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A new Cumulative Damage Model for Fatigue Life Prediction under Shot Peening Treatment

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Abstract

In this paper, fatigue damage accumulation were studied using many methods i.e.Corton-Dalon (CD),Corton-Dalon-Marsh(CDM), new non-linear model and experimental method. The prediction of fatigue lifetimes based on the two classical methods, Corton-Dalon (CD)andCorton-Dalon-Marsh (CDM), are uneconomic and non-conservative respectively. However satisfactory predictions were obtained by applying the proposed non-linear model (present model) for medium carbon steel compared with experimental work. Many shortcomings of the two classical methods are related to their inability to take into account the surface treatment effect as shot peening. It is clear that the new model shows that a much better and conservative prediction of fatigue life in comparison with CD and CDM methods. The prediction of the present model gave slightly below the experimental data while the CDM gave overestimate prediction and CD showed strongly underestimates the life of specimens.

Keywords: *Cumulative fatigue damage, Shot peening, Non-linear model.*

1. Introduction

Only a few machine parts are subjected to static loading but many of machine parts are subjected to variable loads. The variable loads have been found by experiment that when a material is subjected to dynamic loads. It fails at a stress below the yield point; such type of failure is known as fatigue. Fatigue may be constant or variable. Constant fatigue loading is defined as fatigue under cyclic loading with constant amplitude and a constant mean stress or load. But in service the structures or components are subjected to variable amplitude loading, which can be a rather complex load time history [1].

Variable loading or cumulative damage is usually investigated by testing specimens with a definite number of cycles at one stress level, and then to continue the test at other stress level until failure. In these various stress level tests, the stresses may be either in an increasing or decreasing order or mixed together [2].In this study a new cumulative fatigue damage model for life prediction will presented involving the effects of loading sequences and the surface shot peening treatment.

2. Fatigue Damage Accumulation

For long time, researchers have tried to find the best theory to explain the fatigue damage accumulation behavior. A comprehensive review can be found in [3]. Only a few damage accumulation theories are briefly described below.

Miner [4] first expressed the concept of cumulative fatigue damage in a mathematical formula as,

$$D = \sum \frac{n_i}{N_{fi}} = 1 \qquad ...(1)$$

where, D is the cumulative fatigue damage and n_i, N_{fi} are the applied cycles and the number of cycles to failure under i-th constant S-N curve stress level respectively.

Corton-Dolan theory [5] was based on the modification the S-N diagram. They suggested obtaining the slope of the modified S-N line from the average results of the few repeated two-step block tests expressed as:

$$N_g = \frac{N_h}{\beta_h + (1-\beta_h)R^{1/a}} \qquad ...(2)$$

where N_g is the number of cycles to failure, N_h is the number of cycles to failure at high stress σ_h in a constant amplitude test, β_h is the fraction of cycles at σ_h , R is the ratio of rate of damage, and a is an exponent.

Corton-Dolan found that $R^{1/a}$ was related to the stress amplitude by the empirical equation:

$$R^{1/a} = [\frac{\sigma_l}{\sigma_h}]^{\alpha} \qquad ...(3)$$

where, σ_l is the lower stress, and α is the inverse slope of S-N curve on a log-log plot.

Marsh [6] modified the Corton-Dolan method to include the stress amplitude below the fatigue limit into account. Miller et al [7] showed that damage can be initiated by cycling at stresses below the fatigue limit and so the 0.8 of the fatigue limit stress level was used in conjunction with the Corton-Dolan S-N curve rule. The new method is presented here was named as Corton-Dolan-Marsh theory (CDM). More details about CDM theory can be seen in [7].

Yougming and Sankaran [8] proposed a general methodology for stochastic fatigue damage modeling under variable amplitude loading. This model describes the cumulative fatigue damage in a nonlinear formula which predicts the fatigue life and improves the accuracy of the Miner rule. Two levels fatigue damage model was proposed by Z. Yang et al [9] for low cycle fatigue (LCF) and high cycle fatigue cumulative fatigue damage. The results showed that the predictions of the lives are in good agreement with the experimental results.

