

Fatigue Behavior Optimization of the 16MnCr5 Steel Used in Machine Tool Spindle via Different Surface Treatments

M. N. Yoozbashi *¹

University of Applied Science and Technology, Tabriz, Iran

Abstract

Since the sub-axis of machine tool spindles subjected to fatigue loading, the effects of different surface heat treatments on fatigue behavior of 16MnCr5 steel have been investigated in the current work. The steel specimens were prepared and surface heat treatments including carburizing, carbonitriding and a practical type of treatment involving an initial nitriding followed by carburizing were done on samples. Rotating bending fatigue tests performed on the samples. In addition, microhardness and microstructural evaluations were applied to analyze the achieved results. The fatigue fracture surfaces were evaluated by scanning electron microscopy (SEM). The results showed that the fatigue strength of the samples has been improved considerably by the use of surface heat treatments. In addition, the initiation region of the fatigue crack from the samples surface has been transmitted to the interface of the hardened layer and the base metal in the surface treated steels. Also a reduction in the number of crack initiation places in the treated samples is specified compared to raw samples.

Keywords: Fatigue; 16MnCr5; Spindle; Carburizing; Carbonitriding; Nitriding.

1. Introduction

16MnCr5 Steel is a cemented steel with extensive uses in the manufacture of poultry tendons, steering components, pins, spindles of machines ¹⁾. Cemented steels have hard surfaces, soft and tough core and high abrasion resistance ²⁻⁴⁾.

Spindle of machine tool as one of the parts that 16MnCr5 steel is used in the making of its sub-axis. Spindle is one of the important components of Computer Numerical Control (CNC) machines. This complex

which is an alternating current motor, has a significant contribution in the speed, accuracy and quality of machining of CNC machines. In theory, the word of spindle refers to a transferring rod of rotating force; but in general, the set of rotating systems and all its axes of a rotating CNC machine is called a spindle. The main spindle of the device is the motor that is used to rotate the tool. In sub-axis spindle milling machines, the axis is a rotary which rotates the pieces ⁵⁻¹⁰⁾. In this study, the fatigue behavior of a rotating axis which is made of the mentioned steel, will be evaluated.

According to the base studies of materials engineering, it is essential to have a combination of high fracture toughness and good fatigue strength to increase the range of applied load and safety factor in engineering structures ¹¹⁾. The fracture toughness shows the resistance of pieces against the impact loading. Fatigue indicates metal behavior under repetitive loading. If the load is exceeded or the number of loading cycles becomes more than nor-

*Corresponding author

Email: nariman_yoozbashi@yahoo.com

Address: University of Applied Science and Technology, Tabriz, Iran

1. Assistant Professor

mal, it will result in a sudden fracture of the piece. The importance of fatigue fracture is such that at least 90% of fractures due to mechanical reasons during work are because of the fatigue loading¹²⁻¹⁵.

According to the loading conditions applied to the sub-axis of rotating spindle, it has been observed that this axle is mainly subjected to fatigue and abrasion condition. Therefore, this steel used by engineers in the carburizing condition in the sub-axis of spindle. In several studies, the mechanical properties of the steel have been studied under the conditions of various surface treatment such as carburizing, carbonitriding, and nitriding¹⁶⁻¹⁸. Investigating on abrasive behavior of 16MnCr5 steel under the influence of various surface treatment has been studied by Yoozbashi et al.¹⁹. Yoozbashi et al.²⁰, also conducted research on the effect of tempering treatment on the abrasion behavior of 16MnCr5 steel used in high speed spindles. The results indicate that the abrasive behavior of the steel has improved with the application of the mentioned thermal treatment.

Therefore, due to the lack of existing research and in

order to use the results of this research in spindles manufacturing industry, the fatigue behavior of the mentioned steel in carburizing conditions has been evaluated and compared to other surface treatments. Also, in order to investigate the effect of surface treatment on the fatigue strength, the fatigue behavior of the steel in the base condition has also been evaluated. The surface treatment used in this research have been selected in accordance with conventional industrial treatment. Also used cycles are selected according to the previous works of Yoozbashi et al.¹⁹⁻²⁰, which have showed the highest wear resistance among the used cycles.

