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MATHEMATICAL MODEL DESIGN TO PREDICT THE FATIGUE LIFE BEHAVIOR FOR BEARING STEELS

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ABSTRACT

Conventional and ultrasonic fatigue testing is usually conducted under axial or rotating- bending loading. In spite of the differences in shape and design of the fatigue specimens, the stressed volume plays a mutual role in assessing the fatigue life. This is due to the fact that the probability of finding voids or inclusions, which are the sources of cracks, increases as the stressed volume increases. The fatigue life of bearing steel generally extends to the Giga cycle regime so conducting such fatigue testing in the laboratory is time consuming and costly. In this work, a model based on neural network techniques has been suggested to predict the fatigue strength of bearing steel. The input data for this model includes hardness, the stressed volume, stress ratio and number of cycles. The model captures reasonable trends and is able to estimate unseen experimental results on high strength bearing steel AISI 52100. Extrapolation has been conducted for the rolling contact fatigue life and the results show good agreement with the experimental data.

Keywords : fatigue, stressed volume, bearing steel, rolling contact fatigue, modelling.

تصميم موديل رياضي للتنبؤ بتصرف عمر الكلال لفولاذ المحامل

اسيل الحمداني جيمس نيقبرد ظافر الفتال

الخلاصة :-

اختبارات الكلال التقليديه والفوق صوتيه عاده يتم اجراءها تحت احمال افقيه او انحناءات دوريه . على الرغم من اختلافات التصميم وشكل العينات. يلعب الاجهاد الحجمي دور رئيسي في تقييم عمر الكلال نتيجة لحقيقه انه كلما زاد الاجهاد الحجمي زادت احتماليه وجود فجوات وشوائب والتي تعتبر مصدر لخلق الشقوق. ان عمر الكلال لفولاذ المساند عاده يمتد الى منطقه تتجاوز فيها عدد الدورات (10^9دورة) لذا لايمكن اجراؤها في المختبر لانها تاخذ وقتا طويلا وكلفة عالية . تم في هذا العمل اقتراح نموذج رياضي مبني على مبدا الشبكه العصبيه يتنبئ بعمر اجهاد الكلال لمعدن المساند وكانت المدخلات لهذا الموديل تتضمن الاجهاد الحجمي ، والصلاده ونسبه الاجهاد وعدد الدورات.
اتضح ان الانموذج المقترح يمثل حاله منطقيه لتخمين اعمار فولاذ المساند نوع (AISI 52100) وتم تطبيق هذا الانموذج على مساند حقيقيه واعطت نتائج مرضيه .

مفتاح الكلمات : فولاذ المساند ، اختبارات الكلال ، الاجهاد الحجمي ، انموذج رياضي

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1- INTRODUCTION :-

Fatigue testing is one of the most important experimental methods designed for understanding the mechanical properties of bearing steels. It occurs Strain is accumulated slowly under a repeated stress cycle, often below the yield strength of the material, eventually leading to failure [Bhadeshia 2012]. In the classical axial-loading fatigue test, the stresses are distributed uniformly over the cross-section of the sample gauge length, while in the rotating-bending test the surface undergoes cyclic tension and compression during each stress cycle and the distribution of stress across the sample is not uniform, being maximum at the outer surface and zero along the central sample axis [Liat atel 2011]. In recent years, attempts to accelerate fatigue testing have been made in an effort to reduce test duration, particularly for bearing steels where gigacycle fatigue testing has evolved [Sakai 2009, Furuya 2010 and Bathiac 2010]. Rolling-bearings are utilized in a wide variety of industrial and civil applications. Several mathematical models have been conducted to estimate the lives of bearing components under axial, bending and gigacycle fatigue, but similar estimates for the rolling contact fatigue (RCF) life are often inadequate and sensitive to multiple parameters during testing. These models are typically based on empirical engineering models, analytical research models or computational models that can be seen reviewed elsewhere [Sadeghi atel 2009]. A simplified approach utilizing fewer input parameters and calibrated using standardized test methods would provide a more desirable model. The goal of this work is to present a model capable of predicting the fatigue behavior by taking into account the stressed volume and other readily calculated variables, and is achieved using the neural network method .

2- METHOD :-

The model manager program has been trained the input parameters; this method has been explained in [Bhadeshia 1999 and Al-hamdany 2012].

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Inputs data

In order to build a mathematical model based on stress volume, Input data have been collected from literature [Al-hamdany 2016] for conventional and Giga cycle fatigue tests, both methods are for axial and rotating bending fatigue. In this model few parameters have been chosen to reduce the number of inputs parameters.

The volume under stresses

The stressed volume is one of most important input parameters; data for this variable has been calculated from the shape of specimen in this study [Al-hamdany]. Calculations have been carried out to get the stressed volume for an hourglass shaped specimen to a certain distance from the maximum stress, σ_{max}.It was found from recent work that calculated the stressed volume as a sphere (eq.1) or a cylinder (**Figure1 equation2**) and the volume of hourglass did not give accurate results for all the category of fatigue tests including rolling contact fatigue (RCF) test.

$$Vs = \frac{4}{3}\pi r^3 \tag{1}$$

$$Vs = \pi r^2 h. \tag{2}$$

The minimum radius is(r) in mm and the distance of the stressed volume is *(h)* in mm. In this work, the used approach to calculate the stressed volume which can help to build a model able to estimate the RCF stress is as shown below (refer to **Figure1 a and b**):

$$R'^2\theta^2 = \Delta r^2 + h^2 \tag{3}$$

$$\Delta r = R'(1-\cos\theta) \tag{4}$$

Substitute in equation (3) to get

$$h^2 = R'^2\left(\theta^2 - (1-\cos\theta)^2\right) \tag{5}$$

Use for example R=15 mm, h=5 mm as in **Figure (1b),** then find out θ numerically from eq.(6).

$$\frac{h^2}{R'^2} = (\theta^2 - (1-\cos\theta)^2) \tag{6}$$

When θ is found, substitute it in eq.3 to find *Δr*.

$$d = 2(r + \Delta r) \tag{7}$$

The cross section area = $\pi\dfrac{d^2}{4}$

Add all the areas from θ=0 to a exact value of θ, which will give an accurate value of the area to get the overall stressed volume in mm^3. In Appendix 1 shows a table of the values of the calculated stress volume.

