SHOT-PEENING OF SUPERALLOYS AND ITS FATIGUE PROPERTIES AT ELEVATED TEMPERATURE

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ABSTRACT

The effects of shot-peening on the elevated temperature fatigue properties (550—800°C) of four iron base, four wrought nickel base and one cast nickel base superalloys were investigated. It was found that the elevated temperature fatigue strength of all superalloys can be improved by shot-peening in different degree, and the effects of fatigue improvement are more pronounced for notched specimens.

KEYWORDS

Shot-peening; elevated temperature fatigue (superalloys); subgrain; lattice distortion; residual stress; fractography.

INTRODUCTION

Shot-peening technology developed in the 40's of 20th century has been proved to be efficient to improve the fatigue properties and corrosion resistance of materials (Manson, 1971; Almen, 1963; Liu So, 1977). The application of shot-peening to improving fatigue of parts working in the elevated temperature (especially turbojet parts) was not conducted extensively for a period of time. In the past decade, the investigation and practice of this technology indicated that it can be effectively used to improve the elevated temperature fatigue properties of superalloys. However, the practice of this technology has gone far ahead analytical works. The mechanism of shot-peening is not fully recognized.

Generally speaking, shot-peening process is a process that the surface layer of materials subjects to the plastic deformation. This plastic deformation is taken place under alternating stresses. As a result of cyclic straining, the surface layer subjects to "cyclic hardening" or "cyclic softening" (Wang, 1981).

Two following changes in the straining layer are taken place after shot-peening; the changes in the microstructure (dislocation density and its arrangment; the subgrain size, the phase transformation, etc.), and the changes in the residual stresses in the surface layer. All these changes may affect the fatigue strength of alloys at room and elevated temperature. Hence, an attempt has been made to study the effect of shot-peening process on the elevated temperature fatigue of superalloys as well as the role of two above mentioned factors in the improvement of fatigue properties.

MATERIALS AND EXPERIMENTAL PROCEDURES

Four kinds of iron base superalloys (GH135, GH140, GH132, GH36), four kinds of wrought nickel base superalloys (GH30, GH32, GH33, GH37) and one cast nickel base superalloy (K6) are used. Chemical compositions of them are summarized in Table 1 and Table 2. The geometry and the size of fatigue specimens are shown in Fig. 1.

TABLE 1. Chemical Compositions of Iron Base Alloys

Material	Chemical compositions (%)							
	C	Cr	Ni	Ti	Al	W	Mo	Fe
GH36	0.38	12	8	0.12	—	—	1.30	Bal.
GH132	0.08	14.5	25.5	2.0	0.40	—	1.25	Bal.
GH135	0.08	15	34.5	2.3	2.6	1.9	1.90	Bal.
GH140	0.09	21	37.0	0.9	0.3	1.6	2.30	Bal.

TABLE 2. Chemical Compositions of Nickel Base Alloys

Material	Chemical compositions (%)							
	C	Cr	Al	Ti	W	Mo	B	Ni
GH30	0.12	20	0.15	0.25	—	—	—	Bal.
GH32	0.06	20	0.75	2.40	—	—	—	Bal.
GH33	0.06	20	0.75	2.40	—	—	0.01	Bal.
GH37	0.12	15	2.60	1.95	6.0	3.5	0.02	Bal.
K6	0.15	16	3.55	2.50	—	3.5	0.07	Bal.

Residual stress measurement were carried out on 2903 type X-ray strain diffractometer using CuKα (for nickel base alloys) radiation and (420) reflection line.

Using CoKα radiation, (111) and (311) reflection lines (for iron base alloys), CuKα radiation, (111) and (420) reflection lines (for nickel base alloys), subgrain size, D, and lattice distortion, $\Delta a/a$, (a is lattice parameter) were measured on D9-C type X-ray diffrectometer.

Shot-peening parameters for different specimens are summarized in Table 3.

TABLE 3. Shot-Peening Parameters for Different Specimens

Specimen	Shot-peening Parameters		
	Shot material	Shot diameter (mm)	Shot peening intensity, f_I* (mm)
GH30, GH36, GH132, GH135, GH140, specimens	glass	0.05—0.15	0.1—0.15
GH32, GH33 specimens and blades	glass	0.05—0.15	0.1—0.13
GH37 smooth specimens	glass	0.05—0.15	0.1—0.13
GH37 notched specimens	glass	0.25—0.30	0.12
K6 specimens	glass	0.35—0.45	0.15

* f_I is equivalent to A-2 for Almen gages.

