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THE EFFECT OF REST PERIODS ON THE FATIGUE LIFE OF MEDIUM CARBON STEEL UNDER DIFFERENT FATIGUE LOADING

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ABSTRACT

The fatigue crack growth (FGG) behaviour of medium carbon steel alloy under different rest periods is investigated under room temperature and stress ratio R= -1 using replication technique . This work examines the constant and variable amplitude torsional fatigue under different time of rest periods . The short and long fatigue crack growth equations are obtained experimentally . The average grain size diameter is 0.277 mm which separates between short and long crack region. The main remarks can be drawn from this work are :

The fatigue life of specimens is increase by rest periods under constant amplitude tests . The factor of increasing is about 1-12 . While this factor becomes 1.75 – 8.7 times the predicted life for variable amplitude tests . Rest periods generate strain ageing which in terms increase the total fatigue life .

الخلاصة

تم مناقشة تصرف معدل نمو شقوق الكلال لسبيكة الفولاذ متوسط الكاربون عند فترات استراحة مختلفة تحت درجة حرارة الغرفة ونسبة اجهاد R=-1 . هذا العمل يفحص الكلال ثابتة السعة ومتغيرة السعة لكلال الالتوائي عند ازمان مختلفة من فترات الاستراحة . تم استخراج معادلة نمو الشقوق الصغيرة والكبيرة عملياً . معدل حجم الحبيبة لمعدن السبيكة وجد 0.277 ملم والذي يفصل بين منطقة الشقوق الصغيرة والكبيرة . أهم الملاحظات التي تم استخلاصها من هذا العمل هي ان عمر الكلال للعينات ازدادت بواسطة فترات الاستراحة لفحوصات الكلال ثابتة ومتغيرة السعة . عامل الزيادة تتراوح بين 1 – 12 بينما هذا العامل اصبح 1.75 – 8.7 اكثر من العمر المخمن لفحوصات متغيرة السعة . فترات الاستراحة خلقت تعتيق انفعالي والذي بدوره عمل زيادة عمر الكلال الكلي .

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1- INTRODUCTION AND PREVIOUS WORK

In the last fifteen years increasing in test has been focused on short fatigue crack (Higuchi,M,2006),(Chopra,O.K,2005),(Hickling,J,2005),(Van Der Sluys,2003),(LankfordJ,1982), (Chan K.S,1983),(Jan Kohout,2008),(T.Mann,B.W,2006) and (Caglayan,2008).In order to make accurate life time predictions, this area of crack growth needs be well understood. Long crack can be described using linear elastic fracture mechanics (L.E.F.M.), (Taylor, 1981), (Frost, 1965), attempts have been made to apply long crack growth models in the short crack regime (Chapra, 2005)and (Lankford, 1982), but many problems have appeared which gave a non conservative prediction of fatigue life time of the specimens or components. For this reason serious attempts have been made to model the anomalies behavior of short cracks. The aim of the present work is to obtain the effects of different rest periods on short and long fatigue crack of medium carbon steel specimens subjected to reversed torsion. Also the influence of rest period on fatigue life time is investigated under constant and variable amplitude test. Very little informations are available concerning the influence of rest periods on fatigue life. Amit Bhasin (2009), found that rest periods produced an increase in the endurance of iron and plain carbon steels.

Miller and hatter (1974), however, reported a substantial increase in the fatigue life of an alloy (EN25). Schiffner (1999), also demonstrated that the dominant parameter governing the observed effect was the total rest period time, the number, duration and position of individual rests being of secondary importance. Recently, Brown and smith (1984), tested specimens of Ti-6Al-4V alloy and has shown increases in the 10^7 cycles endurance limit stress of 50 Mpa and also increases in shorter fatigue endurance as a result of such interruption.

Investigation on steel (G.De,2010),had previously shown improvements in life as a result of rest periods and these had been attributed to strain ageing as a result of carbon or nitrogen diffusion.

2- EXPERIMENTAL DETAILS

2.1 Material and Specimen design

In order to compare the present work with previously reported data (Takanori, 2007), a similar specimen geometry and material were chosen for this study. Further details of the material used, test – specimen dimensions, alloy composition, heat treatment, and the torsion test rig are presented else where (Takanori, 2007).

2.2 Test Program

Three groups of testing were performed under zero mean stress and room temperature.