3. The Proposed Non-Linear Model

Following the work of Perreira et al [10], they suggested the damage due to fatigue under variable amplitude stress such as for low-high and high-low stress level as:

$$D = [\frac{n_i}{N_{fi}}]^{\alpha} \qquad ...(4)$$

where, (α) is a function of the applied load. In the present work, (α) defined as the effect of loading sequences and surface treatment, here the surface treatment is shot peening technique. Equation (4) can be modified to take the form:

$$D = [\sum \frac{n_i}{N_{fi}}]^{x} \qquad ...(5)$$

where, (x) represents the effect of loading sequences $\frac{\sigma_l}{\sigma_h}$ and shot peening treatment, (β) here (x) defined as:

$$x = \frac{\sigma_l}{\sigma_h}\beta \qquad ...(6)$$

where, β is the inverse slope of the S-N curve. Equation (6) can be applied from low to high stress level. But when the test program is from high to low stress, equation (6) is changed as following:

$$x = \frac{\sigma_h}{\sigma_l}\beta \qquad ...(7)$$

In order to make the prediction safe equation (5) can be divided by the value (x) to become:

$$D = \frac{[\sum \frac{n_i}{N_{fi}}]^{x}}{x} \qquad ...(8)$$

4. Experimental Work

The current work is based on an experimental program which included 72 fatigue specimens, 48 specimens were tested to establish the S-N curves for both dry (without shot peening) and shot peening treatment. The shot peening was done at 10, 20 and 30 minute, 24 specimens were tested under low-high and high-low stress. All specimens were extracted from a medium carbon steel rod with1m long and 10mm in diameter.

The chemical composition of the material used is presented in Table (1) while the experimental mechanical properties with the standard values are listed in Table (2).

Table 1,
Chemical composition of medium carbon steel in wt. %.

Element	C	Si	Mn	S	Fe
Experimental	0.4	0.13	1.04	0.002	Blance

Table 2,
Mechanical properties of medium carbon steel.

Mechanical properties	Yield strength (MPa)	Ultimate strength (MPa)	Elastic modules (GPa)	HV
Experimental	295	585	207	184

5. Fatigue Test Procedure

The specimens were prepared according to DIN 50113.The specimens are manufactured using programmable CNC lathing machine. Figure (1) shows the fatigue test specimens and its configuration.

All fatigue tests were carried out in the laboratories of electromechanical engineering department, University of Technology using fatigue testing machine type PUNN rotating bending Figure (2). The experiments were conducted at room temperature and at stress ratio R=-1(minimum stress to maximum stress in periodic cycle), while the shot peening device with its properties can be seen in Ref. [12].

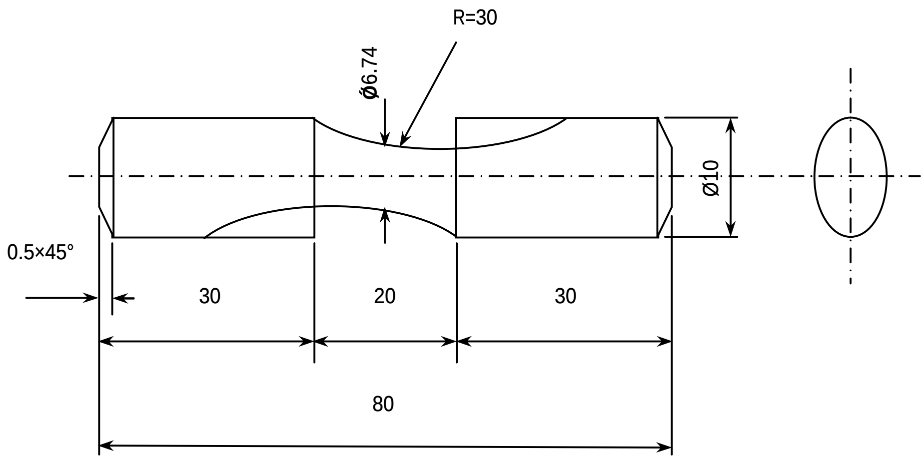

Fig. 1. Specimen geometry and dimensions for fatigue test (all dimensions in mm).