Vickers Hardness (HV)

The data have been collected from the literature [Al-hamdany 2016] for steel AISI 52100 high carbon–chromium. There are many parameters related with fatigue life, few of them are used in this work like hardness in order to reduce the number of variable in the data which is used to build a model, hardness is a function of mechanical properties, chemical composition and heat treatment and

$$H = f(Ci, Ti, ti, \sigma_u) \tag{8}$$

Where *Ci*, *Ti*, *ti* and σ_u are chemical composition, the transformation temperature and time for heat treatment and the tensile strength ultimate respectively.

Stress distribution ratio

The stress ratio R is one of the input parameters because it represents the distribution of the load during fatigue test as in eq.9. The value is from -1, to 0.5.

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} \tag{9}$$

Where the minimum and the maximum stress are σ_{min} and σ_{max} respectively.

S-N curve parameters

From the S-N curves from literature both of the number of cycles and fatigue stresses were collected. After collecting results were digitized and modified were proposed by taking the logarithm number of cycles to make the model more physically meaningful.

The fatigue stress is a function of:

$$Fa = f\left(H_s Vs, R, \log(NC)\right) \qquad (10)$$

Where the Vickers hardness is *H*, the fatigue stress is *Fa* in MPa, stressed volume *Vs* is in mm^3, the stress ratio is *R* and the number of cycles to failure is NC. In **table 1** (984) experiments were collected from literatures. **Figure(2)** shows how the variables distribute in the dataset, both of hardness and logarithmic numbers of cycles are homogeneously distributed, while the other variables are randomly distributed.

Training

The most important part in the mathematical model of this study is training the dataset in **table 1**. The dataset have been trained used Model Manager Program. After training the dataset, a group of sub models were goatherd to get the optimum committee; this committee has three sub-models in this trained. A committee is used to find out the effects of each variable, in order checking the results if they are suitable from the physical principles. **Figure(3**) indicates the sigma error, σν, and the significances for the input data parameters in the committee, as realized by the committee model. The significance showed the scale of assistance to the output data, as linear regression analysis in a partial correlation coefficient. It is clear that hardness and volume which is stressed gets highest significance respectively in the optimized committee model as shown in **figure(3)** this results are reasonable and physically meaningful.

Checking the validation of the Mathematical Model

Checking the validation of the model is one of the most important issues. First checking has been done as shown in **Figure(4)** the prediction of the actual values against predicted values for the all data in table **2.** It is clear that all points in this graph lie on the line 45° with a small error bars. A second test was used to check the model validation; predictions were made using software called Predictor to see the trends of the input variables which is effect on the fatigue stress amplitude. The fatigue stress amplitude verses the inputs parameters, hardness, stress ratio, log number of cycles and stressed volume as shown in **Figures(5, 6, 7 and 8)** respectively, all these graphs shows physically acceptable trained. shows the effect of the stressed volume on the fatigue stress amplitude as the stress volume increase the fatigue stress decrease this behavior is acceptable, when the stress volume increase the ability of finding voids or defects are increases, these voids and defects are sources for initiating cracks which leads to decrease the fatigue stress amplitude [Li a et al 2011]. **Figure(9)** shows how the effects of both log number of cycles and volume stressed increasing, when these tow parameters increasing the fatigue stress amplitude decreasing, this combined effects are reasonable from the physical point of view. **Figures (10 and 11)** show the fatigue life stress amplitude for a wide range of hardness starting from 700-800 HV when R=0.94 and volume 176.82 mm^3 conditions. After all the tests which have been down this mathematical model are physically correct and it is valid.

3- RESULTS AND DISCUSSION :-

Tests were conducted for final checking the mathematical model which is proposed in this study. **Figures(12 and 13**) show the predicted fatigue stress amplitude against log number of cycles. The experimental dots in **Figure(12)** shows the experiments which are the triangle green points for hour-glass sample examined to get the fatigue live S-N curve, and the stressed volume is 209 mm^3 [Li a l 2011]. The circle red marks perform the predicted fatigue stress amplitude for the same value which is 209 mm^3. The square points explain other predictions for a stressed volume of 100 mm^3. **Figure(13)** shows the S-N graph for

high carbon-chromium bearing steel cycled with a cycling of 20 kHz and stress ratio is -1[Lia 2013], the square marks have been represented the predicted values for the same conditions.
Figure (14) shows most marks lie on the 45° line in the cure which presented the relation between the predicted and the actual fatigue stress amplitude in the fatigue model,

4- EXTRAPOLATION :-

In this study a model was built with four basic parameters that were chosen for traditional fatigue tests for bearing steel. Extrapolation has been conducted to find the effect of small volume which is almost equal to the stressed volume on the Rolling Contact Fatigue (RCF) and the stress ratio used was zero. **Figure(15)** shows the comparison between this study and the experimental results [Harris 2001] for a general condition. **Figure (16)** shows comparison between this work prediction and the experimental values [Stickels 1984]. Half the hertz pressure was chosen to calculate the stress amplitude value. The blue points represent the prediction results and the other colored points represent the life of bearing with 10% and 50% probability of failure, L_{10} and L_{50} respectively. It is shown that the experimental points lie close to the range of this work's prediction. In other words, this work is able to predict the fatigue life for the RCF based on the small value of stressed volume and at a stress ratio of zero. The stressed volume for the RCF is $Vs=az_0(2\pi r_r)$ [Lundberg and Palmgren 1947,Sadeghi atel2010, Jalalahmadi 2010 and Warhadpande 2010]. Here a is half the stress contact line=1mm, z_0 is the depth of stressed area =40 μm and r_r is the radius of the sample under stress=4.75mm. The stressed volume was about 1.19 mm^3. It should be noted that all data shown in **Figures(15 and 16)** are for bearing steel AISI-52100. From these comparisons, the model can estimate the rolling fatigue life successfully

5- CONCLUSIONS :-

A model was conducted to get the fatigue stress based on the stressed volume. The following are the main conclusions obtained:

1. The stress volume which are proposed and calculated as sphere or cylindrical did not give accurate fatigue stress amplitude as it was numerically calculated for the hourglass shape in this study.
2. The model has been proven that the prediction of the fatigue life is acceptable and valid after testing it.
3. Using the model to find out the fatigue life behaviour taking into account the small stressed volume encountered in rolling contact fatigue in bearing steel has been shown to be successful.