First Group: Three replicated specimens were tested under constant stress amplitude and different stress levels. In order to deduct and measure the crack length during the test using replication technique (W.V.Mars, 2004).Crack growth model may be derived from the crack length and number of cycle data.

Second Group: Five specimens were tested under constant stress amplitude with different rest periods.

Third Group: Five specimen were tested under cumulative fatigue damage (variable stresses).

3- RESULTS

Table (a) gives the results of the first group

Table (a)

Specimen No.	Min.Dia. d(mm)	Average Roughness Ra(μm)	Finish Max. Peak Rt(μm)	Twist Angle θ(deg.)	Torque T(Nm)	Shear * Stress (τ) N/mm^2	Cycles To failure Nf
1	7.19	Etched	Etched	0.735	10.35	141.887	$3.2*10^6$
2	7.26	Etched	Etched	0.8	11.675	155.466	$1.04*10^6$
3	7.245	Etched	Etched	1.34	14.75	197.636	$9.4*10^4$

40 cracks were monitored and measured with corresponding number of cycles.

Appendix (A) illustrates these results. The last column of this appendix refers to a_{av} , which is calculated by the equation (Lankford J,1982) .

$$a_{av} = \frac{a_{i+1} + a_i}{2} \tag{1}$$

Where i is the replica number, and da/dN was calculated by

$$\frac{da}{dN} = \frac{a_{i+1} - a_i}{N_{i+1} - N_i} \tag{2}$$

An empirical model was derived from the crack growth results of appendix (A) . This model consists of two equations, one for short crack and the other for long cracks and these equations may tack the form

$$\frac{da}{dN} = 9.22 * 10^{-37}\ \tau^{13.4} (D_{av} - a_{av})^{-0.42} \tag{3}$$

Where $D_{av.}$ = Average grain size diameter. (277 μm)

For Short fatigue cracks

$$\frac{da}{dN} = 1.8 * 10^{-25}\ \ \tau^{8.8}\ a_{av}{}^{1.2} \tag{4}$$

For long fatigue cracks

*Shear stress was calculated using the formula

$\tau = \dfrac{16T}{\pi d^3}$ For a solid shaft rotates under twisting moment.

The above model is derived following the procedure of refs. (Taylor,D, 1981)and(Bhasin,2008). The limit of equation (3) is up to 227 μm crack length and equation (4) until fracture of the specimen (8mm) Table (b) illustrates the constant shear stress amplitude fatigue tests with different rest periods (second group) (Schiffner,1999).

Table (b)

Specimen No.	Shear stress (N/mm^2)	Rest periods (hours)	Nf exp. Cycles
A	251	19	$2.53*10^4$
A1	330	72	$4.0*10^3$
A2	200	18	$1.26*10^6$
A3	195	10	$1.8*10^6$
A4	150	96	$2.78*10^6$

Table (c) gives the variable stress amplitude fatigue tests with different rest periods (third group)

Table (c)

Specimen No.	Stress vibration (N/mm^2)	Average Stress (N/mm^2)	Rest periods (hours)	Nf exp.
B	175—300 L to H	237.5	18	$4.22*10^4$
B1	250—159 H to L	204.5	24	$8.7*10^5$
B2	211—150 H to L	180.5	96	$1.6*10^6$
B3	200—175 H to L	187.5	48	$1.1*10^6$
B4	200—225 L to H	212.5	30	$2.7*10^5$

L : Low stress level

H: high stress level

4 APPLICATIONS OF THE EXPERIMENTAL RESULTS

4.1 The S-N curve

Following the work of Ref.(Takanori Sugimolo,2007), the continuous cycling S-N curve equation was as follows :

$$\tau = 429.57\, N_f^{-0.0822} \quad (5)$$

Fig .(1) show the comparison between the continuous cycling S-N curve and rest periods S-N curve.

Table (d) demonstrates the life predicted using equation (5) and the rest periods experimental results

Table (d)

Specimen No.	N/mm^2	Rest periods (hr)	Nf exp. Cycles	Nf predicted
A	251	19	$2.53*10^4$	690
A1	330	72	$4.0*10^3$	25
A2	200	18	$1.26*10^6$	10935
A3	195	10	$1.8*10^6$	14879
A4	150	96	$4.78*10^6$	361999

* This specimen is subjected to high stress within Low-cycle fatigue then it is ignored because of the stress level is out of the region of equation (5)

4.2 Crack Growth Model And Constant Amplitude Tests

Table (e) illustrates the experimental results compared with the predicted lives .