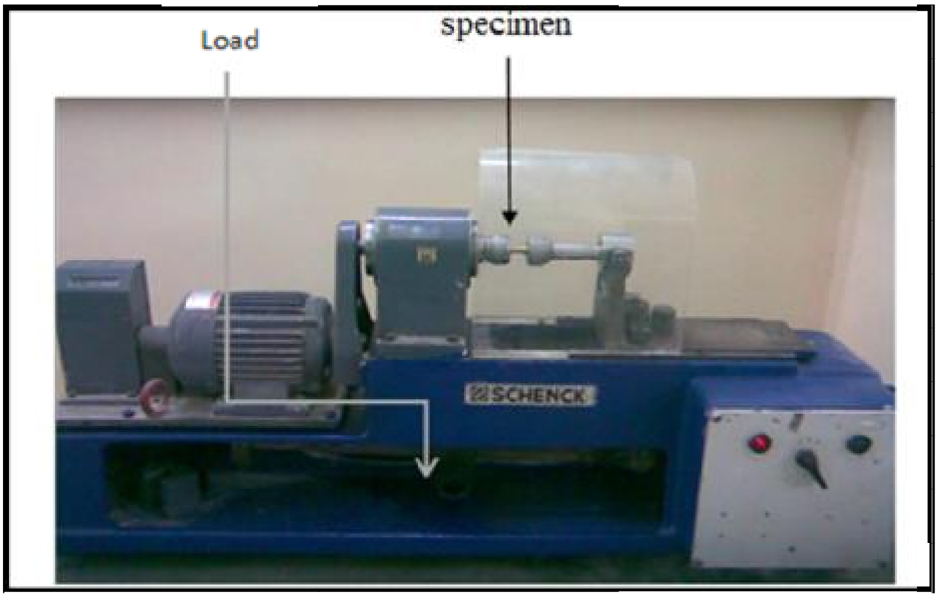

Fig. 2. PUNN rotary fatigue bending machine.

6. Results and Discussion

Constant stress amplitude with stress ratio (R=-1) at room temperature tests were conducted in order to use the parameter ($\boldsymbol{\beta}$, inverse slope of S-N curve) for driving the present model. The final results can be summarized in Table (3) equation of power law regression is given by (fatigue life formula).

$$\boldsymbol{\sigma = aN^b} \quad \text{... (9)}$$

where, ($\boldsymbol{\sigma}$) is the applied stress, and ($\boldsymbol{a}$),($\boldsymbol{b}$) are the fitting parameters. The regression constants represent of the fatigue trends.

Table 3,
Basic S-N fatigue results at room temperature (RT).

Description	a	b
Dry (without shot peening)	5623	-0.235
with shot peening (SPT) 10 min.	7650	-0.296
with shot peening (SPT) 20 min.	9120	-0.252
with shot peening (SPT) 30 min.	10690	-0.272

6.1. Variable Amplitude Results (Cumulative Fatigue Damage)

The cumulative fatigue damage tests have been conducted for two-steps program low-high and high-low stress for the conditions mentioned in Table (4). The experimental cumulative fatigue damage results are listed in Table (4).

Table 4,
Experimental cumulative fatigue damage results.