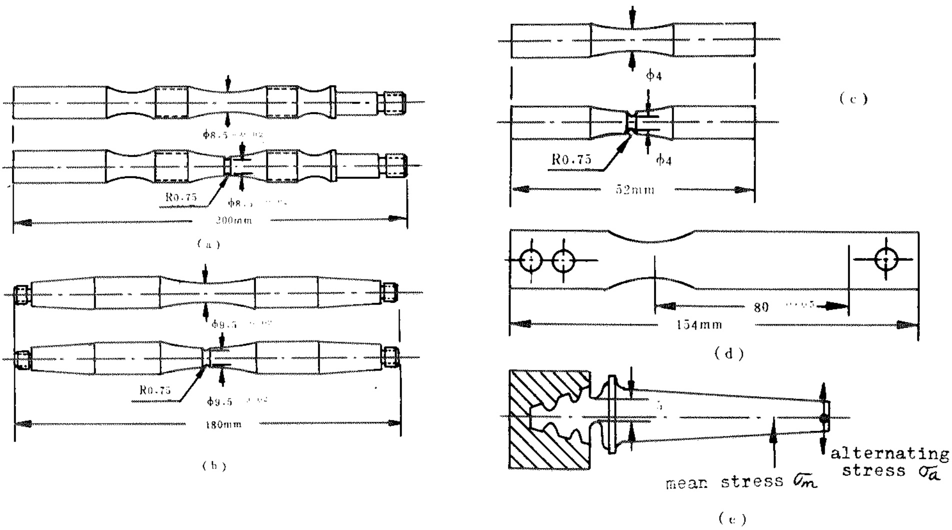


Fig. 1. Geometry and size of fatigue specimens; (a) smooth and notched (stress concentration factor $K_t=2$) rotating bending specimen (for GH33); (b) smooth and notched ($K_t=2$) rotating bending specimen (for GH36, GH132, GH135 and GH37); (c) smooth and notched ($K_t=2$) rotating bending specimen (for K6); (d) repeated bending specimen (for GH30, GH140); (e) bending specimen of blade dovetail (for GH33).

TEST RESULTS

(1) Fatigue results

The elevated temperature fatigue S-N curves for different alloys are shown in Fig. 2 through Fig. 6. The elevated temperature bending fatigue limit ($N=10^7$) of GH32 and GH33 blades are summarized in Table 4; fatigue test results of GH33, GH37 and GH135 alloys are summarized in Table 5.

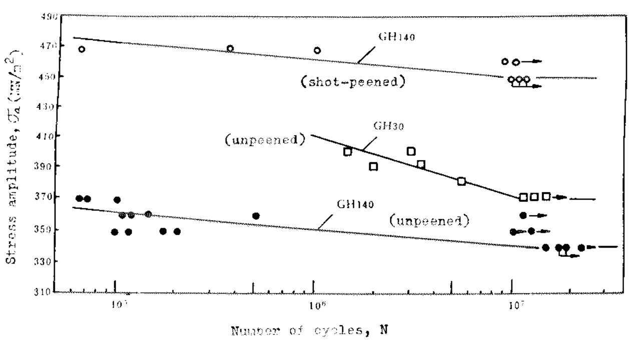


Fig. 2. Elevated temperature (550°C) repeated bending fatigue S-N curves for GH30 and GH140 plane specimens.

(2) Microstructure in shot-peening surface straining layer

In order to observe the microstructural changes in the shot-peening surface layer, GH33 alloy was heat treated at 900°C (held the heat for 20 min). It can be observed from Fig. 7 that the new fine recrystallization grains which are much smaller than the virgin coarse grains in the center of specimen, are existed in the surface straining layer.

The test results of D and $\Delta a/a$ for several alloys are listed in Table 6. D is fragmentized and $\Delta a/a$ is increased during shot-peening process. In the elevated temperature fatigue process, D and $\Delta a/a$ values may be, however, gradually changed due to the effect of temperature and alternating

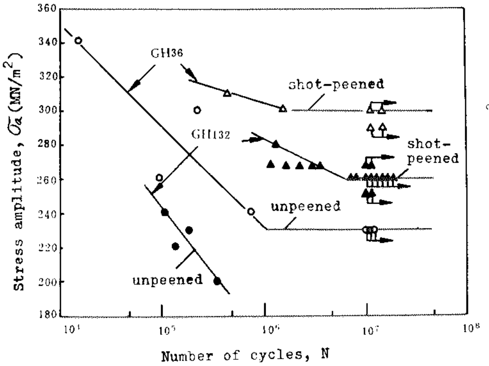


Fig. 3. Elevated temperature (600°C for GH36, 650°C for GH132) rotating bending fatigue S-N curves for notched specimens.

