to determine the optimized conditions of shot peening on disks alloys a study of various shot peening parameters has been carried on concerning laboratory test specimens of two disks materials : a titanium and a nickel based alloys.

Experimental methods

Materials - The titanium based alloy Ti 6-4 (TA6V4) is broadly used in aeronautical industry, owing to its low density and high associated mechanical resistance up to 350°C : in turboengines, many compressor blades and disks are Ti6-4 forged. However, this alloy is sensitive to notch effect (2) and therefore, it is usually not employed as machined, but shot peening is often processed on high stressed zones of critical parts.
The nickel base superalloy INCONEL 718 (NC19FeNb) is very currently used for compressor and turbine disks manufacturing. Both alloys have been investigated in classical heat treated conditions :

. Ti 6-4 : 955°C/1 h/WQ + 700°C/2 h/AC. α/β structure with homogeneous α noduli
. INCO 718 : 955°C/1 h/AS + 720°C/8 h/AC 620°C/8 h/AC. Recrystallized fine grained structure. GS : ASTM 9-10

Surface conditioning - The test specimens are shot peened according to industrial process : steel shots 0.315 mm dia (SS315) or glass beads 0.160 mm dia (GB160) or 0.250 mm (GB250) for Ti 6-4. Glass beads shot peening operations are achieved either in water flow (W) or in dry gas (D). INCO 718 specimens are shot peened with steel shots (SS315) ; various industrial conditioned surfaces are considered : turned, milled, abrasive clothed and electrochemical machined. Shot peening intensities are defined using classical ALMEN strips (1,3). Reference ALMEN deflections in this study are 0.15 or 0.20 mm on A-type specimen (noted F15A/F20A) and 0.30 mm on N-type specimen (F30N).

Physical measurements - The roughness Ra is defined as an arithmetic average value derived from the variations between the actual outline and the center line of the surface. This measurement is performed by integrating the signal generated by a sharp "pencil" following the contour of the surface.
The residual stresses are determined by X-rays diffraction, using $\sin^2\psi$ classical law (4). Residual stresses profiles are sometimes drawn by successive applications of the previous method, after electrolytical dissolutions which eliminate a 15-20 μm depth layer.

Mechanical testing - Stress controlled fatigue tests are performed at room temperature on Ti 6-4 hourglass specimens (fig. 1) in axial loading :

.../...

SURFACE CONDITION	$\sigma 10^4$ cycles MPa	Residual stress MPa	Roughness Ra µm
Low stress grinding + polishing	975	150	0,13
" " + SS 315 F15A	950	830	1,53
" " + GB 160W F30N	950	510	1,13
Turning + Etching	1000	NO VALUE	NO VALUE
" " + SS 315 F15A	970	NO VALUE	NO VALUE

TABLE 1

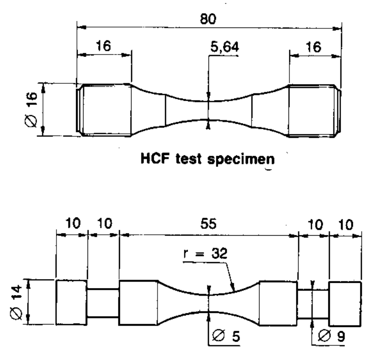


Figure 1 Ti6-4 Fatigue specimens

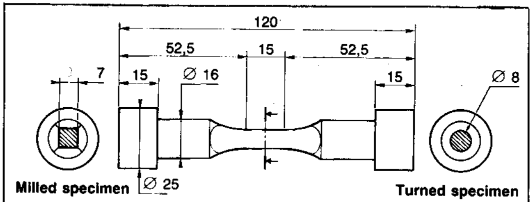


Figure 2 INCO 718 Fatigue specimens

. Low cycle fatigue : 0,5 hz frequency sine waves or 0.01 hz frequency trapezoïdal waves, between 5.10^3 and 2.10^4 cycles ;
. High cycle fatigue : 100 hz frequency sine waves up to 10^7 cycles.

Stress controlled low cycle fatigue tests are carried out at 550°C on INCO 718, using smooth cylindrical or square specimens (fig. 2), with 0,5 hz frequency. Scanning microscopic investigations are achieved to compare surface conditions and to determine the fatigue crack initiation locations.