2. Experimental Procedures

In the present study, rotational bending fatigue behavior of 16MnCr5 steel used in spindle of machine tool has been studied according to DIN 50 113 standard²¹. Dimensions of fatigue samples which prepared in accordance with the mentioned standard has been shown in Fig. 1.

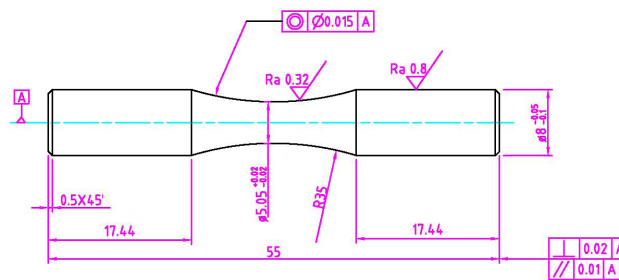


Fig. 1. Dimensions of samples of rotational bending fatigue test.

Experimental samples of fatigue, microhardness and microstructure were divided into four series after preparation. A number of samples remained in raw condition, in other words tempered quench manner. Other series have been subjected to surface treatment in accordance with the following designed cycle in order to achieve high surface resistance.

1- Surface treatment of carburizing:

- 1.1. Preheat at 550 °C for 2 hours;
 - 1.2. Carburizing at 920 °C for 5 hours;
 - 1.3. Normalizing;
 - 1.4. Austenitizing at 840 °C for 30 minutes;
 - 1.5. Quenching in oil;
 - 1.6. Tempering at 200 °C for 1 hour.
- Samples of this series were named CS (Carburized Samples).

2- Surface Treatment of carbonitriding:

2. 1. Preheat at 550 °C for 2 hours;

2. 2. Carbonitriding at 920 °C for 5 hours in a gaseous compound of 60% air, 20% ammonia and 20% LPG (Liquefied Petroleum Gas) with 1 Bar inlet gas pressure;
 2. 3. Tempering at 200 °C for 1 hour.
- Samples of this series were named CNS (Carbonitrided Samples).

3- Practical treatment of first nitriding and then carburizing:

This treatment has been selected exactly according to what is used in the industry as follows:

- a- Nitriding of samples at 540 °C for 10 hours in a gaseous compound of 40% ammonia, 60% nitrogen and 1 bar with inlet gas pressure;
- b- Carburizing treatment of Nitrided samples as follows;
 - i. Preheat at 540 °C for 2 hours;
 - ii. Carburizing at 920 °C for 5 hours;
 - iii. Rapid transfer to 840 °C and keeping at this temperature for 30 minutes;
 - iv. Quenching in oil;
 - v. Tempering at 200 °C for 1 hour.

Samples were named PNCS (Practical Nitrided Carburized Samples). Raw samples were also named RS (Raw Samples).

After performing various surface heat treatments, the cross-sectional area of the samples was examined by optical microscopy (OM) at different magnifications. Also hardness variations profile of the samples from the surface to the core of sample were achieved by microhardness test under 100 gf load. For each surface treatments, three different samples have been used for microhardness evaluations. To investigate the depth of carbon diffusion, in addition to the obtained microhardness profile, a scanning electron microscope (SEM) equipped with an energy dispersive spectroscopy (EDS) was used. Phase analysis using X-Ray Diffraction (XRD) was used to investigate the formation of carbide and nitride phases. XRD analysis was carried out using a Bruker™-D8 advance diffractometer with monochromated $\text{CuK}\alpha$, radiation at 40 kV and 40 mA according to the ASTM E975-84 standard²². Scanning was performed in the 2θ range of 10° - 120° at a rate of $0.6^\circ \text{ min}^{-1}$.