Table (e)

Spec.No.	N/mm^2	Rest period (hr)	Nf exp. Cycles	£ Nf predicted
A	251	19	$2.53*10^4$	$1.46*10^4$
A1	330	72	$4.0*10^3$	$1.234*10^3$
A2	200	18	$1.26*10^6$	$1.24*10^5$
A3	195	10	$1.8*10^6$	$1.6*10^5$
A4	150	96	$4.78*10^6$	$2.4*10^6$

£ These results are estimated using the proposed model with replicated rest period specimens (each replica takes one minute)

4.3 Crack Growth Model (C.G.M) And Cumulative Test Results

Table (F) gives the experimental results in comparison with the predicted life of specimens subjected to varying stresses (cumulative fatigue damage using the (C.G.M).

Table (F)

Spec. No.	Stress vibration (N/mm^2)	Average Stress (N/mm^2)	Rest periods (hr)	Nf exp. Cycles	Nf pred.
B	175-—300	237.5	18	$4.22*10^4$	$2.4*10^4$
B1	250-—159	204.5	24	$8.7*10^5$	$1*10^4$
B2	211—-150	180.5	96	$1.6*10^6$	$0.63*10^6$
B3	200-—175	187.5	48	$1.1*10^6$	$0.23*10^6$
B4	200-—225	212.5	30	$2.7*10^5$	$0.69*10^5$

5. DISCUSSION

Effect of Rest period on fatigue life

It has been suggested, by many researchers (Kuzmanovic, 1972) and (De Los Rios, 1985), that there is an increasing benefit in fatigue life with decreasing stress. The introduction of a rest period can cause substantial increases in fatigue life time (Chopra, O.K, 2002). Strains have been measured during alternating stress experiments and found that rests seemed to improve the material and decrease the strain for a certain stress (De Los Rios, 1985).

Rest Period Mechanism

When a medium carbon steel material is subjected to dynamic loading (alternating stress) a strain aging takes place simultaneously with plastic deformation .under such plastic deformations a large number of slip bands are created in parallel, all the slip planes being "pinned " together by point defects on these slip bands a round dislocations (De Los Rios, 1985), a "cloud " of foreign atoms is created.

Rest periods will enable "clouds" to catch up with dislocations there by acting as barriers to the traveling of dislocations (G.De-Deus, 2010). Short cracks start from these slip bands (Ritchie R.O, 1982), and thus many barriers will cause arrest for these cracks and this due to rest periods effects. Then, the speed of short cracks will be very slow depending on the time of rest period and finally will increase the life of components and structures.

S-N Curves

Fig. (2) Show a large difference between the lives of specimens with and without rest periods.

While the difference becomes about (1-12) times, Life at rest period/Life under dry fatigue. between the predicted and the experimental lives. These results are in agreement with pervious work for steels (Schiffner,K,1999)and(G.De-Deus,2010),which concluded that rest periods at room temperature can increase the total life to failure , probably as a results of strain ageing taking place during the rest periods .The above results are in good agreement with the finding of Ref (Miller,K.J,1974)and (Schiffner,K,1999).

Cumulative fatigue test results

Fig (3) shows the difference from 1.75 to 8.7 times, Life at rest period/Life under dry fatigue and this due to the effect of rest periods during the cumulative fatigue tests. These results are well agreed with pervious work on titanium alloy (Brown R,1984),which suggested that the observed effects are due to localized hardening and strain ageing as a rest periods effect. The above results are well agreed with the results of Ref (Kuzmanovic, 1972)and(De Los Rios, 1985).Many workers concluded that the difference in cumulative fatigue life due to rest period is about 2-10 times (Brown R,1984)and(G.De-Deus,2010).

