

Surface Finish Effects on Fatigue Behavior of Forgings

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ABSTRACT

Fatigue fractures are the most common type of mechanical failures of components and structures. It is widely recognized that surface finish has a significant effect on fatigue behavior. Forgings can be accompanied by significant surface roughness and decarburization. The correction factors used in many mechanical design textbooks to correct for the as-forged surface condition are typically based on data published in the 1940's. It has been found by several investigators that the existing data for as-forged surface condition is too conservative. Such conservative values often result in over-engineered designs of many forged parts, leading not only to increased cost, but also inefficiencies associated with increased weight, such as increased fuel consumption in the automotive industry. In addition, this can reduce forging competitiveness as a manufacturing process in terms of cost and performance prediction in the early design stage, compared to alternative manufacturing processes. In this paper two surface conditions are evaluated, a smooth-polished surface finish to be used as the reference surface and a hot-forged surface finish, in order to quantify forged surface finish effect at several hardness levels (19 HRC, 25 HRC, 35 HRC and 45 HRC) on bending fatigue of a commonly used forged steel (10B40).

INTRODUCTION

Forging is a process where compressive stresses are used to form or shape material. There are three types of forging: cold forging, warm forging, and hot forging. Cold, warm and hot refer to the temperatures at which the process takes place. Cold forging typically takes place at around room temperature. Hot forging is done at a temperature which allows recrystallization of the material being forged. Hot

forged parts can be heated using gas furnace heating or induction heating.

Induction heating is a process in which electrical currents are used to heat up the material, and only the material, unlike gas furnace heating, where the whole atmosphere inside the furnace needs to be brought to temperature in order to heat the material [1]. Induction heating also heats the material more rapidly and uniformly. Gas furnaces usually produce a poorer quality of surface finish than induction heating; more scale formation, oxidation, decarburization and grain coarsening. The decarburization and scale formation is significantly decreased for induction heating. Therefore, induction heating is a more consistent and efficient process than the gas furnace heating. The data reported in this paper, however, are from hot forged specimens by use of gas furnace heat. Fatigue data from the hot forged specimens by using induction heating are reported in [2].

Heat treating is commonly done to forged parts to increase their strength. Typically, the fatigue strength increases as the hardness increases in the HCF region. However there is an increasing detrimental effect in the LCF region as hardness increases due to reduced ductility [3]. There is also a near linear relationship between hardness and tensile strength.

Decarburization results from the forging process as well as heat treatment and can be described as a reduction of carbon starting from the surface. Decarburized parts generally show a reduction in fatigue life in the HCF region when compared to parts without decarburization [4]. This is because the decarburization causes a reduction of strength in the decarburized area, which is near the surface where fatigue cracks normally form. Surface treatments such as sand blasting decrease the effect of the as-forged surface finish by removing scale defects, as well as some of the decarburized

layer, and by inducing compressive residual stresses at the surface.

In addition to decarburization, the surface roughness resulting from the forging process has an effect on the fatigue life. In general fatigue life decreases as surface roughness increases in the HCF region. The surface roughness has less of an effect in the LCF region due to plastic deformation [5].

Figure 1 shows two S-N curves, one for smooth and polished surface and another for forged surface. The surface finish factor for a given hardness is calculated by dividing the fatigue strength of the as-forged surface finish part by the fatigue strength of the smooth and polished surface part at long life (typically at 106 cycles to failure for steels).

Fatigue strength for a given number of cycles to failure can be determined from the S-N line equation represented by:

$$\sigma = A(N_f)^B \quad (1)$$

where A is the fatigue strength coefficient and B is the fatigue strength exponent (slope of the S-N line in log-log scale).

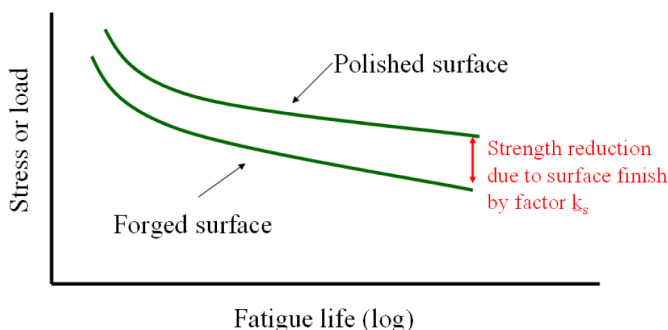


Figure 1. Surface finish effect on S-N curve.