The fatigue tests were performed by the rotational bending fatigue machine at 2800 rpm in laboratory conditions and ambient temperature. Because the samples were subjected to surface treatments; estimating the first maximum applied stress of steel from the references did not yield the desired result. Therefore, the maximum applied stress of samples were determined according to the trial and error. For each stress level, two to three samples were tested and subsequent samples were tested in applied stress with 50 MPa steps. If the sample is not fractured under the applied stress after about rounds; it is considered as a fatigue limit. To avoid the dispersion of fatigue results, the diameter of the samples was measured with a micrometer with an accuracy of 0.01. Also, after placing the end of the specimens in the jaw of the device, the exact distance from the end of jaw to the exact location of the force effect was measured with Collis, so that the distance is equal.

3. Results and Discussion

3.1. Hardness and microstructure properties

Table 1 shows the hardness values of raw sample and samples subjected to surface heat treatments. It is observed that due to surface treatment, the hardness of raw samples has increased significantly. Also, the CS samples have shown more hardness than other samples. This behavior can be attributed to the formation of carbide compounds at the sample surfaces, which are harder than nitride compounds.

Table 1. Hardness values of raw and surface treated samples.

Sample	RS	CS	CNS	PNCS
Hardness (VHN)	150±15	1050±15	980±15	750±15

According to the nature of the martensite transformation and the change in the chemical composition of the surface which occurs as a result of surface treatment, the increase in surface hardness to certain distances from the surface is predictable and can be described by using microhardness results. Fig. 2 shows a profile of the microhardness variations in terms of relative Vickers hardness as a distance from the surface. Considering the hardness criterion of 550 Vickers²⁾, to determine the depth of the hardened layer, the depth of this layer in different surface treatments is about 1 mm. According to the mentioned contents in references, the depth of the hardened layer is reported to be a maximum of 1.5 to 2 mm that the obtained number is somehow in agreement with other references²⁾.

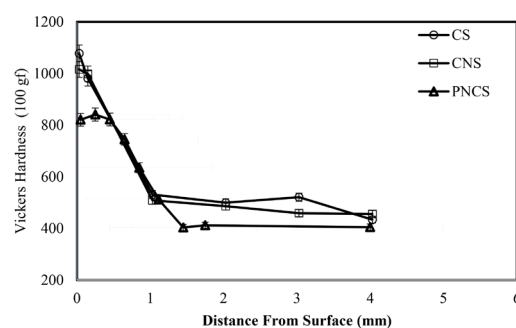


Fig. 2. Microhardness variations of 16MnCr5 steel after different surface treatments.

The results of spectroscopy analysis of the carburizing samples based on the scattering of EDS is shown in Fig. 3. Given that EDS analysis is not very accurate in determining the amount of elements and it is a semi-quantitative method; however because the height of the carbon peak is comparable to the iron peak, it can be mentioned that the concentration of carbon at the surface of the samples has increased.

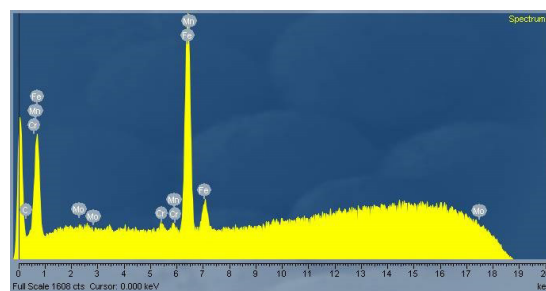


Fig. 3. The results of EDS analysis of the surface of the carburized sample.

