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Extreme value statistical analysis to determine the endurance limit of a 1045 induction hardened steel alloy

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Abstract

Surface hardened components are used in fatigue critical applications such as axles and gears. Inclusions are critical microstructural features where fatigue cracks have been observed to nucleate in these parts. In this investigation, the effect of inclusion populations on fatigue performance of induction hardened 1045 steel was examined. The steel was heat treated to have a tempered martensite starting microstructure and was induction hardened to two different case depths. Utilizing extreme value statistical analysis, the largest inclusion as well as the largest inclusion in each of five categories, MnS, MnCaS, MnAlS, Al_2O_3, and Al_2O_3-MgO, was estimated for a critically stressed area in a fully reversed cantilever bending fatigue sample. The inclusion size estimates were used to predict the endurance limit of the sample with a fracture mechanics-based model. This methodology has been traditionally used for homogeneous materials but has been modified here for bending fatigue and inhomogeneous case hardened material. The predicted endurance limits are closely correlated to experimentally measured endurance limits.

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Keywords: Fatigue life; Inclusion; Gumbel distribution; Extreme value statistics; Steel

1. Introduction

The mechanical performance of steel is affected by the exogenous and endogenous inclusions that are present in a given heat of material, and fatigue performance can be strongly influenced by the largest inclusions in a given sample [1]. Extreme value statistics (EVS) is a common method employed to

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estimate the largest inclusion in a volume of material [2] or to infer properties about a material based on the largest estimated inclusion in a given area or volume [3]. By assuming that the distribution of the square root area of inclusions in a material conforms to a Gumbel distribution, then the largest inclusion in an area of interest can be determined probabilistically using EVS analysis.

Predicting the endurance limit for surface hardened components is complicated compared to a homogeneous through hardened component due to the inhomogeneous microstructure, hardness profile, inclusion distribution, and residual stresses in a surface hardened part after processing. Murakami *et al.* [4] showed that the fatigue limit for a non-case hardened SAE 10L45 steel alloy can be accurately predicted using EVS analysis, but the predictions become non-conservative as the hardness of the material increases whereas Zhang *et al.* [5] demonstrated that the EVS analysis provides a more conservative estimate of the experimentally determined endurance limit of a modified 43CrMo steel. Choi *et al.* [6] are among the few that have applied this approach to predict the endurance limit of induction hardened steels; they showed that EVS analysis predictions of endurance limit are non-conservative for an induction hardened 1.05Cr-0.23Mo steel component.

In this investigation, the EVS analysis approach, using multiple inclusion populations, was used to predict the endurance limit of induction hardened steel. The analysis is unique because very few investigations have used this approach to predict fatigue limits in case-hardened alloys.

2. Experimental Procedures

A 1045 steel alloy was selected for this study with the composition shown in Table 1. The steel was hot rolled to 31.75 mm diameter bars and then machined into bending fatigue test specimens, which were designed to maximize the area of the sample exposed to stresses greater than 95% of the maximum stress (Figure 1). After machining, the specimens were austenitized at 900°C for thirty minutes in a carbon neutral atmosphere, immediately oil quenched, and then tempered at 500°C for one hour followed by an air cool. The resulting tempered martensitic microstructure had an average hardness of 30.5 ± 0.2 HRC. The heat treated specimens were then induction hardened with a radio-frequency power source, a scanning coil with an integrated quench ring, and a four percent polymer quenchant. A constant scan speed of 6.98 mm/s was used for all samples, and the power settings were adjusted to obtain the desired case depth. To prevent post-induction cracking of the samples, the specimens were tempered at 176 °C for 1.5 hours within four hours of induction hardening in accordance with the SAE AMS2745 standard [7]. The objective of induction hardening was to produce two distinct case depths, labeled as the "low case depth" (1.19 mm) and "high case depth" (1.64 mm) conditions, to assess the effects of case depth on crack nucleation mechanisms and fatigue performance. The case depth is defined as the distance from the surface of the part to the depth at which the hardness drops below 450 HV [8].

Table 1. Composition of the 1045 steel alloy used for this study, wt pct.

Alloy	C	Mn	Si	Ni	Cr	Mo	V	Al	N	S	P	Cu
1045	0.45	0.75	0.25	0.12	0.10	0.05	0.001	0.036	0.0084	0.018	0.006	0.21

The induction hardened specimens were fatigue tested using load-controlled, fully reversed (R = -1) cantilever bending on two Baldwin SF-1-U fatigue testers. The samples were polished to a 1 μm diamond finish on a lathe prior to testing. The endurance limit in this study is defined as the applied stress in which five consecutive samples reach 1.5×10^7 cycles after dropping the applied stress by 5 MPa from a stress level where finite life is observed.