6- ACKNOWLEDGMENTS :-

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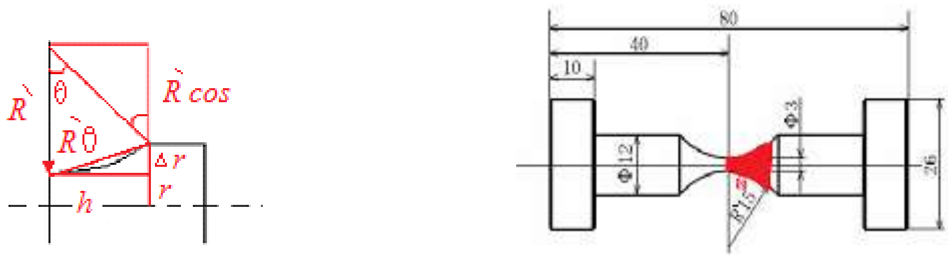
Table 1 : The parameters represent in the dataset of 984 experiments.

	Min	Max	Average	Stander Dev.
Volume/ mm^3	2.57	757	176.81	255.13
Hardness / HV	700	860	758.05	33.70
Stress distribution ratio (R)	-1	0.5	-0.944	0.25
Log(No. of cycle)	2.61	10.53	6.60	1.79
Fa /MPa	295	2094	1058	287

Table 2 : The range of testing both models is listed.

Variables	Min value	Max value	Step	Or
Volume/mm^3	2.56	757	20	176.8
Hardness	700	860	10	758
R (stress ratio)	-1	0.5	0.1	-0.94
Log (NC)	2.6	10.5	1	6.6



(a) **(b)**

Figure 1: A diagram showing: (a) half the specimen, b) half the stressed volume

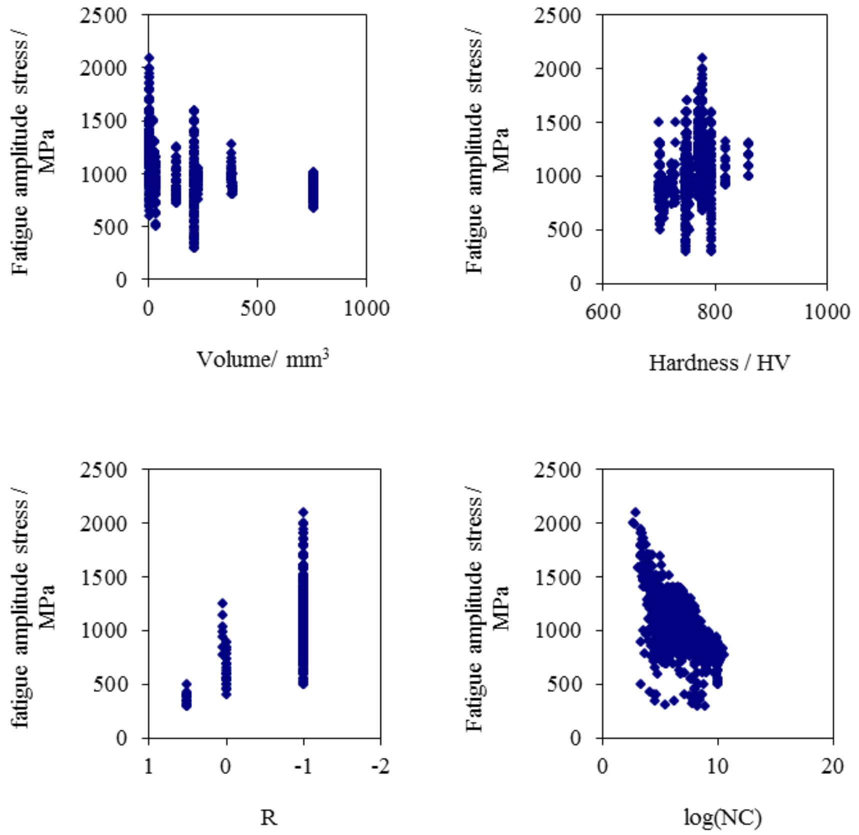


Fig.(2) The input data against fatigue stress amplitude distribution.

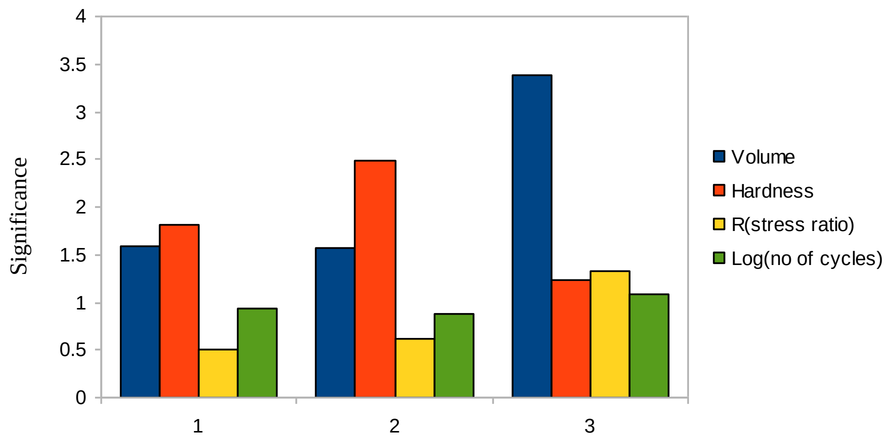
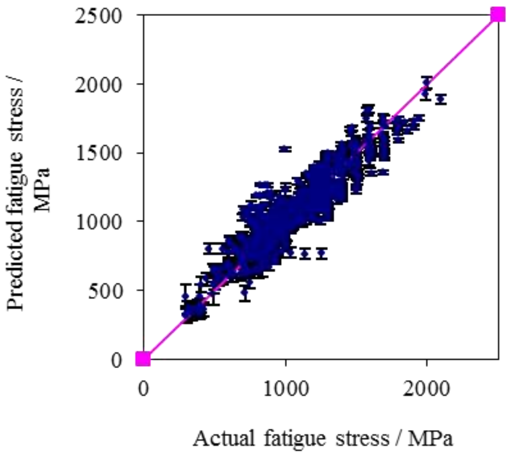


Fig.(3) Significance of parameters with σν=0.06



Fig,(4) Fatigue stress verses actual fatigue stress prediction , for trained data with the error bars.