It is observed that with the addition of nitrogen in the carbonitriding treatment, despite the low hardness of nitride compounds compared to carbide compounds, carbonitriding samples show a similar microhardness

distribution with carburized samples. Also, the diffusion depth of carbon and nitrogen elements is equal and more than 0.5 mm. The reason for this is firstly the formation of epsilon (ϵ) carbonitrided phase and chromium nitride. Formation of the hard phase of iron nitride on the surface of carbonitriding samples, determined by using XRD, has been shown in the Fig. 4. Also, nitrogen by reducing the critical cooling rate, leads to hardenability enhancement. Diffusion of nitrogen into the inner layers and its augmentation in the internal layers of the samples, causes the stability of the austenite. Therefore, the reduction of hardness in the inner layers of the samples has been occurred. Finally, re-austenitization of the carburized samples at 840 °C led to decarburization at this stage and reduces the hardness of samples compared to the real condition. Also the use of nitriding in PNCS series samples causes stabilization of retained austenite in the interior layer of the samples. Therefore, these samples have shown less hardness in the internal layers.

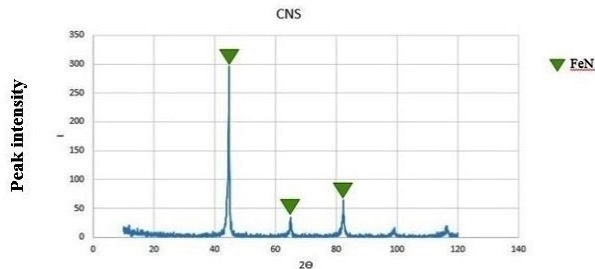


Fig. 4. The results of XRD analysis of surface of carbonitrided sample.

The increase in hardness of samples from the surface to the inside of the sample as a result of surface treatment can be also described using microstructural studies. The microstructure of the surface area of the samples after the various surface treatment, which provided using OM and SEM, is shown in Fig. 5. According to the figure, it is clear that the surface microstructure of the samples has changed due to surface treatment.

According to the references ²⁻³⁾, the carbon diffusion depth in the carburized samples is reported to be a maximum of 1.5 to 2 mm; while the carbon diffusion depth according to Fig. 5 is less than 1 mm. This difference can be attributed to the relatively high concentration of manganese (0.7-0.9 wt. %) in the chemical composition of the steel, which delays the diffusion of carbon into the samples. According to ²⁻³⁾, the manganese element reduces the activity of the carbon element.

Fig. 5b shows the microstructure of the surface of carbonitriding samples. The observed white inner layer is related to the formation of nitride compound during the carbonitriding process. Due to the low temperature of the carbonitriding treatment and the short duration of this treatment, the thickness of this white layer is relatively low.

The formation of an inner white layer consisting of iron nitrides is also observed in Fig. 5c for the samples of PNCS. The nitride layer formed during primary nitriding prevents carbon diffusion during the subsequent carburizing. As a result, the only effect that carburizing treatment have had on the microstructure of this sample is the growth of the grains formed at the surface of the sample.

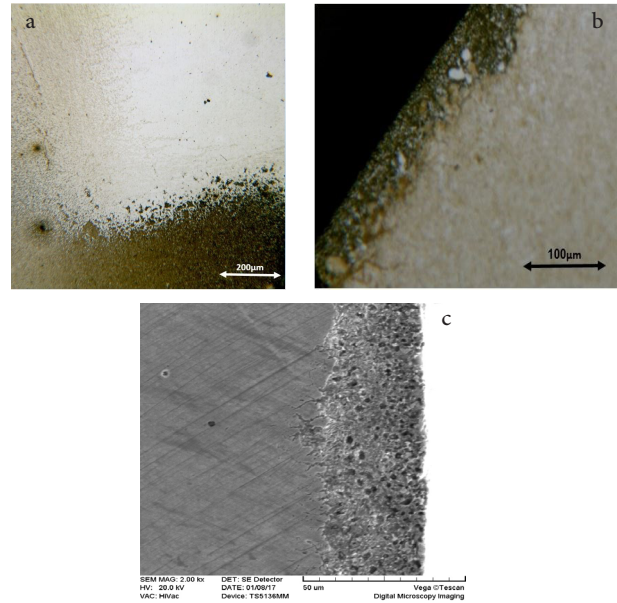


Fig. 5. Images of OM and SEM of the surface of samples; a) Carburizing, b) Carbonitriding and c) First nitriding and then carburizing

The results of EDS analysis of surface of PNCS series is shown in Fig. 6. It is observed that concentrations of carbon and nitrogen elements as a result of PNCS treatment have increased on the sample surface compared to other alloying elements. Also, in these samples, the diffusion of nitrogen and carbon are observed in small quantities.