6. CONCLUSIONS

1- A crack growth model derived from replicated specimens is formulated which takes the from:

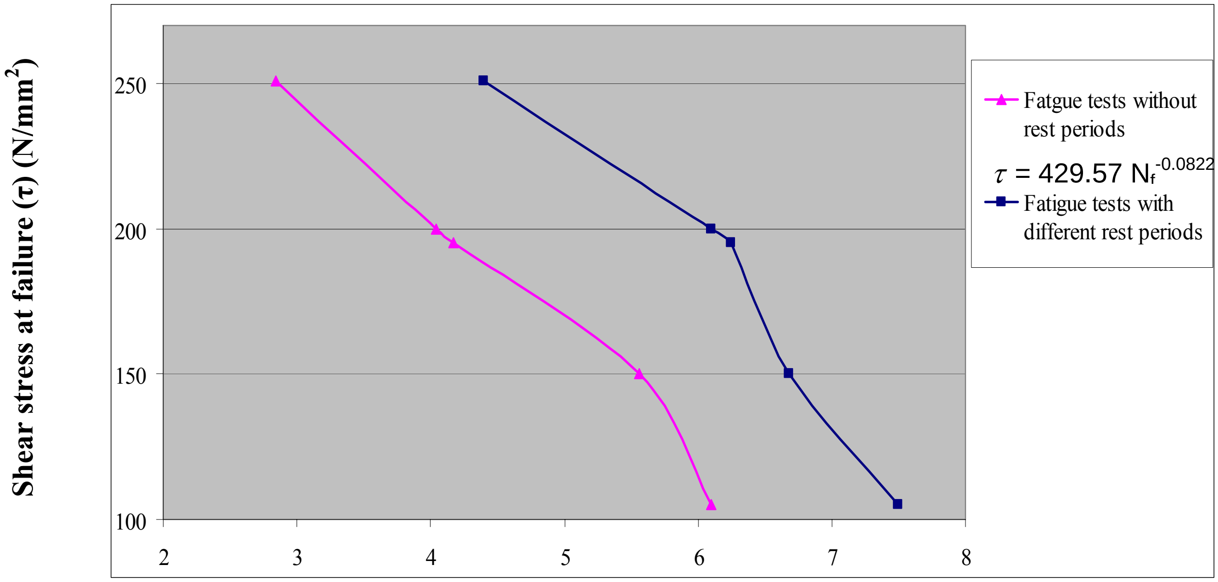
$$\frac{da}{dN} = 9.22 * 10^{-37} \tau^{13.4} (D_{av} - a_{av})^{-0.42}$$

