The Effect of Interaction Between Hardness, Inclusion and Microstructures on the Fatigue Behavior of Steel

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1- Introduction

Fatigue is one of the main reasons for the destruction and failure of parts subjected to dynamic loads. Almost all failures due to fatigue are caused by cracks originating from stress concentration areas. Inclusions that are the source of stress concentration in parts, have a strong effect on fatigue strength. Constructing a suitable method to predict the fatigue limit in the presence of inclusions has been a long-time need for engineers. In the past years, many empirical relationships between ultimate tensile strength and hardness with fatigue limit have been proposed. For example, Murakami has predicted two equations for estimation of the lowest and highest fatigue strength. When metals are without defects, the highest fatigue limit can be obtained from Eq. 1 for HV<400.

$$\sigma_{wm} = 1.6H_V \qquad (1)$$

When fatigue failure occurs by defects or non-metallic impurities, the lowest fatigue strength is achieved. Murakami et al. presented a useful and simple method based on two fundamental quantities for predicting σ_w. These two fundamental quantities are Vickers hardness, which represents the strength of the steel and √area. Area is defined as the biggest inclusion projected area perpendicular to the axis of the applied stress. Area is a factor for geometric expression of defect.

$$\sigma_{wd}=\frac{1.41(H_V+120)}{(\sqrt{area})^{1/6}} \qquad (2)$$

Eq. 1 and Eq. 2 suggest a range of fatigue limits from the highest value for a perfect defect-free specimen to the lowest value for a defected specimen. A specific procedure (by using only Vickers hardness) for exact estimation of the fatigue limit in steels due to the effect of non-metallic impurities as the main cause of fatigue failure has still not been reported. Therefore, the aim of this paper is to offer a simple and relatively accurate new method for estimating fatigue limit by using the Vickers hardness due to the effect of non-metallic impurities and surface roughness.

2- Experimental

In this study for fatigue tests, fatigue standard samples of four types of commercial steels (DIN 1.7218،1.7176،1.1302،1.1186) were prepared following DIN 50113. In order to get different hardness values, each steel was subjected to a specific heat treatment cycle. These cycles are summarized in Table 1. After heat treatment, the microstructure and fatigue properties of the samples were investigated. Experiments continued until fracture of specimens or 10^7 stress cycles were reached. In each group, at least four hardness measurements on the heat-treated samples were conducted. The average hardness value was reported. To know the exact size and place of inclusions which caused fatigue failure and to better understand how the fracture occurred, the fracture surface of failed samples were studied by scanning electron microscopy (SEM).

Table 1 Heat treatment process and hardness of studied steels

Steel	Quenching media, Austenitizing time (min), Austenitizing temp. (°C)	Tempering temp. (°C)	Average hardness (H_v)
1.1186	Hot Rolled	-	195
1.1302	Air-1200(°C)	-	297
1.7218	Warm Oil, 30(min), 850(°C)	400	392
1.7176	Warm Oil, 55(min), 870(°C)	420	553

3- Results and Discussion

3-1- Microstructure Observation

Microstructure observations showed that 1.1186 steel has a relatively fine ferrite-pearlite microstructure with 40% ferrite. 1.1302 steel has 30% ferrite and the rest is perlite with relatively course ferrite-pearlite structure. 1.7218 steel has 8% ferrite, 32% bainite and the remaining is tempered martensite. The microstructure of 1.7176 steel is completely tempered martensite. Both 1.1186 and 1.1302 steels have ferrite-pearlite structure; but because of the higher amount of ferrite in 1.1186 steel, this steel has a lower hardness value.

3-2- S-N curve

Fig. 1 shows S-N curves resulting from fatigue testing of all studied samples. A plateau in the range of 10^6 to 10^7 cycles can be seen in Fig. 1. This plateau is considered the fatigue limit. The fatigue limit for 1.1186, 1.1302, 1.7218 and 1.7176 steel is 240, 330, 410 and 320 MPa, respectively

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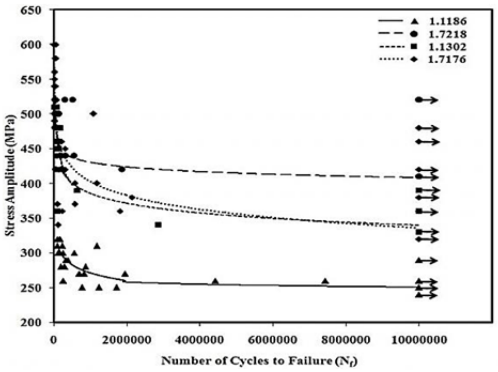