Vehicles are made of up to 25% forged components [6]. The existing data for as-forged surface condition is too conservative. The surface finish factors used in design for the as-forged surface condition are based on data published in the 1930's and 1940's [6, 7]. This results in an over-engineered design of many mechanical parts, which is accompanied by an increase in weight and production cost [8]. Figure 2 shows the surface finish factor at 106 cycles versus tensile strength or Brinell hardness. The curved line in Figure 2 is based on data taken from [7] and the points were calculated using data from the current investigation. It can be seen that there is a significant difference between data from the current investigation and data taken from [7].

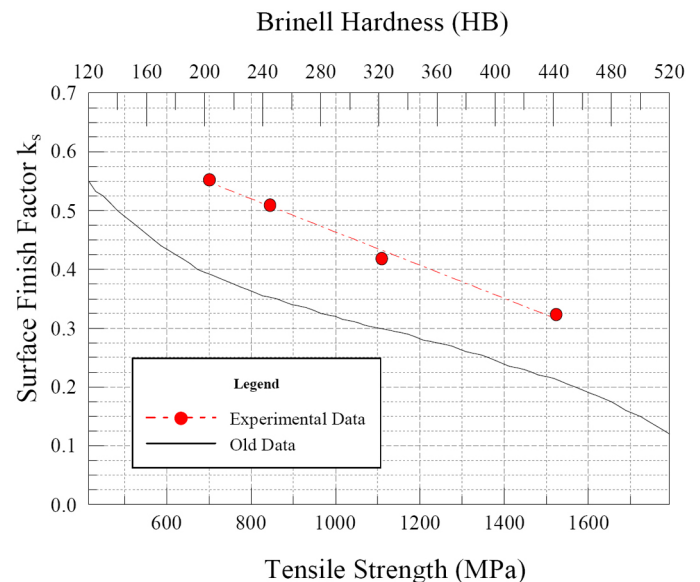


Figure 2. Forged surface finish factor vs. Brinell hardness (data taken from [7]).

This paper first discusses the experimental program including the material used, specimen geometry and treatments, as well as test equipment and procedures. Then, the obtained fatigue test results are presented and discussed. This is followed by comparisons of the four hardness levels for the as-forged and polished surface conditions. Finally, fatigue behavior of the polished surface finish specimens is compared with the fatigue behavior of as-forged surface finish specimens to evaluate the forged surface finish effect. The experimental results are also compared with surface finish effect predictions based on the old data.

EXPERIMENTAL PROGRAM

MATERIAL AND SPECIMENS

The steel used was 10B40 steel. The composition of the material is shown in Table 1. The specimen configuration and nominal dimensions are shown in Figure 3.

The specimens were hot-forged from a rolled bar using either gas furnace heating or induction heating. However, only data from specimens forged by gas furnace heating are presented in this paper. Figure 4 shows near the surface close up of the gage section cross section of a forged specimen. The lighter color area is where the decarburization has occurred. The decarburization depth is around 0.3 mm.

Table 1. Chemical composition of 10B40 steel (courtesy of Robert Cryderman of Gerdau-MacSteel)

Element	% Weight	Element	% Weight
C	0.38	Sn	0.012
Mn	0.94	Al	0.03
P	0.01	V	0.007
S	0.021	B	0.0017
Si	0.24	Ti	0.042
Ni	0.08	Nb	0.002
Cr	0.16	N	0.0084
Mo	0.03	Fe	Balance
Cu	0.2		

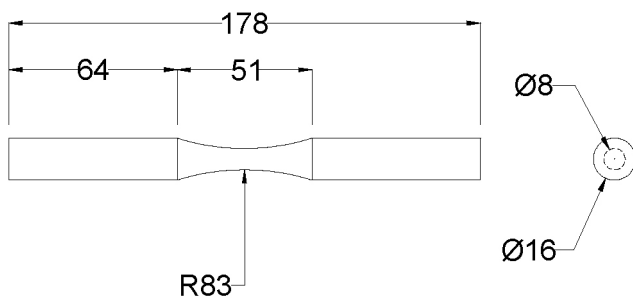


Figure 3. Specimen configuration and nominal dimensions (mm) for as-forged surface finish specimens.

