Characterization and performance of high strength steel 51CrV4 under cyclic loading

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Abstract. The high alloyed spring steel 51CrV4 is widely used in engineering applications with high requirements on strength, durability, and safety. The present paper contains experimental results regarding its microstructural characterization and the mechanical behaviour, especially the fatigue life of 51CrV4. Fundamental S-N curves at fully reversed tension-compression and rotating bending have been determined covering the whole area of practical interest, from the Low Cycle Fatigue regime until the engineering endurance limit. These S-N curves can be directly used for the design as well as for the fatigue assessment of engineering components made of this material. The international literature contains very few and isolated data regarding the mechanical behaviour of 51CrV4, while corresponding material properties are totally missing. The material data and properties provided here may be implemented in international cyclic material databases for further exploitation in Industry and Academia.

1 Introduction

The present paper contains comprehensive experimental results regarding the characterization and the mechanical behaviour, especially, the fatigue life of 51CrV4. This steel grade is widely used in various engineering applications, where high requirements on strength, durability and safety are required. The steel microstructure has been acquired by means of optical microscopy. Fatigue tests at fully reversed rotating bending and uniaxial cyclic loading at the stress ratio R=-1 have been executed to determine the fundamental S-N curves of this material. The results cover the whole area of practical interest for engineering applications, from the Low Cycle Fatigue until the so-called “engineering” endurance limit. In addition, the comparison of the results at bending and tension-compression reveals the influence of stress gradient on the fatigue life.

Furthermore, strain measurements performed during the tests exhibit the stress-strain behaviour under cyclic loading. Therewith the corresponding elastoplastic cyclic material properties have been accurately determined. They can be directly implemented in material databanks and used for the fatigue design of engineering components made of 51CrV4 in the as-here investigated conditions.

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2 Material manufacturing and chemical composition

2.1 Manufacturing process

The steel grade 51CrV4 has been produced in flat bars via the basic oxygen steelmaking process shown in Figure 1.

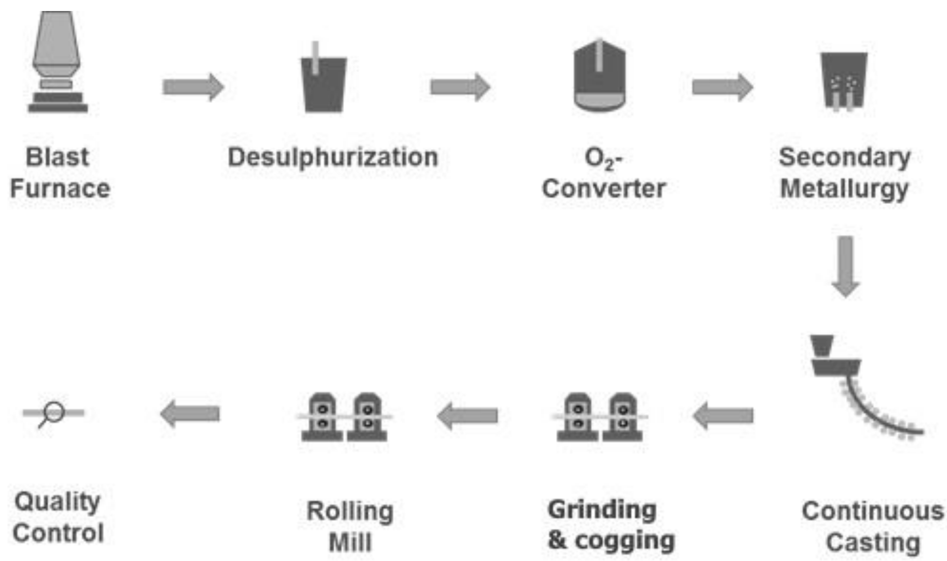

Fig. 1. Production of the as-rolled flat bars.

As shown in Figure 1, the desulphurized hot metal deriving from the blast furnace is mixed with recycled steel scrap and further processed in a basic oxygen furnace. The crude steel undergoes a secondary refining process including aluminium deoxidation, calcium treatment, RH-degassing, alloy addition and purging. The refined steel is cast into billets by continuous casting. After grinding, the billets are heated in the rolling mill furnace with a defined time-temperature-profile to ensure a uniform temperature distribution within the billets and to avoid decarburization. After discharging from the rolling mill furnace the billets pass a high-pressure water descaler and are twist free rolled to flat bars with a cross section of 90 mm x 32 mm according to DIN EN 10092-1 [1]. Continuous dimension control is carried out by laser diameters. Furthermore, the temperature of the strand is continuously controlled because a well-defined time-temperature-regime during rolling is very important for a fine internal material structure and a low decarburization.

2.2 Chemical composition

The chemical composition of the steel grade 51CrV4 according to DIN EN 10089 [2] and that of the here produced heat are shown in Table 1. Due to the aluminium deoxidation, the aluminium content, which is not specified in DIN EN 10089, is 0.025 wt.-%.