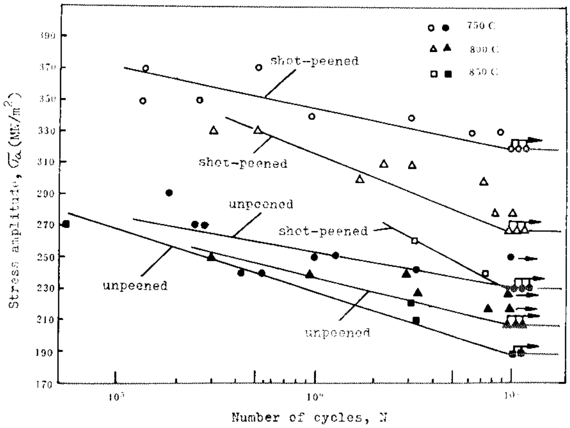


Fig. 4. Elevated temperature (750, 800 and 850°C) rotating bending fatigue S-N curves for GH37 notched specimens.

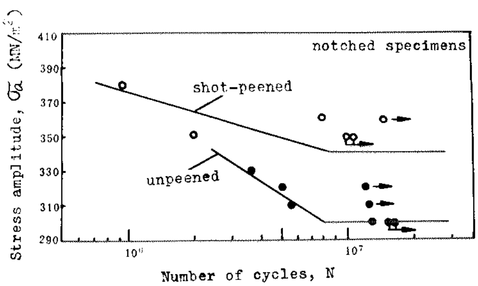


Fig. 5. Elevated temperature (550°C) rotating bending fatigue S-N curves for K6 notched specimens.

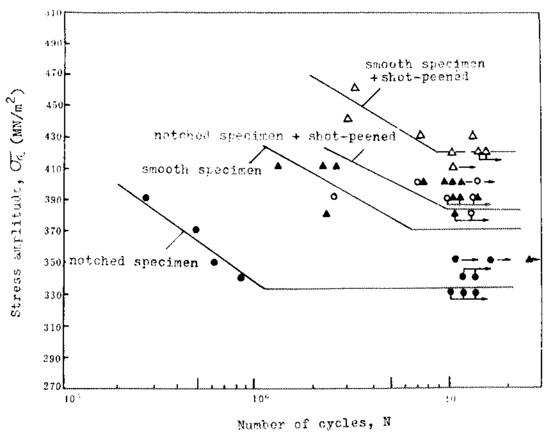


Fig. 6. Elevated temperature (650°C) rotating bending fatigue S-N curves for K6 smooth and notched specimens.

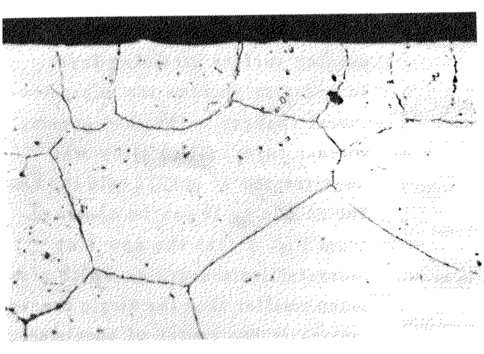


Fig. 7. Microstructure of straining layer and virgin material for GH33 alloy after shot-peening and heat-treatment, 200×.

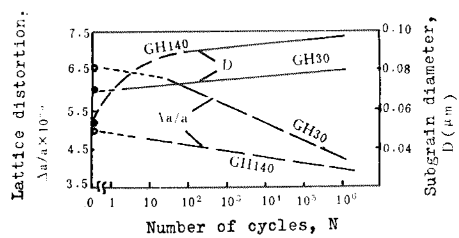


Fig. 8. Variations of D and $\Delta a/a$ with increasing number of cycles at 550°C for GH30 and GH140 alloys after shot-peening (stress amplitude $\sigma_a = 333$ MN/m^2).