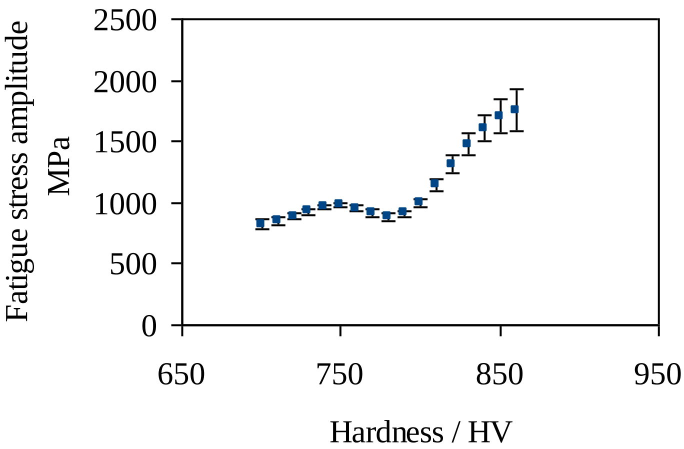


Fig.(5) The effect of hardness/ HV on the fatigue stress predictions using the fatigue model with the stress ratio (-0.94)and logarithmic number of cycles (No. of cycle) =6.6.

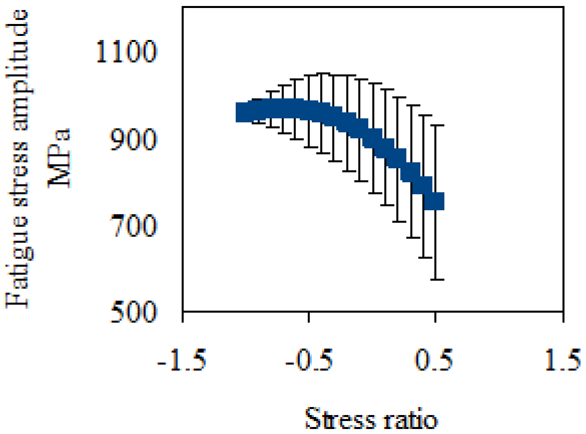


Fig.(6) The fatigue stress versus stress ratio using the model with hardness =758HV, and logarithmic number of cycles (No. of cycle) =6.6.

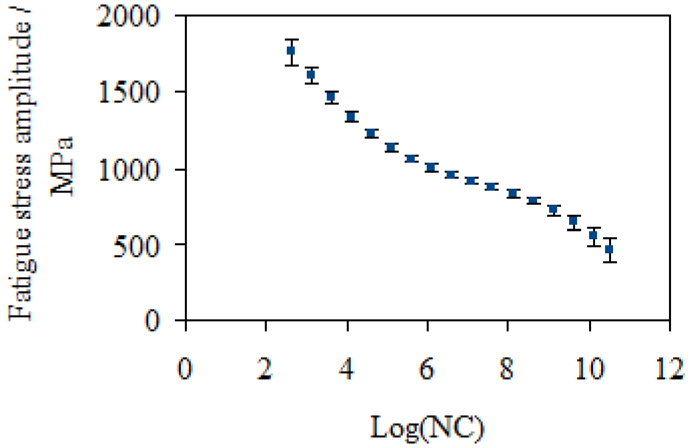


Fig.(7) : The fatigue stress versus logarithmic number cycles (NC) with stress ratio(-0.94) using the present model

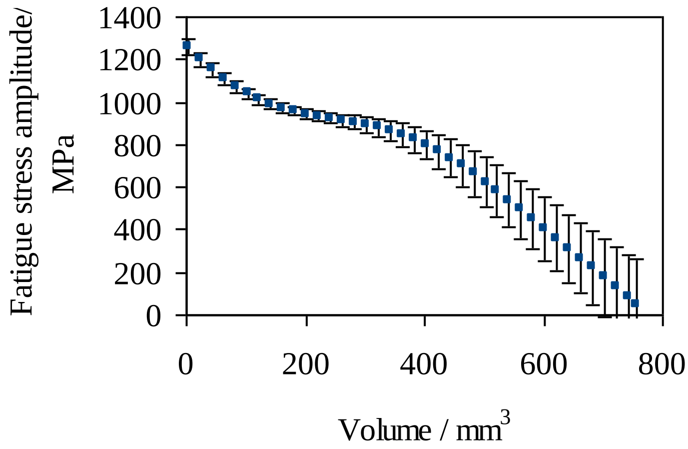


Fig.(8) The fatigue stress predictions versus the stressed volume of specimens using the model with hardness =758HV, stress ratio (-0.94) and logarithmic number of cycles (6.6) .

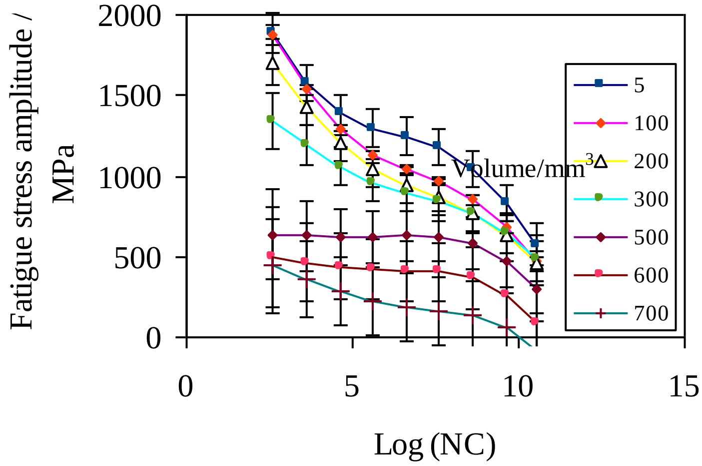


Fig. (9) The combined effect of different stressed volume and logarithmic number of cycles (NC) on the fatigue stress predictions when, stress ratio is (0.94) and hardness =758HV using the model

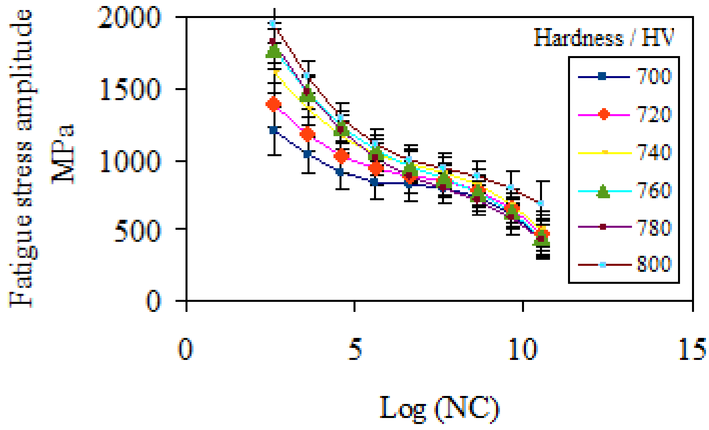


Fig. (10) The combined effect of different hardness and logarithmic number of cycles (NC) on the fatigue stress predictions, when stress ratio is (0.94) and the stressed volume =176.82 mm^3 using the model.