For Short fatigue cracks

$$\frac{da}{dN} = 1.8 * 10^{-25} \tau^{8.8} a_{av}^{1.2}$$

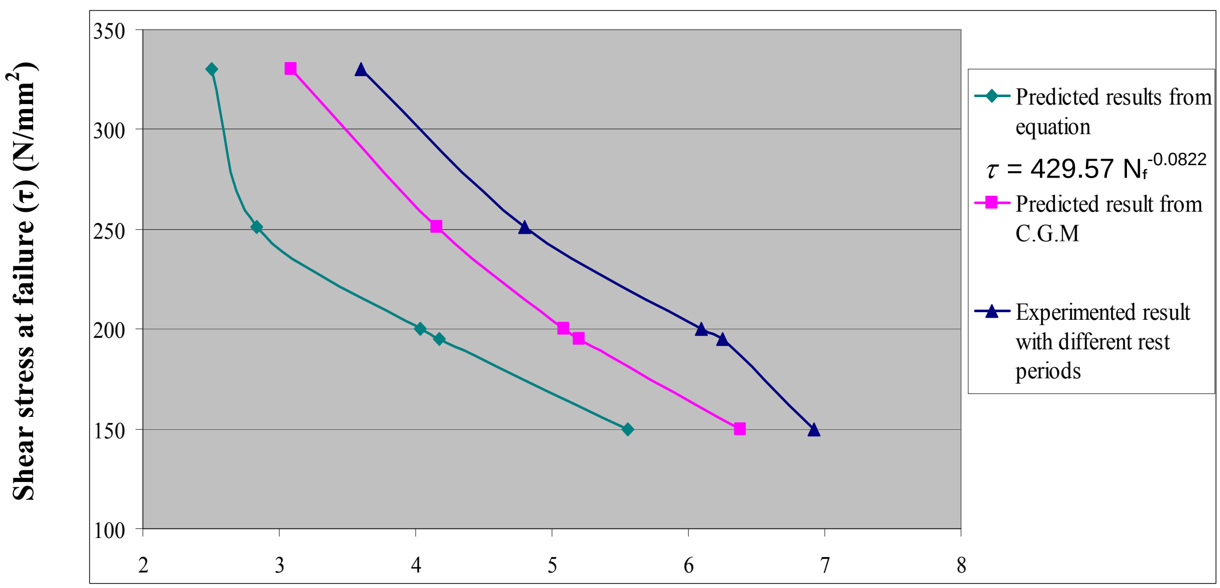
For long fatigue cracks

2- Rest periods have a beneficial effect on fatigue lives and it is suggested that this due to strain ageing mechanism.
3- The replicated rest periods lives are less than the rest periods lives.
4- For constant fatigue test rest periods will increase the total life from 1-12 times compared with replicated results.
5- Cumulative fatigue rest periods will increase the life of specimens form 1.75 to 8.7 times compared with the C.G.M. predictions.



Number of cycles to failure (log N_f)

Fig (1) Constant amplitude fatigue life test data



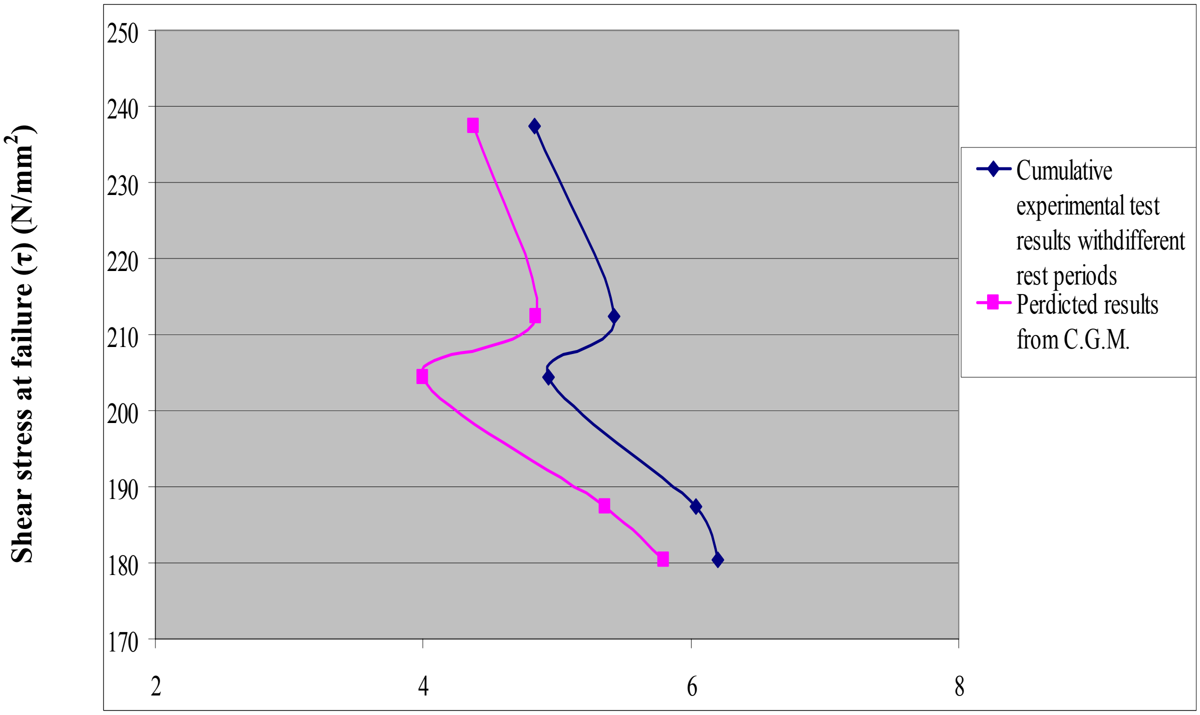
Number of cycles to failure (log N_f)

Fig (2) Constant amplitude result from different methods

With different rest periods (Large rest Periods)

With replicated reset periods (very small rest periods)

With Zero test periods



Number of cycles to failure (log N_f)