An inclusion analysis of the 1045 steel was performed utilizing an ASPEX eXplorer personal scanning electron microscope (PSEM). All samples examined were polished to a mirror finish, and all image analysis was conducted in the PSEM with a 20kV accelerating voltage. Energy dispersive spectroscopy (EDS) was utilized to identify five different inclusion types: manganese sulfide (MnS), manganese sulfide with calcium (MnCaS), manganese sulfide with aluminum (MnAlS), alumina (Al_2O_3), and alumina-magnesia (Al_2O_3-MgO). Three samples were examined, which provided a total examination area of 650 mm^2.

An extreme value statistical (EVS) analysis was conducted using the data obtained by the PSEM. The samples were divided into smaller subregions of 1.25 mm by 2 mm for a total of 260 views across all samples. The largest inclusion, regardless of type, within each subregion was recorded (Max. Inclusion). Additionally, the largest inclusion of each category (MnS, MnCaS, MnAlS, Al_2O_3, and Al_2O_3-MgO) was also recorded for each subregion. If the inclusion type was not present in the subregion, then no data point was recorded.

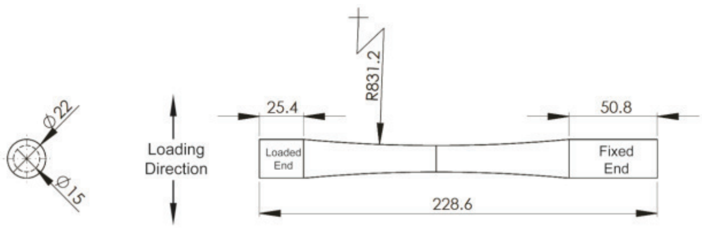

Fig. 1. Cantilever bending fatigue sample design for all induction hardened steel specimens, all dimensions in mm.

3. Endurance Limit Estimation

The experimentally determined endurance limits for the low and high case depth 1045-Q&T samples are 470 MPa and 495 MPa, respectively. All fatigue crack nucleation locations were observed to be in the core and at inclusions within the 1045-Q&T induction hardened steel fatigue samples. The average inclusion area at the nucleation site of the 1045-Q&T samples was found to be 2307 μm^2, while the largest inclusion was 4593 μm^2 and the smallest inclusion was 650 μm^2. The elemental make-up of the inclusions, as determined by EDS analysis, revealed that the inclusions at the crack nucleation sites were comprised of one or more of the following elements: Mn, S, Ca, Al, Mg, and O. These elements indicated the presence of the following inclusion compounds: MnS, MnS with Ca, MnS with Al_2O_3, Al_2O_3, and Al_2O_3-MgO.

Since the inclusion populations in the 1045 Q&T steel contributed significantly to fatigue life, an EVS analysis of the inclusion population was undertaken. First, the square root of the inclusion area was ranked and plotted as described by Murakami [3], and maximum likelihood (ML) estimators were used to fit the distribution as opposed to a linear regression, which does not perform as well. A lower 99% one sided confidence bound for the distribution was based on the properties of the ML estimators [9]. At a 99% confidence level, all of the experimental data for each inclusion type (except Al_2O_3-MgO) was encompassed indicating good agreement between the data and a fitted Gumbel distribution The EVS analysis of the maximum inclusion size as well as each individual inclusion type with the corresponding best fit line and confidence bound is plotted in Figure 2.

Using the method outlined by Murakami [3], ASTM E2283-08 [10], and Choi *et al.* [6], the endurance limit for two case depth conditions was predicted. The first step is to determine the critical area of the specimen vulnerable to fatigue crack nucleation. Since all of the fatigue failures nucleated near and subsurface to the case/core interface, the critical area is defined as the region below the case/core interface that is subjected to at least 90% or 95% of the stress at the case/core interface. This depth is multiplied by the length of the sample subjected to 95% of the maximum stress at the surface. The area is multiplied by two because both the top and bottom of the specimen are subjected to the maximum stress (R = -1).