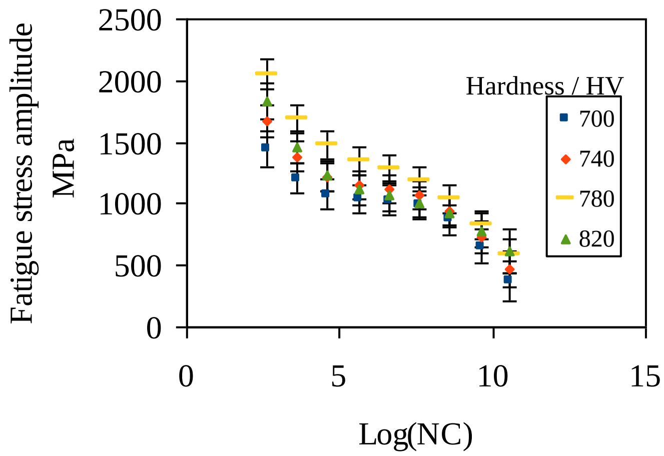


Fig.(11) Predictions of fatigue stress versus log (NC) with *R*=-0.94 and volume= 2.5 mm^3 using the model with different hardness.

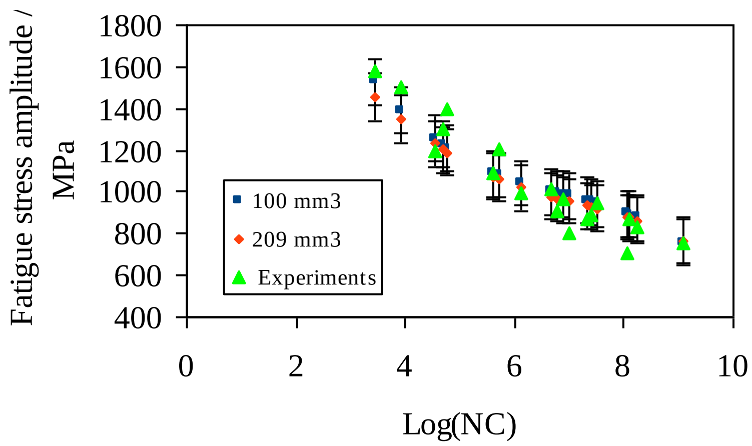


Fig. (12) Predictions for the fatigue stress and the real fatigue stress amplitude (the green points) versus log (NC) in the model, hardness=749 HV.

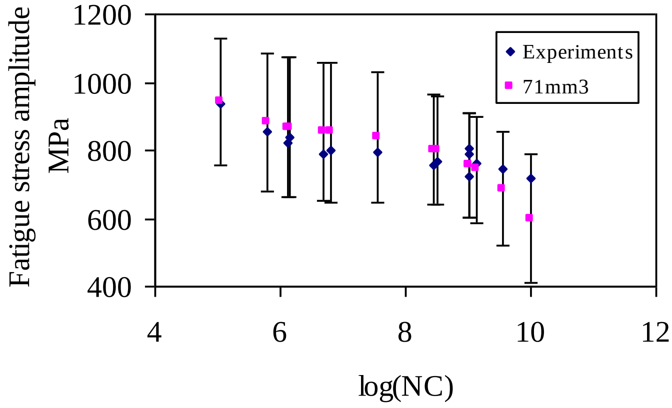


Fig. (13) Predictions for the fatigue stress and real fatigue stress amplitude (the pink points) versus log (NC) in the model, hardness=704 HV.

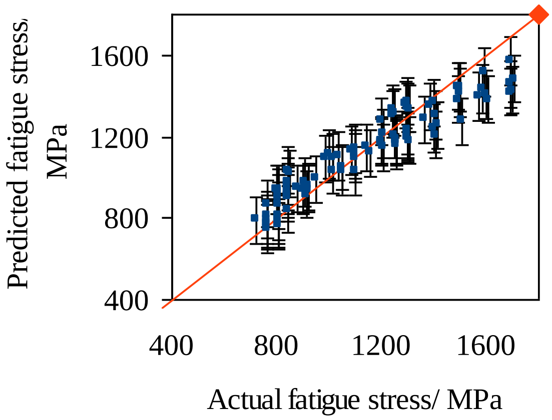


Fig. (14) Fatigue stress verses actual fatigue stress prediction, to the untrained data with the error bars.

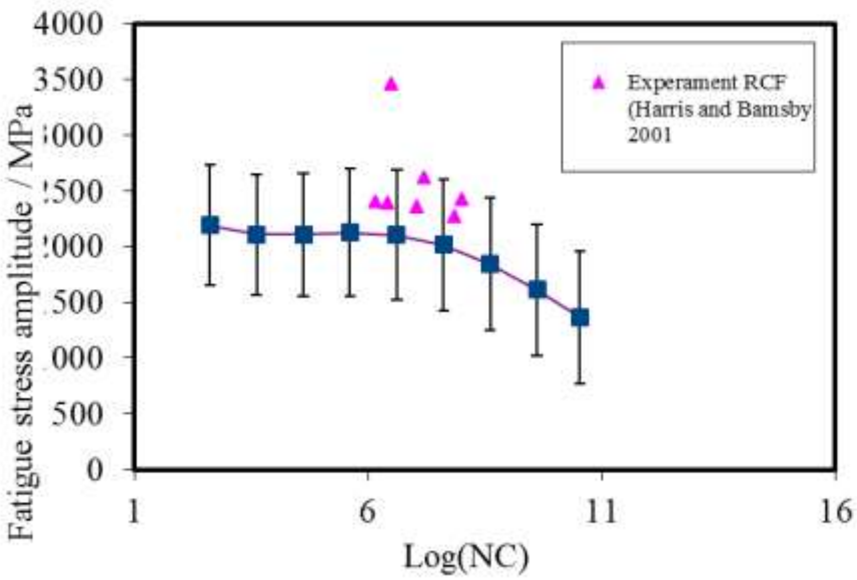


Fig. (15) Verification of the current life equation with the experimental results Obtained by Haris and Bamsby(2001) for RCF. The predicted S-N curve with R=0 and hardness=758HV.