Table 1. Chemical composition of the steel grade 51CrV4 in [wt %].

	C	Si	Mn	P	S	Cr	V	Al
DIN EN 10089	0.47 – 0.55	≤ 0.40	0.70 – 1.10	≤ 0.025	≤ 0.025	0.90 – 1.20	0.10 – 0.25	
Present heat	0.52	0.34	0.98	0.014	0.009	1.06	0.12	0.025

3 Metallographic analysis

The microstructure of the conventional 51CrV4 has been analysed by means of light optical microscopy on small samples been taken from the flat bars. The small samples were grinded, polished, and etched in a solution of 2.5 % nitric acid in ethanol (nital). The microstructure, the grain size according to DIN EN ISO 643 [3] and the total decarburization according to DIN EN ISO 3887 [4] have been measured. Figure 2 shows the microstructure of the steel grade.

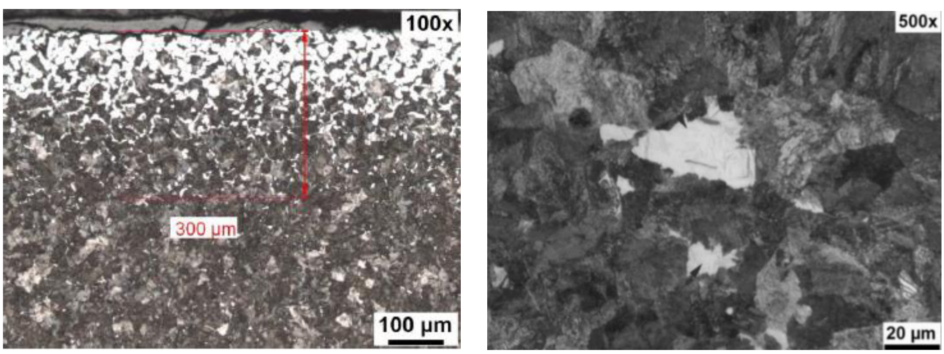

Fig. 2. Representative microscopic images of the surface (left), and core zone (right) of 51CrV4 in the as-rolled condition.

In the as-rolled condition the steel 51CrV4 shows a pearlitic microstructure with 1 % ferrite and some single martensitic grains in the core region. The specimens are free from ferrite decarburization; the maximum total decarburization is 0.30 mm. The total decarburization zone amounts to approx. 300 µm measured from the surface towards the core. A grain size of 7 - 9 has been determined.

4 Mechanical properties

4.1 Tensile tests

A total of eight uniaxial tensile tests has been performed at 20°C according to DIN EN ISO 6892-1 [5] on standardised material specimens of the type DIN 50125 - B6 x 30 to determine the fundamental mechanical properties at monotonic loading.

The steel 51CrV4 produced here exhibits a mean yield strength of 616 MPa and a mean tensile strength of 999 MPa in the as-rolled condition. The mean elongation to fracture of 14.7 % and the mean reduction of area of 50.4 % were determined. It should be further noticed that the scatter bands of the abovementioned mechanical properties were found very low.

4.2 Cyclic tension-compression tests

Comprehensive sets of fatigue tests with constant amplitudes have been performed under rotating bending and fully reversed uniaxial loading (stress ratio R=-1) to determine the corresponding S-N curves of the material. The technical drawings of the specimens are shown in Figures 3 and 4 for uniaxial and rotating bending, respectively.