Fig (3) Cumulative results with different rest periods and the

Corresponding predicted data using C.G.M

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Appendix (A)*

Crack Growth Results Under Constant Stress Amplitude

Specimen No.	**Crack No.**	**No.of cycles observed**	**Cycles to fail (Nf)**	**Fraction of life N/N**	**Crack length observed (a)µm**	**Δa µm growth**	**ΔNo.of Cycles Required**	**da/dN mm_f Cycles**	**Average Crack Length (observed) a_{av} (µm)**
		328021		0.103	86	86	328021	$2.62*10^{-7}$	43
		439200		0.137	280	194	111179	$1.74*10^{-6}$	183
		848548		0.266	405	125	409348	$3.05*10^{-7}$	343
1	1	1077441	$3.2*10^{6}$	0.338	405	0	-	0	405
		1457880		0.457	446	61	609332	$1.0*10^{-7}$	436
		1580250		0.496	1026	560	122370	$4.57*10^{-6}$	746
		2669200		0.838	3222	2196	1088950	$2.01*10^{-6}$	2124
D=405µm	joining	$3.2*10^{6}$		1.0	joining				
		328021		0.103	100	100	328021	$3.0*10^{-7}$	50
		439200		0.137	260	160	111179	$1.43*10^{-6}$	180
1	2	848548		0.266	260	-	-		260
		1077441	$3.2*10^{6}$	0.338	370	110	638241	$1.7*10^{-7}$	315
		145880		0.457	370				370
		1580250		0.496	400	30	502809	$5.96*10^{-8}$	385
		2669200		0.838	1762	1362	1088950	$1.25*10^{-6}$	1081
D=370µm	joining	$3.2*10^{6}$		1.0	joining				

*Selected crack growth results are taken form the original results in order to reduce the No. of page of this paper

Appendix (A)*

Crack Growth Results Under Constant Stress Amplitude

Specime No.	Crack No.	No.of cycles observed	Cycles tc fail (N_f)	Fractio of life N/N	Crack length observed (a)µm	Δa µm growth	ΔNo.of Cycles Requirec	da/dN mm_f Cycles	Average Crack Length (observed) a_{av} (µm)
		328021		0.103	122	122	328021	3.71*10	61
		439200		0.137	180	58	111179	$5.2*10^{-7}$	151
		848548		0.266	180			0	180
1	3	1077441	$3.2*10^6$	0.338	180			0	180
		1457880		0.457	180			0	180
		1580250		0.496	180			0	180
		2669200		0.838	180			0	180
D=180µı		$3.2*10^6$		1.0	180			0	180
		328021		0.103	76	76	328021	2.31*10	38
		439200		0.137	205	129	111179	1.16*10	141
1	4	848548		0.266	205	0			205
		1077441	$3.2*10^6$	0.338	205	45	638241	$7.0*10^{-8}$	228
		145880		0.457	318	68	380439	1.78*10	284
		1580250		0.496	846	528	122370	$4.3*10^{-6}$	582
	joining	2669200		0.838	-				
D=205µı		$3.2*10^6$		1.0	-				

Appendix (A)*

Crack Growth Results Under Constant Stress Amplitude

Specime No.	Crack No.	No.of cycles observed	Cycles tc fail (N_f)	Fractio of life N/N	Crack length observed (a)µm	Δa µm growth	ΔNo.of Cycles Requirec	da/dN mm_f Cycles	Average Crack Length (observed a_{av} (µm)
		101524		0.098	154	154	101524	1.516*10	77
		118938		0.115	154				154
		158394		0.153	154				154
2	1	234404	$1.03*10^6$	0.226	154				154
		274026		0.265	338	184	172402	$1.06*10^{-6}$	246
		609141		0.589	825	487	335115	$1.45*10^{-6}$	582

		822557		0.795	1220	395	213416	$1.85*10^{-6}$	1023
D=154µr		$1.03*10^{6}$		1.0					
		101524		0.098					
		118938		0.115	100	100	118938	$8.4*10^{-7}$	50
2	2	158394	$1.03*10^{6}$	0.153	100	0			100
		235404		0.226	202	102	115566	$8.82*10^{-7}$	151
		274026		0.265	202	0			202
		609141		0.589	322	120	374637	$3.2*10^{-7}$	262
		822557		0.795	1032	710	213416	$3.3*10^{-7}$	677
D=202µr		$1.03*10^{6}$		1.0					