Influence of shot peening on low cycle fatigue resistance of Ti 6-4

Surface condition effects - The experimental results for two different surface conditions are shown in table 1. It can be seen that in spite of important residual compressive stresses generation, shot peening does not improve the low cycle fatigue resistance.

However, in the previous conditions, shot peening was achieved on initial elaborate surfaces : in this case, it has a very limited effect. On the contrary, the results concerning initial deteriorate surfaces are quite different : when shot peening is processed on an initial conditioned surface exhibiting circumferencial misoriented scratches (fig. 3), a beneficient influence is then observed :

- reference (circumferencial scratches) : Nf = 3.685 cycles for σ_{max} = 900 MPa (R_σ = 0)
- reference + shot peening (SS315-F15A) : Nf = 4.812 cycles for σ_{max} = 900 MPa (R_σ = 0)

i.e. 30 % life improvement.

Those results confirm that Ti 6-4 is very notch sensitive : it has been pointed out that (5) the scratches sharpness is more damaging than their depth. Altogether, the tests results show that shot peening main effect on Ti 6-4 smooth specimens fatigue lives is due to the improvement of the surface condition, by eliminating ill-oriented machining defects, and not to the generation of compressive residual stresses.

Influence of shot peening time exposure - The basic reference peening time, determined by saturation curves on ALMEN strips (3), has been multiplied by a factor 8. The over-peened specimens exhibit many flakes and upsets, but their fatigue life is not altered, as shown in table 2 and fig. 4.

Discussion - It appears that low cycle fatigue life on Ti 6-4 smooth specimens is strongly influenced by microgeometrical surface conditions, on account of notch sensitivity of this alloy. So the possible positive effects of shot peening will be, in that case, mostly due to surface condition improvement, rather than to local surface compressive stresses. Therefore, Ti 6-4 parts shot peening is beneficient provided it is processed using adequate conditions, that mean sufficient peening time to eliminate defects.

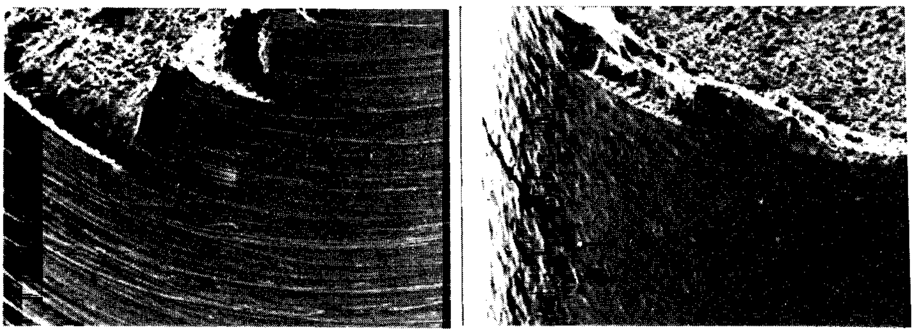
Influence of shot peening or high cycle fatigue resistance of Ti 6-4

Correlation between endurance limit, roughness and residual stresses - Many studies have been devoted to shot peening effects quantizing and as far as endurance limit is concerned, inconsistent results are found. The residual stress level appears to influence crack initiation life (5) but no obvious relation can be established (6) between endurance limit, roughness and surface stresses. The effect of roughness on rotative bending endurance limit has been emphasized (7): in that case, the beneficient shot peening effect may be due to the existence of a stress gradient, since the surface compressive stresses significantly lower the maximum resulting stress.

High cycle fatigue tests, in axial loading sense (i.e. no stress gradient) have performed on specimens which have been shot peened under various conditions.

Shot Peening Time / σ Max MPa	To		8 To	
	N_F	Residual stress MPa	N_F	Residual stress MPa
900	9378	- 410	10774	- 570
850	27437	- 470	27978	- 580