Description	Loading program	Amplitude stress (MPa)	N*f*(Cycles) Average
dry	Low-High	275-450	487000
(without shot peening)	High-Low	450-270	130467
with shot peening (SPT)	Low-High	275-450	954000
10 min.	High-Low	450-270	195000
with shot peening (SPT)	Low-High	275-450	1623330
20 min.	High-Low	450-270	353210
with shot peening (SPT)	Low-High	275-450	1077261
30 min.	High-Low	450-270	188200

6.2. Comparison Between Fatigue Life Prediction Methods

Comparisons between the four methods of fatigue life prediction can now be done. The predictions of fatigue lifetime using Corton-Dolan (CD) and Corton-Dolan-Marsh (CDM) methods with the experimental and the new model results are illustrate in Table (5).

Table 5,
Comparison between fatigue lives prediction between four methods.

SPT Min.	Loading program	N*f* Cycles CD	N*f* Cycles CDM	N*f* Cycles experimental	N*f* Cycles Model
dry	Low-High	32103	1388436	487000	469913
	High-Low	85837	494209	130467	124605
SPT10	Low-High	45299	2312581	954000	849175
	High-Low	68259	670972	195000	183003
SPT20	Low-High	50813	3538197	1623330	1288140
	High-Low	70423	1402019	353210	238894
SPT30	Low-High	42319	2635364	1077261	805395
	High-Low	57176	460404	188200	159619

The CD and CDM have been shown not to be satisfactory for predicting life in a two-step loading due to their inability to take into account the effect of shot peening which decelerate the short cracks. Figures (3 and 4) show the four methods in comparison for predicting the fatigue life with the experimental results.

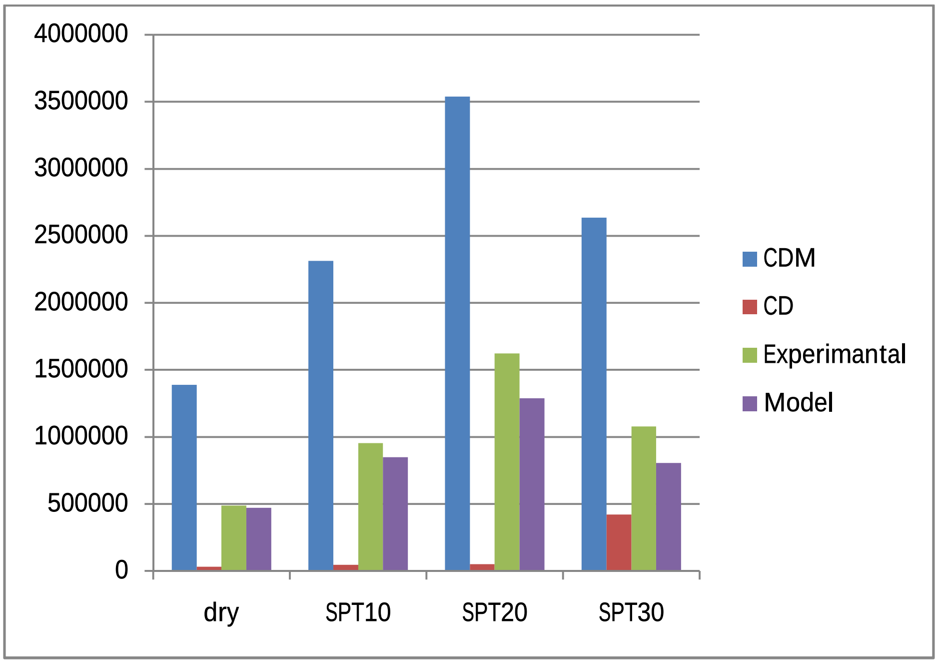

Fig. 3. shows the Low-High cumulative fatigue life prediction for four methods.