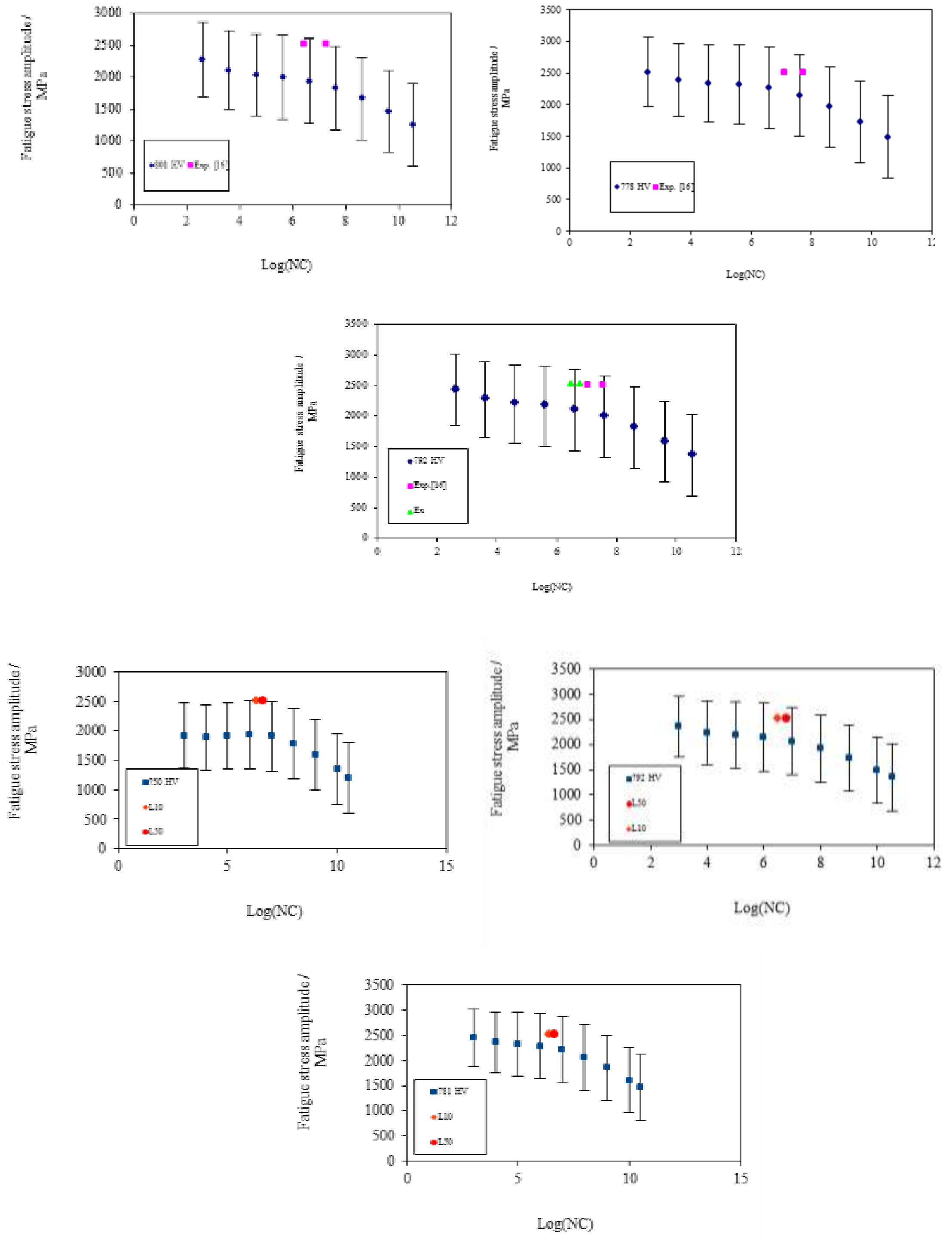


Fig. (16) Comparison of current life equation with the experimental results (S-N curve) for RCF [Stickels 1984], for different hardness.

REFERENCES :-

A.Al Hamdany, D. Al Fattal, T. A. Jabbar, H. K. D. H. Bhadeshia, Estimation of Fracture Toughness of Tempered Nanostructured Bainite. Materials Science and Technology, 28: 685-689, 2012.

A.Al Hamdany Fatigue model of bearing steel based on stressed volume, Materials Science and Technology , 32, 2016

A.Warhadpande, An Elastic-Plastic Finite Element Model For Rolling Contact Fatigue, Thesis, Purdue University, West Lafayette, Indiana ,2010.

B. Jalalahmadi, A New Voronoi Finite Element Fatigue Damage Model, Thesis, Purdue University, West Lafayette, Indiana, 2010.

C. Bathiac, Gigacycle Fatigue Properties of Bearing Steels. J ASTM Int, 7 JAI 102712, 2010.

C. A. Stickels, Rolling contact Fatigue Tests of 52100 Bearing Steel using a Modified NASA Ball Test Rig, *Wear*, vol.98, pp 199-210, 1984

E. Bayraktar, I. M. Garcias , C. Bathias, Failure Mechanisms of Automotive Metallic Alloys in Very High Cycle Fatigue Range, International Journal of Fatigue, 28: 1590–1602, 2006.

F. Sadeghi, B. Jalalahmadi, T. S. Slack, N. Raje, N. K. Arakere, A Review of Rolling Contact Fatigue, Journal of Tribology, Vol. 131 , 041403-1, 2009.

G. Lundberg and A. Palmgren, Dynamic Capacity of Rolling Bearings, Acta Polytech. Scand., Mech. Eng. Ser., 1, pp. 1–52,1947

H. K. D. H. Bhadeshia, Steels for Bearings, Progress in Materials Science, 57: 268-435, 2012.

H. K. D. H. Bhadeshia, Neural Networks in Materials Science, ISIJ In., 39: 966-979, 1999.

T. A. Harris, and R. M Barnsby, Life Ratings for Ball and Roller Bearings, Proc. Inst. Mech. Eng., Part J: J. Eng. Tribol., 215, pp. 577–595. 2001

T. Sakai. Review and Prospects for Current Studies on Very High Cycle Fatigue of Metallic Materials for Machine Structural use Journal of Solid Mechanics and Materials Engineering, 3:425-439, 2009.

Y. Furuya. Size Effects in Gigacycle Fatigue of High-Strength Steel under Ultrasonic Fatigue Testing. Procedia Engineering, 2:485-490, 2010.