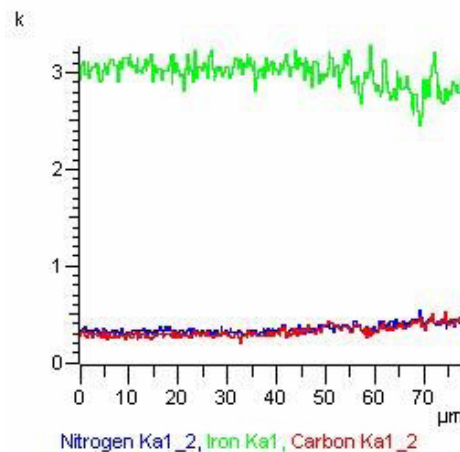


Fig. 6. EDS analysis results of surfaces of PNCS.

3. 2. Fatigue behavior of raw and surface treated samples

One way to present the fatigue results is to use the Wohler curve (S-N curves), which is a graph of the maximum applied stress in terms of the number of fracture cycles. The fatigue curves of the raw and the surface treated samples are shown in Fig. 7. As shown in the figure, in

all fatigue tests, the broken samples at high stress levels have endured low cycle of fatigue. So that with decreasing stress, the number of fracture cycles has increased. Also, in table 2 the fatigue limit values of the raw and surface treated samples are shown. Thus, the importance of surface treatment in improving fatigue strength can be realized. For example, as a result of the surface heat treatment of carburizing, the fatigue limit has been enhanced by 130% compared to the raw state.

Table 2. Fatigue limit of raw and surface treated samples.

Sample	RS	CS	CNS	PNCS
Fatigue Limit (MPa)	350±10	800±10	750±10	850±10

At high stress levels, as the number of cycles decreases and failure approaches the semi-static state; the controlling factor of the fatigue fracture is the propagation of crack stage. In other word, the more resistant to the propagation of fatigue crack, the materials are, the higher fatigue strength, they show ¹²⁻¹³. Due to the relatively high depth of carbon diffusion and its effect on the major share of sample diameters, it can be concluded that the stage of propagation of fatigue crack has also been affected by surface treatment.

As shown in Fig. 7, at low stress level, the samples are broken in larger number of cycles. At this level of stresses, the controlling factor of fatigue fracture is the fatigue crack initiation stage. This means that material, with more resistant against initiation of fatigue crack, will show higher fatigue strength. Because of the occurrence of relatively large gap between of the fatigue curves of the CS and RS at low stress surfaces, it can be inferred that carburizing treatment has had the greatest effect on the initiation stage of fatigue fracture.

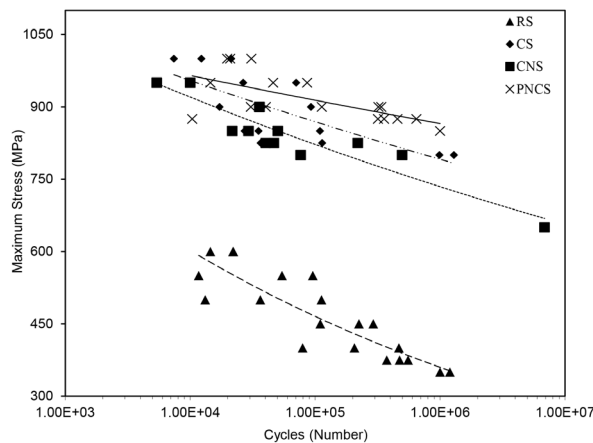


Fig. 7. Maximum applied stress variations based on the number of fracture cycles.