Appendix (A)*

Crack Growth Results Under Constant Stress Amplitude

Specimen No.	Crack No.	No.of cycles observed	Cycles to fail (N_f)	Fraction of life N/N	Crack length observed (a)µm	Δa µm growth	ΔNo.of Cycles Required	da/dN mm_f Cycles	Average Crack Length (observed a_{av} (µm)
		101524		0.098					
		118938		0.115	110	110	118938	$9.24*10^{-7}$	55
		158394		0.153	110	0			110
2	3	234404	$1.03*10^{6}$	0.226	444	334	115566	$2.89*10^{-6}$	227
		274026		0.265	444	0			444
		609141		0.589	489	45	374637	$1.2*10^{-7}$	467
		822557		0.795	1520	1031	213416	$4.83*10^{-6}$	1005
D=444µr		$1.03*10^{6}$		1.0					
		101524		0.098	50	50	101524	$4.92*10^{-7}$	25
		118938		0.115	50	0	101524		50
2	4	158394	$1.03*10^{6}$	0.153	80	30	56870	$4.27*10^{-7}$	65
		235404		0.226	458	378	76110	4.966*10	269
		274026		0.265	588	130	39522	$3.28*10^{-6}$	523
		609141		0.589	588	0			588
		822557		0.795	882	294	548531	$5.34*10^{-7}$	735
D=588µr	joining	$1.03*10^{6}$		1.0	8252	7370	211621	$3.48*10^{-5}$	4.567

Appendix (A)*

Crack Growth Results Under Constant Stress Amplitude

Specime No.	Crack No.	No.of cycles observed	Cycles tc fail (N_f)	Fractior of life N/N	Crack length observed (a)µm	Δa µm growth	ΔNo.of Cycles Requirec	da/dN mm_f Cycles	Average Crack Length (observed a_{av} (µm)
		1000		0.01					
		3538		0.037					
		5360		0.057	176	176	3560	$3.28*10^{-5}$	88
3	1	12240	$9.4*10^4$	0.13	176	0	6880	0	176
		19304		0.2	305	129	13944	$9.25*10^{-6}$	241
		34292		0.36	626	321	14988	$2.06*10^{-5}$	466
D=176µr	joining	$9.4*10^4$		1.0	-	-	-	-	-
		1000		0.01					
		3538		0.037					
3	2	5360	$9.4*10^4$	0.057	102	102	3560	$1.86*10^{-5}$	51
		12240		0.13	222	120	6880	1.744*10	162
		19304		0.2	322	100	7064	$1.41*10^{-5}$	272
		34292		0.36	672	350	14988	$2.33*10^{-5}$	497
D=222µr	joining	$9.4*10^4$		1.0	4884	4212	59235	$7.1*10^{-5}$	2778

Appendix (A)*

Crack Growth Results Under Constant Stress Amplitude

Specime No.	Crack No.	No.of cycles observed	Cycles tc fail (N_f)	Fractior of life N/N	Crack length observed (a)µm	Δa µm growth	ΔNo.of Cycles Requirec	da/dN mm_f Cycles	Average Crack Length (observed a_{av} (µm)
		1000		0.01					
		3538		0.037					
		5360		0.057	90	90	3560	$1.67*10^{-5}$	50
3	3	12240	$9.4*10^4$	0.13	292	202	6880	$2.93*10^{-5}$	191
		19304		0.2	346	54	7064	$7.6*10^{-6}$	319
		34292		0.36	814	468	14988	$3.12*10^{-5}$	1160
D=264µr		$9.4*10^4$		1.0	-		-		
		1000		0.01					

		3538		0.037					
3	4	5360	$9.4*10^4$	0.057	50	50	3560	$9.32*10^{-6}$	25
		12240		0.13	50	-	-	-	50
		19304		0.2	364	314	13944	$2.25*10^{-5}$	207
		34292		0.36	508	144	14988	$9.6*10^{-6}$	436
D=220µm		$9.4*10^4$		1.0					

NOTATIONS

d : minimum diameter of test specimens (mm)

Ra : average surface roughness (µm)

Rt : peak roughness (µm)

θ : twist angle (degree)

T : applied torque (N.m)

τ : Shear stress N/mm2

N_f : cycles to failure .

D : grain size diameter (microstructure parameter)

$D_{av.}$: average grain size diameter .(277µm)

N : number of cycle

a : crack length (µm)

a_{av} : average crack length (µm)

da/dn : crack growth rate (mm/cycle)

$Nf_{exp.}$: experimented number of cycle to failure

$Nf_{pre.}$: predicted number of cycles to failure