Fig. 1 S-N curve for the studied steels

3-3-Relationship between hardness and fatigue limit

The effect of inclusion size is expressed by the stress intensity factor (K_{Imax}) via the following equation:

$$K_{Imax} = C_1\, \sigma \sqrt{\pi\sqrt{area}} \quad (3)$$

Where σ is the applied stress, √area is inclusion size and C_1 is a constant related to the location of the impurities. To determine the amount of √area, all broken specimens were examined using a SEM. After determining the inclusion which caused the failure, its dimensions are measured and √area is calculated. The relationship between stress intensity (K_{Imax}) generated by non-metallic impurities and the number of cycles that lead to failure (N_f), for all tested samples is shown in Fig. 2. It can be observed that by reducing K_{Imax}, N_f increases. According to Eq. 3, stress intensity depends on the applied stress and size of impurities.

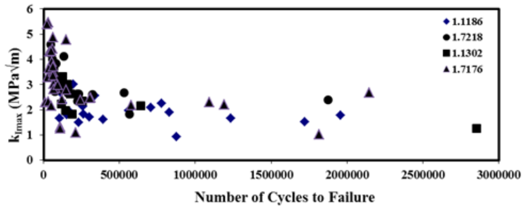

Fig. 2 Relationship between KImax and Nf in the studied samples

The stress intensity factor represents the increased amount of stress applied to the sample by impurities in the boundary between it and the matrix. The lowest K_{Imax} for each type of steel (called K_{Ith}), is the maximum strength of the matrix in fatigue testing. When stress values lower than K_{Ith} are applied to the sample, the microstructure will be able to resist fatigue fracture. According to this description, K_{Ith} factor could be a suitable measure for estimating the fatigue limit. Fig. 3 shows the relationship between fatigue limit and K_{Ith}. In this figure, we can see that with increase in K_{Ith}, σ_w also increases. Fig. 3 also shows the relationship between these two factors obtained using a trendline accordance to Eq. 4.

$$\sigma_w = (158.46\, K_{Ith}) + 125.51 \quad (4)$$

The relationship between the hardness of the examined steels and K_{Ith} is shown in Fig. 4. According to Fig. 3 with an increase in σ_w, K_{Ith} also increases. K_{Ith} can be a suitable criterion for estimating the fatigue limit since both have the same process as H_v. Eq. 5 which is obtained in the range of H_v <400, enables the prediction of the threshold stress intensity factor (K_{Ith}) with H_v.

$$K_{Ith} = (0.0046\, H_v) - 0.010 \quad (5)$$

By replacing Eq. 5 in Eq. 4, a new equation (Eq. 6) based on H_v results which can predict σ_w.

$$\sigma_w = (0.73\, H_v) + 123.8 \quad (6)$$

Eq. 6 can be used to determine the fatigue limit without any time-consuming and costly fatigue test. This equation is for steels with hardness values up to 400 HV.

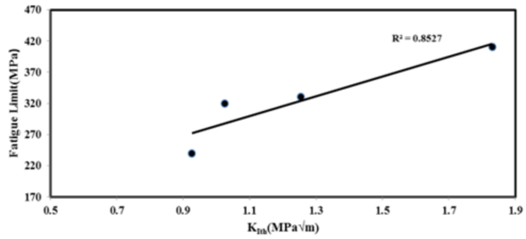

Fig. 3 Relationship between the threshold stress intensity factor (K_{Ith}) and fatigue limit for the examined steels

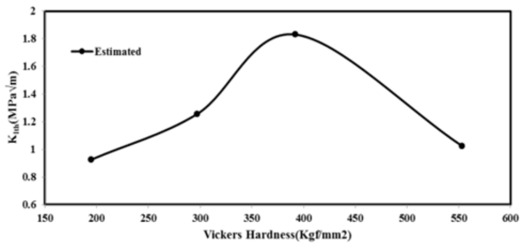

Fig. 4 Relationship between the stress intensity factor (K_{Ith}) and hardness for the examined steels

4- Conclusions

According to the fatigue tests conducted in this study and microstructural observations, the following results were obtained.

1- The fatigue limit of four commercial steels 1.1186, 1.1302, 1.7218 and 1.7176 with various hardness values, up to 400 Vickers hardness increases and then decreases at higher Vickers values.
2- The relationship between threshold stress intensity factor caused by non-metallic impurities and hardness is similar to the relationship between fatigue limit and hardness.
3- Simple equations for predicting σ_w and K_{Ith} using Vickers hardness, which is useful for industrial applications, were presented.