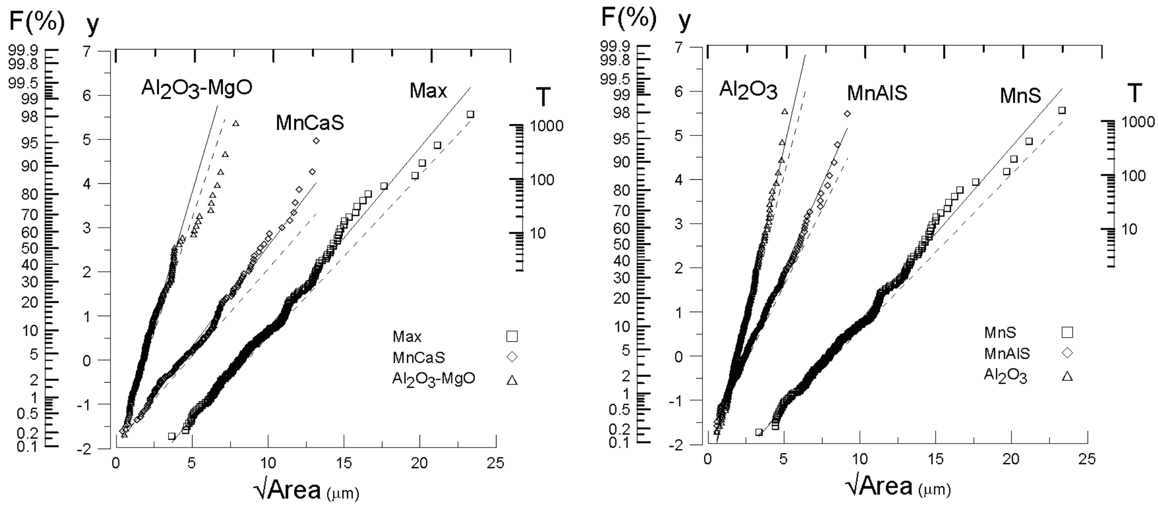

Fig. 2. EVS plots of the maximum inclusion size observed in each subregion and each of the five documented inclusion types tracked. The best fit lines are solid and were generated by the maximum likelihood method while the 99% one-sided confidence bound for each inclusion type are dashed lines.

The return period, *T*, was determined using the critically stressed area calculation (*S*) for both the low and high case depth conditions and the subregion area (S_o) of 2.5 mm^2 utilizing Equation 1,

$$T = S / S_o \quad (1)$$

Once the return period was calculated, the largest expected inclusion for each category was determined by applying Equation 2:

$$\sqrt{area} = -\beta_{ML} \ln\left(-\ln\left(\frac{T-1}{T}\right)\right) + \mu_{ML} \quad (2)$$

where β_{ML} and μ_{ML} were determined for each inclusion type by maximizing the log-likelihood function of the Gumbel distribution (Equation 3), with respect to β and μ:

$$(LL) = \sum_i \ln(f(x_i, \mu, \beta) = \sum_i \ln\left(\frac{1}{\beta}\right) - \left(\frac{x_i - \mu}{\beta}\right) - \exp\left(-\frac{x_i - \mu}{\beta}\right) \quad (3)$$

The predicted maximum inclusion area and the average hardness within the critically stressed region of the core (309 H_v/321 H_v for the 90%/95% low case depth regions and 347 H_v/382 H_v for the 90%/95% high case depth region) were then used in conjunction with Equation 4 to estimate the endurance limit for a subsurface crack nucleating inclusion [3]:

$$\sigma_W = \frac{1.56 \cdot (H_V + 120)}{\left(\sqrt{area}\right)^{1/6}} \quad (4)$$

where H_v is Vickers hardness, σ_w is the stress amplitude, and the area of the inclusion is in microns squared.

The MnS inclusions are the largest in the material and are synonymous with the maximum inclusion size of all the inclusion populations. The endurance limit predictions using either the maximum inclusion size in each inspection field or just the MnS inclusions in the area that experiences 90% of maximum stress are lower than the experimentally observed endurance limits for the low and high case depth conditions. Using a critical area defined by 95% of the maximum stress, the predicted endurance limit is lower than the experimental endurance limit in the low case depth condition. However, in the high case depth condition, the endurance limit is slightly non-conservative. The 95% maximum stress criteria yields a higher endurance limit because the critical volume and area measurements are smaller, which results in a smaller predicted maximum inclusion size within the critically stressed region and thus a higher estimated endurance limit.