TABLE 2

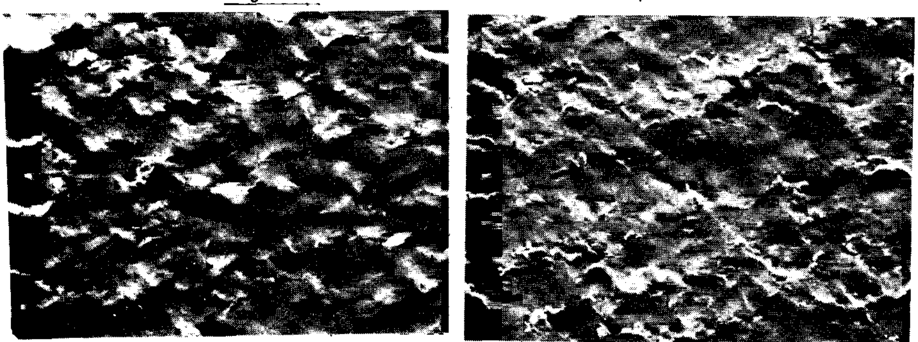


a - Low stress grinding + circumferencial polishing

b - 3 a + shot peening

0.5 mm

Figure 3 Abrasive clothed Ti 6-4 specimens



To

100µm

8 To

Figure 4 Peening time effect on Ti 6-4 specimens surfaces

The results are presented figures 5 to 8.

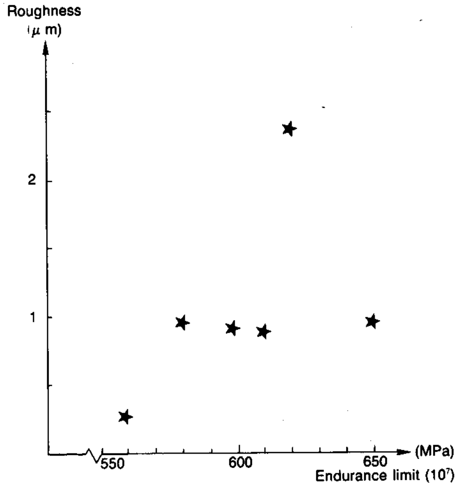


Figure 5 Correlation Roughness/ Endurance limit

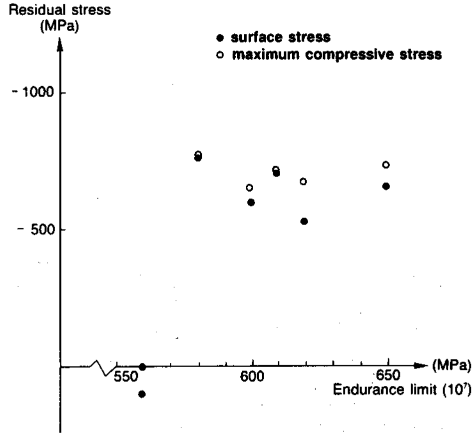


Figure 6 Correlation Residual Stress/ Endurance limit

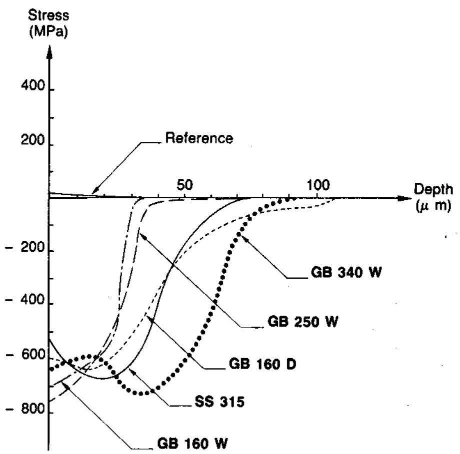


Figure 7 Residual stress profiles on Ti6-4 Shot peened spec.

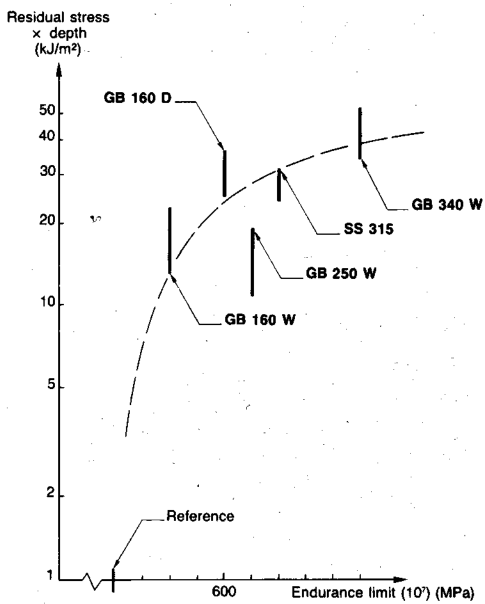


Figure 8 Correlation endurancelimit/ Deformation energy

The endurance limit is always increased on shot peened specimens (+3 to +16%). However, no correlation between endurance limit, roughness (fig. 5) and surface residual stresses (fig. 6) has been established, contrary to pure nickel (8) where a simple relation $Nf = CRa^m$ (Nf : number of cycles to failure - Ra : roughness) is found. Moreover, the residual stresses profiles analysis (fig. 7) reveals that the maximum compressive stress is also an inadequate parameter to account for endurance limit variations. A better correlation is described using the term $\sigma r \times d$ (d : plastified depth) (fig. 8) which represents the plastic deformation energy on shot peened surface unity.