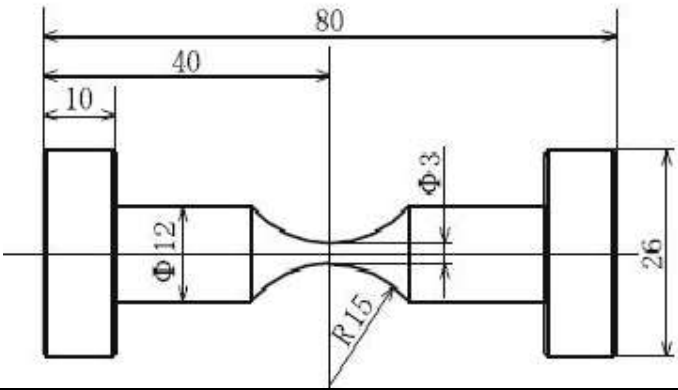
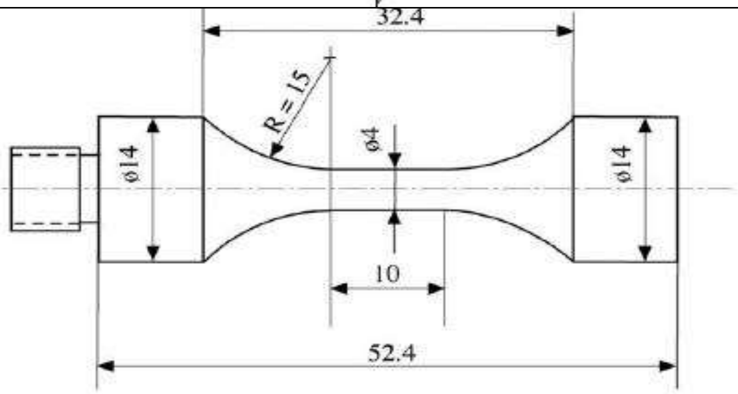
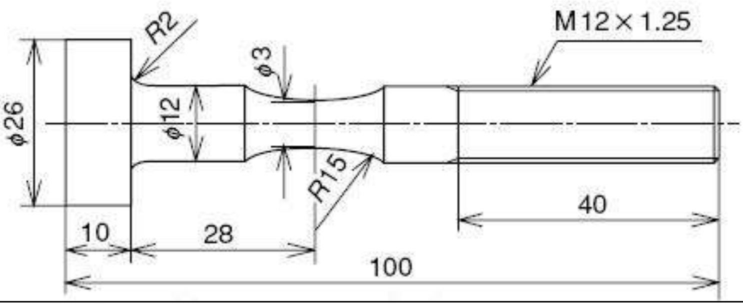
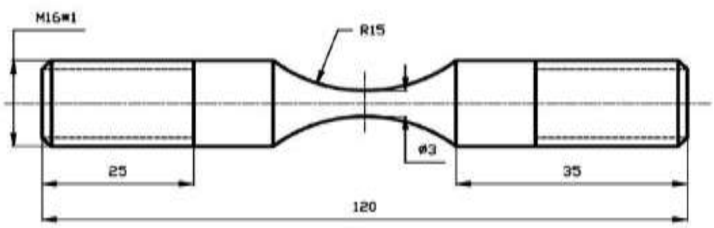
Y. D. Li, W. M. Guo, N. Xu, X. F. Wu, J. B. Shi and H. Ma, Crack Growth Process in GBF Area of SUJ2 bearing Steel in Very High Cycle Fatigue Regime, Materials Science and Technology, 29: 1463-1469 , 2013

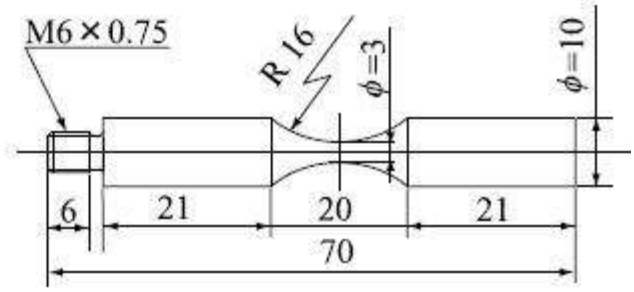
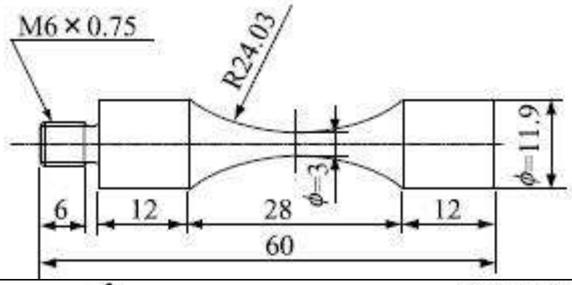
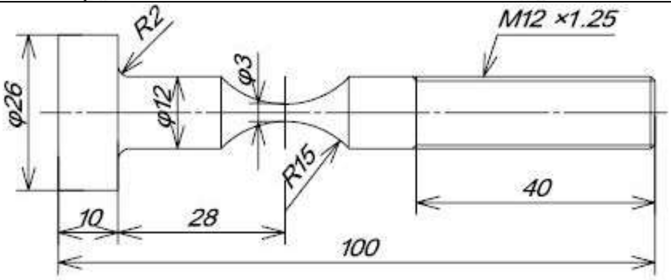
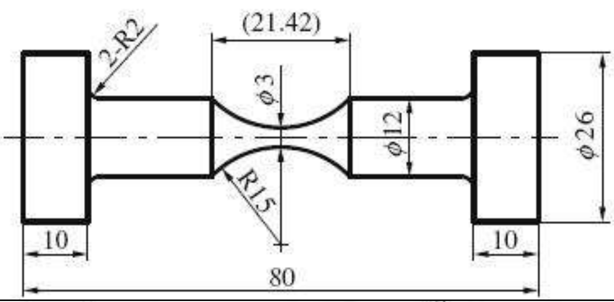
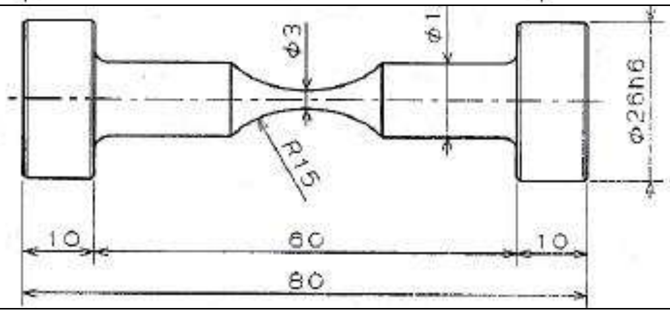
W. Li a, T. Sakaia, Q. Lib, L.T. Luc, P. Wangd, Effect of loading type on Fatigue Properties of High Strength Bearing Steel in Very High Cycle Regime, Materials Science and Engineering, A 528: 5044–5052, 2011 .