3. 3. Examination of fatigue fracture surfaces

In order to investigate the effect of surface treatment on fatigue fracture morphology, typical SEM micrographs of the samples are shown in Fig. 8. Three regions of initiation of crack, crack propagation and final fracture are shown in this figure. It can be easily seen that crack initiation occurred at the interface of the surface treated and the base metal of the specimens and no inclusions were recognized as crack initiation sites. Ring

formation at the interior layer of the treated samples, which indicates a hardened surface, can be a reason for the absence of crack initiation in surface regions of the samples. Also, formation of the ring in the interior layer of the samples, can be evidence of the effect of surface treatments on the fatigue fracture morphology. It can be said that fatigue crack propagation according to what is discussed in the section of the fatigue curve, has been affected by surface treatments. Reduction in the number of crack initiation places in the treated samples com-

pared to the RS, which is quite visible in the figures, can be the result of the major effect of surface treatments on fatigue behavior of samples. From fractography analyses, applying surface treatments has no effect on the final fracture stages.

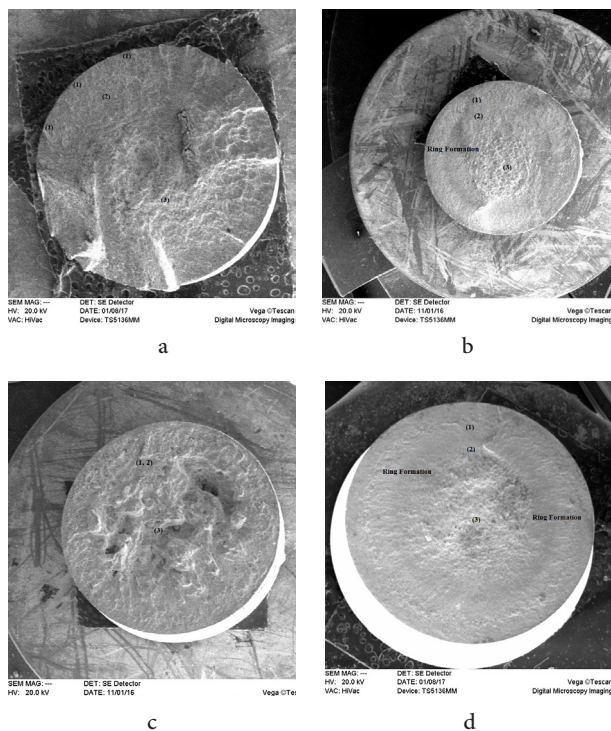


Fig. 8. Typical SEM micrographs of fracture surface of; a) RS broken at 375 MPa at the cycle of 473900, b) CS broken at 800 MPa at the cycle of 986900, c) CNS broken at 750 MPa at the cycle of 496900 and d) PNCS broken at 875 MPa at the cycle of 646400. Numbers 1, 2, and 3 indicate the initiation of crack, crack propagation and final fracture zones, respectively.

4. Conclusion

In this study, the effect of surface heat treatment of carburizing, carbonitriding and first nitriding and then carburizing on microstructure, hardness, rotational bending fatigue strength and the fatigue fracture surfaces of 16MnCr5 steel used in the sub-axis of spindle of the machine tool has been discussed and has given the following results;

The hardness of the surface treated samples has increased considerably compared to the raw sample. Hardness of the raw samples is obtained about 150 HVN, carburized samples 1050 HVN, carbonitriding 980 HVN and first nitriding and then carburizing 750 HVN. Also, according to microhardness test results, the hardened lay-

er depth in all treatments is about 1 mm.

According to the microstructural investigations, the depth of carbon diffusion in the carburized samples obtained less than 1 mm. A low carbon depth can be attributed to the relatively high concentration of manganese (0.7-0.9 Wt. %) in the chemical composition of steel, which delays the diffusion of carbon into the interior layer of samples. The repositioning of carburizing samples at 840 °C, during re-austenitization, resulted in decarburization and consequently reduced carbon diffusion.

According to the microstructural results, the low temperature of carbonitriding treatment and the short duration of this treatment led to relatively low thickness of formed white layer due to the formation of nitride compounds.