Residual stresses influence - The microscopic investigations on failed specimens reveal that fatigue crack initiations on reference condition specimens (low stress grinding + polishing) are located on the surface while those on shot peened specimens occur in a subsurface layer (0.4 to 0.8 mm depth). As already noticed (7) these observations emphasize the role of residual surface stresses to delay crack initiation by shifting the maximum peak stress inwards the specimen.

Discussion - As smooth Ti 6-4 specimens are concerned, shot peening has a beneficient effect on high cycle fatigue resistance, and no influence on low cycle fatigue strength. The former point is due to residual compressive stresses, that delay crack initiation period, which constitutes most of high cycle fatigue life. On the contrary, these surface stresses have small influence on low cycle fatigue life, which may be accounted for by residual stresses relaxation (5,7), due to temperature and/or elastoplastic cycling phenomenon. In that case, the only beneficient effect of shot peening which is possibly observed, is due to the microgeometrical surface improvement.

Influence of shot peening on low cycle fatigue resistance of INCONEL 718

Experimental results - LCF tests at 550°C on shot peened (SS315-F20A) specimens ($R_\sigma = 0$ - 0,5 hz) have been achieved. The results are summed up in table 3.

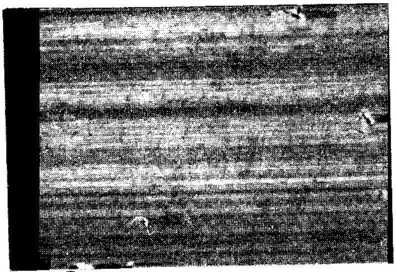
While increasing roughness values, shot peening improves LCF strength of INCONEL 718 up to 50.000 cycles. As for Ti 6-4, the negative effect of ill-oriented scratches (see 1 and 3) is partly balanced by shot peening, as far as scratches may remain after this operation (see fig. 9). The beneficient effect, in comparison with reference (see 0), is the most important for ECM (see 5 and 6) which creates detrimental defects on the surface.

Discussion - The effects of shot peening in superalloys have been much less studied than in steels or aluminium alloys. In the case of a 80 Ni - 20 Co alloy (9), a relaxation of residual stresses is observed on bending cycles specimens with high load (over the elastic strength). The influence of temperature has been evidenced on Nimonic - 20 % Cr (10) : compressive stresses are totaly relaxed over 550°C under fatigue loadings. However, the beneficient effects of shot peening are assumed to be related to hardening substructures on surface layers. As regards INCONEL 718, it has been observed (11) that compressive stresses remain roughly stable below 700°C. A significant improvement of LCF lives is then observed, and this is consistent with our results. In this case, the surface microgeometrical defects are less harmful than on Ti 6-4.

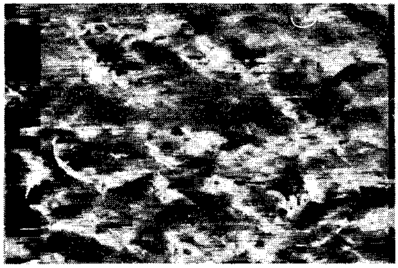
Conclusion

The influence of shot peening on mechanical resistance of Ti 6-4 at room temperature, and INCONEL 718 at 550°C, has been studied, and a general beneficient effect of this process is observed due to :

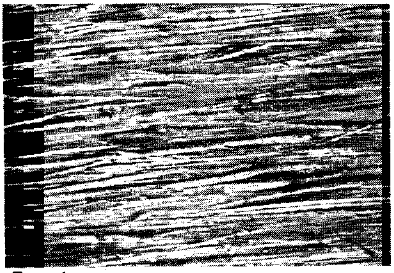
- surface condition improvement, i.e. elimination of small geometrical machi-