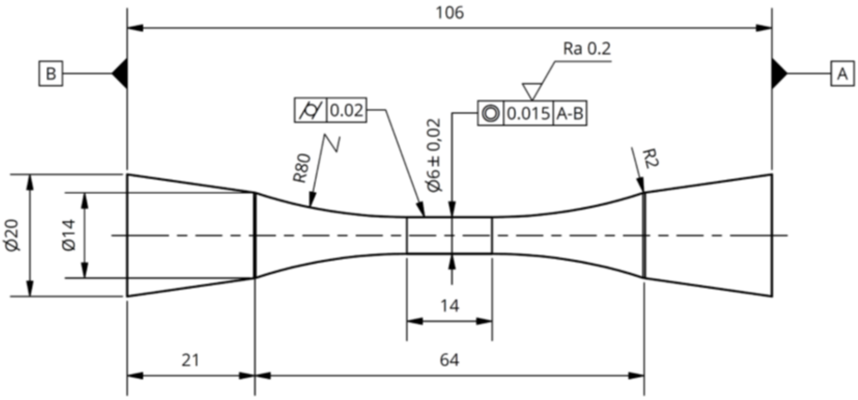

Fig. 3. Uniaxial tension-compression specimen**.**

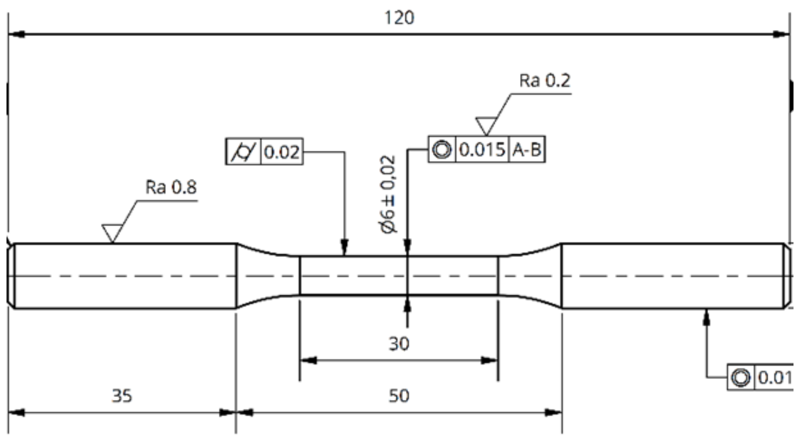

Fig. 4. Rotating bending specimen**.**

Figure 5 contains a comparative illustration of the fatigue life results. Therein, the triangles represent the tests at uniaxial fully reversed loading. The squares stand for the tests at rotating bending. The full symbols indicate the results with fatigue failure and the hollow symbols those that have been stopped without failure.

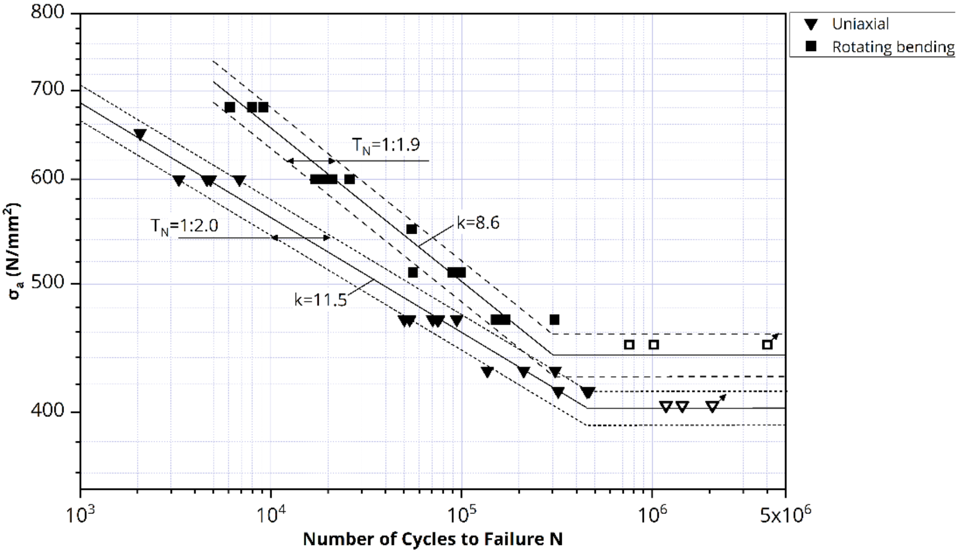

Fig. 5. Fatigue life results at rotating and uniaxial fully reversed loading**.**

The experimental results cover the whole range of practical interest, from the Low Cycle Fatigue regime until the engineering endurance limit (also known as fatigue limit). The linear regression of the individual results at uniaxial loading and rotating bending yield the corresponding S-N curves for the two types of loading. The solid lines are equipped with probability of survival 50%, while the dotted and dashed lines with 10% and 90%, indicating the scatter band of the individual results. The slopes of the S-N curves amount to k=11.5 and 8.6 for uniaxial loading and rotating bending, respectively. The scatter bands (ratio of fatigue lives at probabilities of survival 10% to 90%) have been evaluated to approx. 1:2, which is quite low value. In overall, the fatigue lives at rotating bending are higher than those at uniaxial loading for the same stress amplitude. The engineering endurance limit amounts to 405 N/mm^2 and 444 N/mm^2 for uniaxial loading and rotating bending, respectively. This results to an increase of the fatigue limit of 9.2%, which is conform to the well-known trends regarding the stress gradient effect on high-strength steels [6].

5 Summary and conclusions

The present paper contains a comprehensive dataset of experimental findings regarding the microstructure, characterization, and mechanical properties (monotonic, fatigue) of the high-strength steel grade 51CrV4 in the as-rolled condition. Considering that the international literature contains only isolated data regarding this steel grade, the data provided here may be implemented in international cyclic material databases for further exploitation in Industry and Academia.

The steel grade 51CrV4 exhibits a mainly pearlitic microstructure with grain size 7 to 9 in the as-rolled condition.

Its yield stress and ultimate tensile strength amount to 616 N/mm^2 and 999 N/mm^2, respectively. The corresponding mean elongation to fracture and mean reduction of area amount to 14.7 % and 50.4 %, respectively.

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The slopes of the fundamental S-N curves at uniaxial loading and rotating bending amount to 11.5 and 8.6, respectively. The scatter bands are similar for both types of loading and amount to 1:2. The corresponding engineering endurance limits are 405 and 444 N/mm^2 for uniaxial loading and rotating bending, respectively.

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