TABLE 4. Elevated Temperature (550°C) Fatigue Testing Results for GH32 and GH33 Blades

Material	Blade state	Mean stress (MN/m^2)	Stress amplitude (MN/m^2)	Cycles to failure (Cycles)	Cracks at dovetail root
GH32	after hundreds hours operation (unpeened)	353	176	3.14×10^5	Yes
		373	186	6.14×10^5	Yes
		373	206	3.28×10^5	Yes
GH32	after hundreds hours operation (peened)	373	206	1.00×10^7	No
		392	206	1.00×10^7	No
GH33	new	392	206	1.00×10^6	Yes
	after hundreds hours operation (peened)	392	206	1.00×10^7	No

TABLE 5. Elevated Temperature Rotating Bending Fatigue Testing Results for Superalloys

Material	Specimen mode	Testing temperatnre (°C)	Fatigue limit ($N=10^7$) (MN/m^2)	
			unpeened	peened
GH33	notched	550	290	323
	smooth	550	274	294
	smooth	700	353	392
	smooth	750	312	353
GH37	smooth	750	343	333
	smooth	800	333	324
	smooth	850	294	294
GH135	notched	450	171	270

stresses (Fig. 8).

The changes in the microstructure in the surface layer during the elevated temperature fatigue process may be recognized by X-ray diffraction pattern. Fig. 9 showed X-ray back reflection patterns of different specimens for GH33 alloy.

(3) Shot-peening residual stress and its variations during fatigue process.

The variation of σ_r with δ is changed with increasing shot-peened time (or intensity). The final depth profile of σ_r-δ curve and the depth of residual compressive stresses depend on cyclic hardening (or softening) behaviour of materials and shot-peening intensity.

Fig. 10 shows the σ_r-δ curves of GH33 and GH37 alloys. The hardness of superalloys used in the present test is in the range RC32-36, so that the depth profile of σ_r-δ curve of other superalloys are identified with above alloys. The depth of residual compresive stress is about 200μm. But the surface residual stress values are different between them.

Just like the changes of sub-structure, shot-peening σ_r changes with fatigue test process at room and elevated temperature. The variations of the surface σ_r during the action of temperature of GH37 are shown in Fig. 11. In general, the relaxation of σ_r in the elevated temperature fatigue process exhibits following features; σ_r decreases with increasing heat-temperature and the helding time; the maximum relaxation rate due to the temperature action is taken place at an earlier ten hours, and then changes slowly; residual stresses decrease with

TABLE 6. Subgrain Size, D, and Lattice Distortion, Δa/a, for Several Alloys.

Material	Surface conditions	D (μm)	Δa/a
GH140	quench, aging	0.35	1.01×10^{-3}
	quench, aging+peened	~0.05	5.05×10^{-3}
GH36	quench, aging	2.10	–
	quench, aging+peened	0.030	–
	quench, aging+peened 650°C (5 hr)	0.050	–
GH132	quench, aging	1.2	–
	quench, aging+peened	0.033	–
	quenech, aging+peened+650°C (5 hr)	0.094	–
GH30	quench	~1.00	1.01×10^{-3}
	quench, peened	0.045	6.57×10^{-3}
	quench, peened+600°C (1 hr)	0.045	–
GH33	quench, aging	>5.00	$<1.5\times10^{-4}$
	quench, aging+peened	~0.07	6.05×10^{-3}
	quench, aging+peened+750°C (250 hr)	~0.07	0

(a) (b)
(c) (d)
(e) (f)

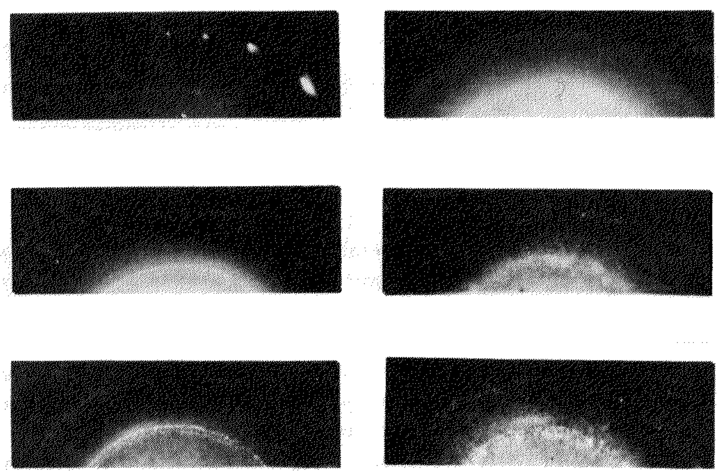


Fig. 9. X-ray back reflection patterns fo (331) and (420) for different specimens and blade of GH33 alloy (CuK_α radiation), (a) virgin material; (b) after shot-peening and fatigue test at 550°C ($N=10^7$); (c) after shot-peening and fatigue test at 700°C ($N=10^7$); (d) after shot-peening and fatigue test at 750°C ($N=10^7$); (e) after shot-peening and heat treatment at 700°C (held the heat for 3 hr); (f) after shot-peening and operating for 254 hr at about 750°C (blade).