1 Turning

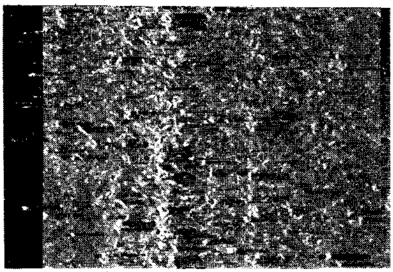


2 - 1 + shot peening (SS315-F20A)

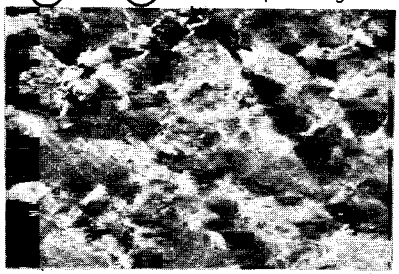


3 Turning + Transverse abrasive clothing

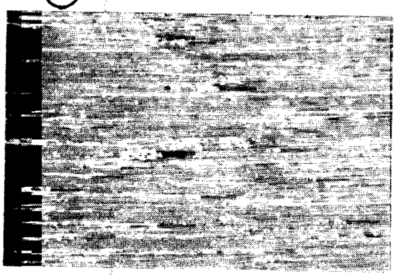
4 - 3 + shot peening



5 E. C. M.

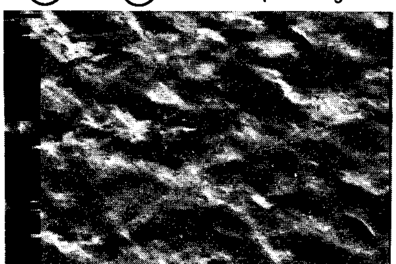


6 - 5 + shot peening



7 Milling

100 µm



8 - 7 + shot peening

Figure 9 Surface conditions on INCO 718 specimens

ning defects, which may promote fatigue crack initiations ;
- superficial compressive stresses generation, which are cause of crack initiation delay.

The later point is the most important, but the effect may be attenuated by relaxation, according to the chosen material and the thermo-mechanical loading conditions.
Nevertheless, the former point will be always achieved by implementing shot peening in well defined conditions (process and quality control). On that point of view, shot peening is an industrial substantial process, and this justified its wide application on aeronautical parts.

SURFACE CONDITION	ROUGHNESS RA μm	LOW CYCLE FATIGUE			
		σ 10^4 MPA	$\frac{\sigma\ I}{\sigma\ REF}$	σ $5\text{-}10^4$ MPA	$\frac{\sigma\ I}{\sigma\ REF}$
0 - REFERENCE LONG STRESS GRINDING + POLISHING	0,09	1190		1115	
1 - TURNING	0,7	1130	0,95	1050	0,94
2 - TURNING + SHOT PEENING	1,1	1190	1	1140	1,02
3 - TURNING + TRANSVERSE ABRASIVE CLOTHING	2,5	1025	0,86	UNDETERMINED	-
4 - TURNING + TRANSVERSE ABRASIVE CLOTHING + SHOT PEENING	1,4	1035	0,87	UNDETERMINED	-
5 - ELECTROCHEMICAL MACHINING	0,9	1110	0,93	1025	0,92
6 - ELECTROCHEMICAL MACHINING + SHOT PEENING	1,5	1190	1	1115	1
7 - MILLING	0,4	1170	0,98	1090	0,98
8 - MILLING + SHOT PEENING	1,1	1190	1	1140	1,02

Table 3

References

(1) A. Niku-Lari - 1st Int. Conf. on Shot Peening (ICSP1) Paris (1983) 1
(2) V. Zaltin and H. Field - Titanium Science Technology (1973) 489
(3) D. Clark and S.S. Birley - ICSP1 (1983) 167
(4) G. Maeder, J.L. Lebrun and A. Diament - ICSP1 (1983) 263
(5) G.R. Leverent, B.S. Langer, A. Yuen and S.W. Hopkins
Met. Trans. 10A (1979) 251
(6) D.N. Williams and R.A. Wood
MCIC. Report 71-01 (1971)
(7) L. Wagner and G. Lutjering - ICSP1 (1983) 453
(8) T.W. Biven and C.E. Price - Sampe Quaterly (1979) 12
(9) B.D. Boggs a,d J.G. Byrne - Met. trans., 4 (1973) 2153
(10) W. Renzhi, Z. Xuecong, S. Deyu and Y. Yuania - ICSP1 (1983) 395)
(11) Machining Data Handbook - 3rd ed. (1980) 117