Examination of the fatigue behavior of the samples indicates that due to the surface treatment, the fatigue strength has significantly improved. For example, as a result of the surface heat treatment of carburizing, the fatigue limit has been improved by 130% compared to the raw samples. The test results showed the fatigue limits of the raw samples to be 350 MPa, carburizing 800 MPa, carbonitriding 750 MPa, and first nitriding and then carburizing 850 MPa.

According to the surfaces of fatigue fracture, there are three regions of initiation of crack, crack propagation and final fracture zones. Also, transfer of crack initiation area from the surface in non-surface treated samples to the interface of the treated and base metal area is obvious. Also, reduction in the number of crack initiation places in the treated samples is specified compared to raw samples.

References

- [1] C.W. Wegst: Key to steel, Verlag Stahlschlüssel Wegst GMBH 0.050, 0-004, (1998).
- [2] G. Krauss: Steels heat treatment and processing principles, ASM International, (1994), 497.
- [3] G. E. Totten and M. AH. Howes: Steel heat treatment handbook. CRC Press, (1997).
- [4] H. Bhadeshia and R. Honeycombe: Steels microstructure and properties. Butterworth-Heinemann, 2017.
- [5] E. Abele, Y. Altintas, and C. Brecher: CIRP Annals-Manufacturing Technology., 59(2) (2010), 781.
- [6] T. Y. Chen, W. J. Wei, and J. C. Tsai: Int. J. Mach. Tools Manuf., 39(12) (1999), (1961).
- [7] P. H. S. Campos, J.R. Ferreira, A. P. De Paiva, P. P. Balestrassi, and J. P. Davim,: Rev. Adv. Mater. Sci., 34(2) (2013), 141.
- [8] J. K. Choi: Int. J. Mach. Tools Manuf., 38(9) (1998), 1017.
- [9] V. Gagnol, B. C. Bouzgarrou, P. Ray, and C. Barra: Adv. Integ. Des. Manuf. Mech. Eng. II, (2007), 505.
- [10] H. Li, and Y. C. Shin: Int. J. Mach. Tools and Manuf., 44(4) (2004), 347.
- [11] S. K. Putatunda: Mater. Sci. Eng. A., 297(1) (2001),

31.

[12] Dieter, George Ellwood, and David J. Bacon. *Mech. Metal.*, Vol. 3. New York: McGraw-hill, (1986).

[13] R. W. Hertzberg: *Def. Frac. Mech. Eng. Mater.*, (1989).

[14] P. G. Forrest: *Fatigue of Metals*. Elsevier, (2013).

[15] D. McLea: *Mechanical Properties of Metals*. Krieger Pub Co, (1977).

[16] W. Dal'Maz Silvaa, J. Dulcya J. Ghanbajaa, A. Redjaimiaa, G. Michelb, S. Thibaultc and T. Belmontea: *Mater. Sci. Eng. A.*, 693(2017), 225.

[17] L. Ceschini, and M. Giangiaco: *Surf. Coat. Techn.*, 202.9(2008), 1778.

[18] L. B. Winck, J. L. A. Ferreira, J. A. Araujo, M. D. Manfrinato, and C. R. M. da Silva: *Surf. Coat. Tech.*,

232(2013), 844.

[19] M. N. Yoozbashi, A. Almasi, *J. Mech. Eng. Uni. of Tabriz.*, 48(1) (2018), 351.

[20] M.N. Yoozbashi, N. Vahedi, A. Almasi: *J. Mech. Eng. Uni. of Tabriz.*, 47(3) (2017), 297.

[21] DIN 50 113, *Rotating Bar Bending Fatigue Test*, German Standards Organization, (1982).

[22] ASTM E975-84, *Standard Practice for X-Ray Determination of Retained Austenite in Steel with Near Random Crystallographic Orientation*, Annual Book of ASTM Standards, 03.01, (1990), 753.

[23] B. C. De Cooman: *Current Opinion in Solid State and Mater. Sci.*, 8(3-4), (2004), 285.