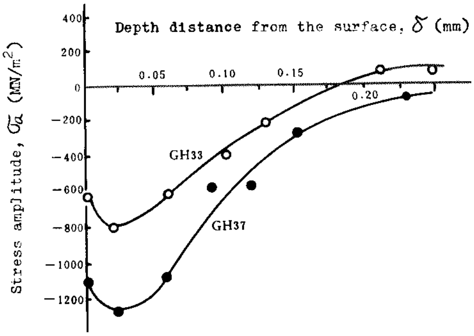


Fig. 10. Depth profile of σ_r–δ curves for GH33 and GH37 alloys.

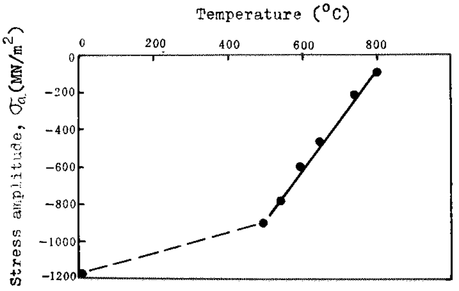
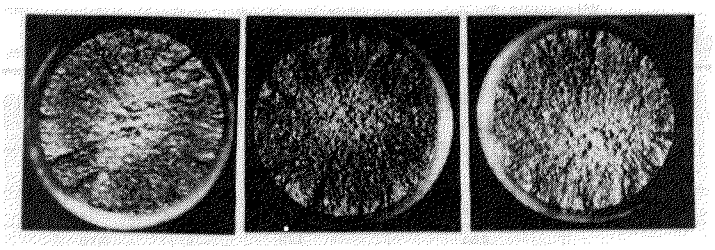


Fig. 11. Variation of σ_r with temperature (held the heat for 30 min) for GH37 alloy.

increasing the number of stress cycles, and the maximum relaxation rate is produced within about ten cycles (Liu So, 1977).

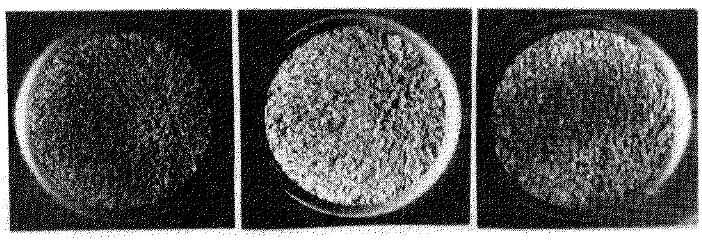
(4) Fractography of the elevated temperature fatigue

Fig. 12. and Fig. 13. show the fractographs of the elevated temperature (650°C) fatigue test for notched specimens of GH132 alloy before and after shot-peening. In general, the number of "steps" appeared at the fracture surface is proportional to the number of fatigue nucleuses as well as alternating stress level.



(a) (b) (c)

Fig. 12. Fractographs after elevated temperature (650°C) fatigue test for notched specimens of GH132 alloy, 3×: (a) σ_a=235 MN/m², N_f=1.58×10⁶; (b) σ_a=225 MN/m², N_f=3.11×10⁶; (c) σ_a=216 MN/m², N_f=1.72×10⁶.



(a) (b) (c)

Fig. 13. Fractographs after shot-peening and elevated temperature (650°C) fatigue test for notched specimens of GH132 alloy, 3×: (a) σ_a=275 MN/m², N_f=1.61×10⁶; (b) σ_a=265 MN/m², N_f=1.76×10⁶; (c) σ_a=255 MN/m², N_f=6.51×10⁶.

DISCUSSION

All elevated temperature fatigue test data can be summarized in Table 7. These test data suggest that the effects of shot-peening on the elevated temperature fatigue properties of superalloys exhibit following features: (1) the elevated temperature fatigue properties of superalloys could be improved by shot-peening in different degree; (2) the improvement of fatigue properties of superalloys by shot-peening depends on the heat-resistance of alloys, and the higher the heat-resistance, the greater fatigue properties improved at higher temperature; (3) under the same test conditions, the effect of shot-peening on the fatigue improvement is much better in the case of notched specimens than smooth specimens; (4) under the same test conditions, the effect of shot-peening on the fatigue improvement is better for iron base alloys than nickel base alloys. Fatigue properties of materials can be improved by shot-peening due to the effect of following two factors: the presence of residual compressive stress (Fig. 10), and the fragmentized sub-structure in the surface straining layer (Table 6).