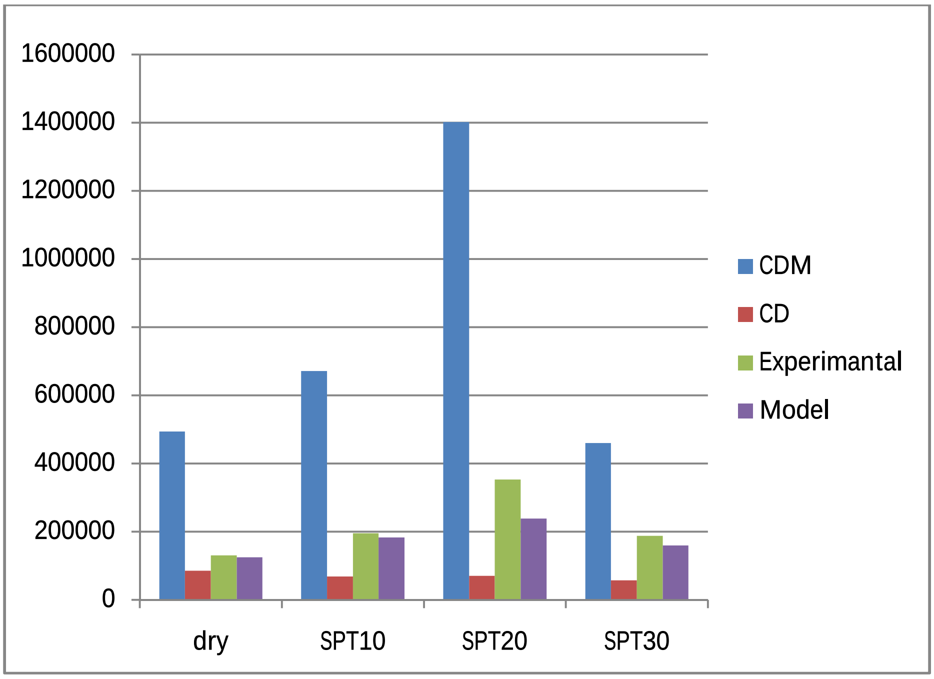

Fig. 4. shows the High-Low cumulative fatigue life prediction for four methods.

It is clear that the new model shows that a much better and conservative prediction of fatigue life in comparison with CD and CDM methods. The prediction of the present model gave slightly below the experimental data while the CDM gave overestimate prediction and CD showed strongly underestimates the life of specimens.

7. Conclusions

1. For this particular loading and metal used, the proposed non-linear model (present model) seems to be a proper choice for cumulative fatigue damage life prediction.
2. The CDM predictions showed that non-conservative prediction (overestimate the life) based on the experimental results.

3. The CD method gave uneconomic predictions(strongly underestimates the life) compared to the experimental results.

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أتموذج الضرر التراكمي الجديد للتنبؤ بعمر الكلال تحت تأثير معالجة السطوح بالنقر المستمر

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الخلاصة

في هذا البحث تم دراسة حساب تراكم ضرر الكلال لسبيكة الصلب المتوسط الكاربو (medium carbon steel) بأستخدام عدة طرق ؛ كورتن- دايلن (CD) ، كورتن – دايلن – مارش (CDM) بضمنها الانموذج المقترح مقارنة بالنتائج العملية. يستند تنبأ عمر الكلال على اسلوبين تقلديين هما كورتن- دايلن (Corton-Dalon) و كورتن- دايلن- مارش (Corton-Dalon-Marsh) وهي غير أقتصادية وغير دقيقة مقارنة مع النتائج العملية على التوالي. في حين كان التنبأ بعمر الكلال للسبيكة التي استخدمت في البحث بأستخدام الانموذج اللاخطي المقترح مناسبا مقارنة بالنتائج العملية. يرتبط العديد من أوجة القصور في الاساليب الكلاسيكية التقليدية المشار اليها بعدم قدرتها على أن تأخذ في الاعتبار تأثير المعالجة السطحية مثل النقر المستمر (shot peening).الانموذج المقترح لتنبأ بعمر الكلال اعطى نتائج تقريبا اقل بقليل من النتائج العملية في حين ان اسلوب CDM اعطى نتائج اعلى بكثير من النتائج العملية وان اسلوب CD اعطى نتائج اقل بكثير من النتائج العملية.