Table 2 shows that the estimated endurance limit varies greatly between individual inclusion populations within the steel. It can be inferred that as the stress level increases, inclusions become "activated" to act as nucleation sites for a fatigue crack. For example, in the low case depth, 90% of maximum stress analysis, every inclusion type is expected to nucleate a propagating fatigue crack at stress amplitudes greater than 525 MPa except for Al_2O_3, which should not produce a propagating fatigue crack at stress amplitudes below 534 MPa. The inclusion type that corresponds to the lowest endurance limit estimation is the most likely to nucleate a fatigue crack at all stress levels, but the other inclusion types may nucleate a fatigue crack if they are in a critically stressed region and the applied stress is sufficiently high. However, this analysis only considers the size of the inclusions in predicting their likelihood of nucleating a critical fatigue crack and does not take into account other factors that may affect an inclusion's probability of acting as a crack nucleation site. It would be beneficial to include an inclusion type detriment factor into the endurance limit life prediction models to account for other properties of the inclusions beyond their size. Additional factors to consider may include residual stresses around the inclusions, adherence of the inclusion to the matrix, hardness, modulus, and deformability of the inclusion.

Table 2. Endurance limit estimation and maximum inclusion size at the nucleation location based on EVS analysis and a 99% one sided lower bound estimate for the 1045Q&T low and high case depth samples with a critically stressed area of 90% or 95% of the maximum stress at the case/core interface.

Max Stress to:	Analysis Method	Type of Inclusion	Low Case Depth		High Case Depth	
			Max. Inclusion Area (lower bound), μm^2	Est. Endurance Limit (Lower Bound), MPa	Max. Inclusion Area, (Lower Bound), μm^2	Est. Endurance Limit (Lower Bound), MPa
90% of Max Stress	Area	Max Inclusion	242 (280)	424 (418)	235 (273)	462 (457)
		MnS	242 (282)	424 (418)	235 (274)	462 (456)
		MnCaS	119 (152)	449 (440)	115 (147)	491 (481)
		MnAlS	40 (49)	492 (484)	39 (48)	537 (528)
		Al_2O_3	15 (18)	534 (527)	14 (17)	583 (575)
		Al_2O_3-MgO	19 (23)	525 (516)	18 (22)	573 (563)
95% of Max Stress	Area	Max Inclusion	168 (192)	449 (444)	162 (185)	512 (507)
		MnS	165 (190)	449 (444)	160 (184)	513 (507)
		MnCaS	73 (93)	481 (471)	70 (89)	550 (539)
		MnAlS	25 (30)	527 (518)	24 (29)	602 (592)
		Al_2O_3	10 (12)	568 (561)	10 (11)	649 (641)
		Al_2O_3-MgO	12 (14)	561 (552)	11 (13)	641 (630)

Even though there is good agreement between the predicted and experimental endurance limits using either the maximum inclusion or MnS populations, the maximum predicted inclusion size is much smaller than the average size of the inclusions observed at the crack nucleation sites (~130 μm^2 versus 2307 μm^2) even when a 99% one-sided confidence interval is considered. Furthermore, the EVS analysis only predicts a maximum inclusion cross-sectional area of 993 μm^2 using the 99% lower bound in the entire sample volume, which is still below the average observed inclusion size of 2307 μm^2 in the crack nucleation region. This discrepancy between the estimated and actual inclusions observed in the samples indicates that the Gumbel distribution fit of the inclusion samples did not adequately capture the largest inclusions in the sample.

4. Summary and Conclusions

A straight-forward approach was developed to identify a critically-stressed area in 1045 induction hardened steels, and it was applied to the procedure outlined by Murakami [3] to predict the endurance limit based on the maximum inclusion size within the critically-stressed region. Good agreement was found between the calculated endurance limit and the experimentally observed endurance limit.

There was, however, a large discrepancy between the estimated and observed inclusion area at the nucleation locations, and the cause of the discrepancy is unclear. The Gumbel distribution may not be appropriately fitting the largest inclusions in the sample; the maximum inclusion size expected in the fatigue sample is smaller than the average inclusion size observed to nucleate fatigue cracks in the low cycle fatigue region.

EVS analysis of each inclusion type indicates that inclusions will be “activated” at different stress levels depending on the maximum size of inclusion expected. The inclusion type with the lowest predicted endurance limit is the most likely to nucleate the dominant fatigue crack, but the other inclusion types may also nucleate a crack if they are located within the critically stressed region and the stress level is sufficiently high. Thus, all the possible inclusion types must be considered to obtain an accurate range of fatigue life properties.

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