Under the elevated temperature fatigue test conditions, the relaxation of residual stress is taken place rapidly by the effects of both temperature and applied alternating stresses. However, the higher heat-resistance, the more stable of residual stresses at high temperature. If only an alternating stress is applied, the residual stresses can also be relaxed. The test results suggest that the surface residual stresses of superalloys have been rapidly relaxed during fatigue process above 550°C. Hence, the effect of shot-peening on the elevated temperature fatigue properties of superalloys would seem primarily to be attributed to the effect of the sub-structure in the surface strain layer. The austenite superalloys used in the present test, in general, exhibit the microstructure with

TABLE 7. Elevated Temperature Fatigue Limit Before and After Shot-Peening for Different Alloys

Material	Specimen mode	Test temperature (°C)	Fatigue limit ($N=10^7$) σ_{-1} (MN/m^2)		Increament of σ_{-1} (%)
			unpeened	peened	
GH140	smooth	550	344	450	31.4
GH135	notched	450	171	270	57
		550	235	294	25*
GH36	notched	600	225	294	30.4
GH132	notched	650	196	250	⩾27.5
GH33	notched	550	290	323	11.9
	smooth	550	274	294	7.2
	smooth	700	353	392	11.0
	smooth	750	314	352	12.5
GH37	smooth	750	343	333	−3
		800	333	324	−3
		850	294	294	0
	notched	750	235	324	29
		800	216	275	27.3
		850	196	235	20
K6	notched	550	304	343	13
		650	333	392	14.7
	smooth	650	380	421	10.3

* These data are taken from Ke Wei (1975).

coarse grains, (Fig. 9, a), and they exhibit "cyclic hardening" properties. The D value of these superalloys are usually 0.4~5μm, whereas it can be fragnentized to 0.03~0.07μm after shot-peening. The value $\Delta a/a$ can be reached to 6×10^{-3} after shot-peening (Table 6). This sub-structure may be, however, changed during the following fatigue process, and the change tendency exhibits following features: (1) $\Delta a/a$ is decreased and D is increased respectively with increasing the number of cycles; (2) when the temperature reaches its recrystallization temperature, the recrystallization of deformation mcirostructure in the surface straining layer may be taken place (Fig.9, c, d, e). Comparing with all these changes, it is found that $\Delta a/a$ is recovered rapidly, but D is changed slowly with increasing fatigue cycles, the recrystallization process is also taken place slowly, and that the coagulation recrystallization is not taken place in the straining layer for 254 hr operation at a given elevated temperature for GH33 (Fig. 9, f). The above experimental datum suggest that it is only the fragmentized subgrains or the new fine recrystallization grains to play a primary role in the improvement of the elevated temperature fatigue properties.

Most of the experimental results have indicated that the material with fine grains exhibits higher fatigue strength than that one with coarse grains for the same material (Hayden, 1973). The materials with fine grains exhibit higher fatigue strength at room and elevated temperature. Most of the experimental data have also indicated that the fatigue strength of material is increased with decreasing subgrain size for a certain conditions (Challenger, 1972; Grosskreutz, 1963).

It can be observed from Fig. 12 and Fig. 13 that the shot-peened specimens have less number of steps at fracture face compared with unpeened specimens. This fact suggests that the presence of fine subgrains (or new fine recrystallization grains) in the surface strainig layer may play an important role in the resistance or retardation of fatigue crack initiation at the specimen surface.

In regard to the phemmenon that the effect of shot-peening on the improvement of fatigue properties is much greater for notched specimens than smooth specimens, and further investigations be conducted in the future.

CONCLUSIONS

(1) Shot-peening may be used to improve the elevated temperature fatigue properties of superalloys. Its effect is more pronounced for notched specimens.

(2) the effects of fatigue improvement are much greater in the case of iron base superalloys than nickel base superalloys under the compatable temperature.

(3) The fine subgrains or new fine recrystallization grains in the surface straining layer produced by shot-peening play a primary role in the improvement of the elevated temperature fatigue properties of supperalloys.

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