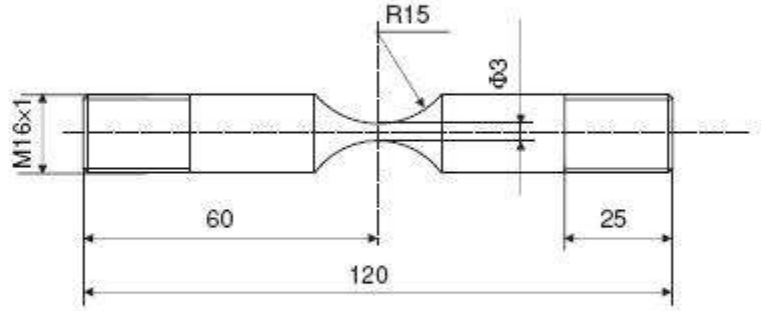
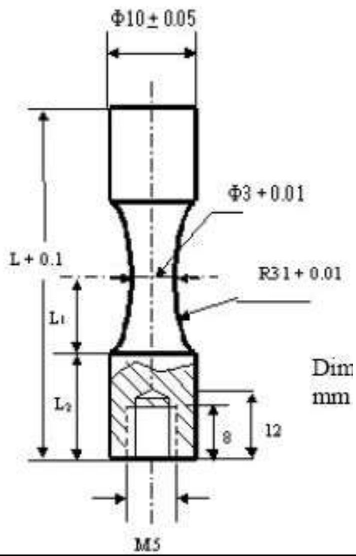
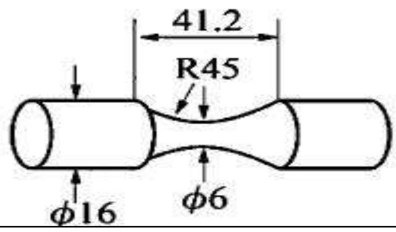
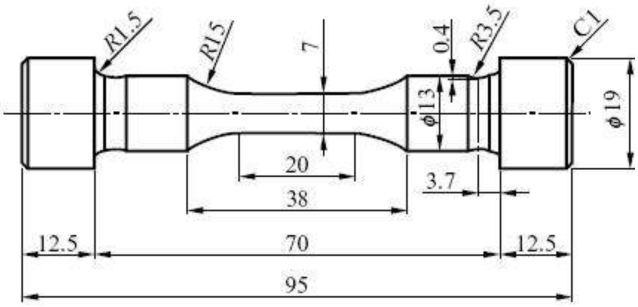
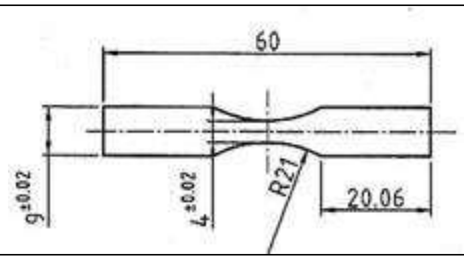
Appendix 1

Axial load and Gigacycle samples

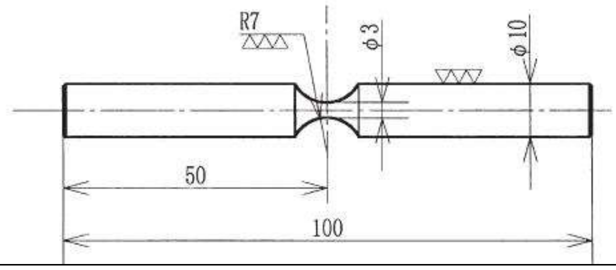
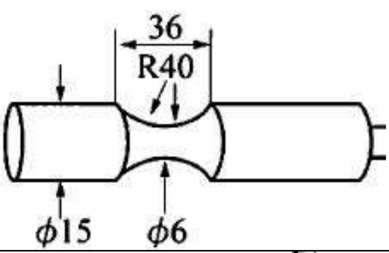
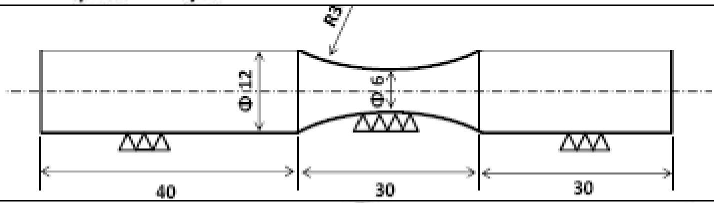
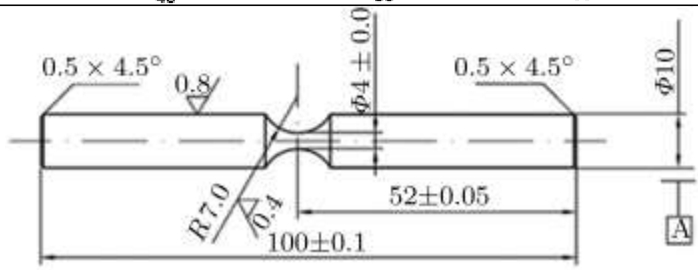
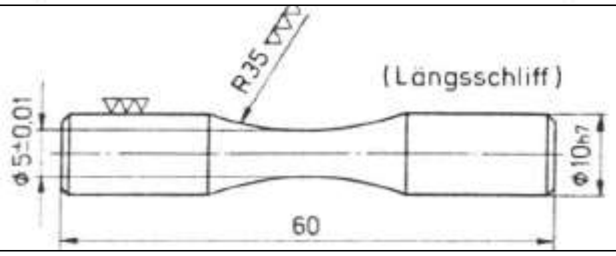
Vs the stressed volume

Ref	Samples shape	Vs
1		209mm^3
2,3		126.89 mm^3
4		209mm^3
5		209mm^3

Ref	Samples shape	Vs
6a		382.4mm^3
6b		126 mm^3
7		209mm^3
8		209mm^3
9		209mm^3

Ref	Samples shape	Vs
10		209mm^3
11, 12, 16 gigacycle		757mm^3
13		227mm^3
14		770mm^3
15		385mm^3

Rotating bending sample

Ref	Samples	Vs
1,2,3,5,7, 8,10,11,12		2.57 mm^3
4		34 mm^3
7		29.5 mm^3
9		5.165 mm^3
13		20.23mm^3