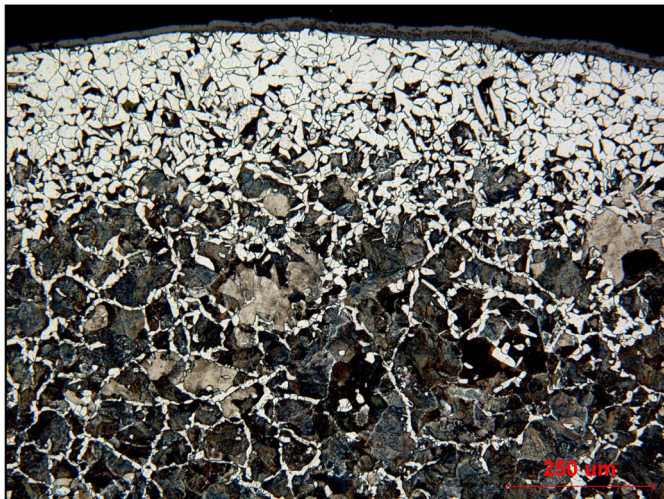


Figure 4. Near surface close-up of the gage section cross section showing decarburization near surface (photo courtesy of Peter Bauerle of Chrysler LLC).

The specimens were shot-cleaned after the forging process prior to heat treatment, in order to remove surface scales left from the forging process. It should be noted, however, that any residual stresses induced during the shot-cleaning process were removed during heat treatment. The specimens were heat treated to four hardness values of 45 HRC, 35 HRC, 25 HRC and 19 HRC.

Micro-hardness measurements across the gage section cross section of a specimen from each hardness level were made. Figure 5 shows variation of hardness versus depth below the surface. It can be seen in this figure that the decarburization results in a reduction of hardness to a depth of about 0.3 mm below the surface. There is less of a difference between surface hardness and core hardness as the core hardness decreases.

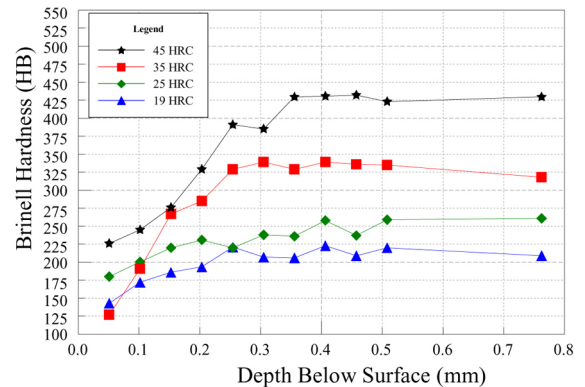


Figure 5. Hardness vs. depth below surface of gas furnace forged specimens at different hardness levels.

Following the heat treatment, the as-forged surface was removed from some specimens using a CNC machine. The machined surface specimens were then polished by a polishing machine. Three different grits of aluminum oxide lapping film with 30 µm, 12 µm, and 3 µm roughness were used for polishing. Polishing marks coincided with the longitudinal direction of the specimens. The polished surfaces were carefully examined under magnification to ensure complete removal of machining marks within the specimen gage section. Measurements of the average surface roughness (R_a) for the as-forged and machined and polished surfaces are listed in Table 2.

Table 2. Specimen gage section surface roughness measurements.

Surface Condition	Hardness (HRC)	Roughness (R_a)	
		Average* (μm)	Range (μm)
Gas Furnace Forging	45	4.4	4.0 - 4.8
	35	4.3	4.2 - 4.7
	25	4.7	4.0 - 5.1
	19	4.7	3.8 - 5.6
	prior to heat treat	4.1	3.7 - 4.5
Machined and Polished	45	0.14	0.12 - 0.15
	35	0.13	0.11 - 0.14
	25	0.12	0.10 - 0.13
	19	0.11	0.10 - 0.12

*Average of 5 specimens and 2 readings from each specimen with cutoff length of 0.8 mm