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Microstructure refinement and its effect on properties of spring steel

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ABSTRACT

Over the last decades considerable efforts have been made to develop high performance spring steels, which would allow vehicles weight reduction. One way of improving steel properties is by refining its microstructure and reducing the amount of inclusions. Therefore, the aim of the current investigation was to determine the effect of cleaner and more uniform microstructure obtained through electro-slag remelting (ESR) on the mechanical and dynamic properties of spring steel. Investigation was performed on hot rolled, soft annealed and vacuum heat treated 51CrV4 spring steel produced by conventional continuous casting and refined through ESR. Effect of microstructure refinement was evaluated in terms of tensile strength, elongation, fracture and impact toughness, and fatigue resistance under bending and tensile loading. Results show that although ESR gives some improvement, especially in terms of better repeatability and reduced scattering, it has a negative effect on the fatigue properties of spring steel.

1. Introduction

The ever-increasing demands of automotive industry on performance improvement, weight reduction and cost savings place a lot of pressure on vehicle components, which require new design concepts and further material development. In this respect, weight reduction is very important as it reduces costs, but more importantly it reduces fuel consumption and CO_2 pollution. The biggest fuel consumers and polluters are trucks, where redesign and use of lighter high strength leaf springs can bring considerable benefits. Besides, the lower weight reduced dimensions also allow increased design flexibility, making room for additional safety components. Parabolic leaf springs used in suspension systems of truck front axles are usually made of two leaves, and serve two main purposes: support the weight of the trailer and provide the spring function in the suspension system. With the new spring designs, eventually aiming at a single leaf solution, savings of over 20% of the total weight of the spring can be expected. However, this would also lead to about 10–15% increase in spring maximum stress, which requires better spring steel with ultimate tensile strength of over 2000 MPa [1,2].

Over the last decades considerable efforts have been made to develop high-strength spring steels to meet the needs of weight and cost savings in the automotive industry [3]. Improved strength of spring steel can be achieved through control of alloy composition, effective heat treatment, micro-alloying, thermomechanical treatment and shot-peening [3–12]. The greatest gains in terms of martensitic steel strength improvement are achievable by lowering the austenitizing and tempering temperature, which increase the ultimate tensile strength but on the other hand reduce material ductility and toughness [8,13]. However, in the case of springs, improvement in strength should not degrade other spring steel properties such as formability and fatigue resistance [6]. Another way of improving spring steel strength is through grain refinement [5,6,14], mainly based on micro-alloying and thermomechanical treatment. The addition of certain alloying elements has been reported to effectively improve spring steel strength as well as sag resistance [3]. Si of up to 2% was found to improve properties through the refinement of tempered carbides obtained by retardation of ε-carbide conversion to cementite during tempering [3,15]. The addition of Nb and V has also been reported beneficial due to the precipitation and dispersion of fine micro-alloyed carbonitrides [9]. Further improvement in tensile properties can be obtained through the deformation of austenite prior to quenching [8]. Improvement is related to refined austenite grains and to the austenite grain substructure. Those conditions reflect in a finer structured martensite, i.e. refined block size, with no or refined carbides at the prior austenite grain boundaries.

Most commercial steels, including spring steels, contain impurities that significantly influence ductility and toughness, with the loss in properties being dependent on the impurity element concentration [16]. The well-known embrittlement phenomena observed around 350 °C is such an example where grain boundary segregation of impurity element together with carbide films at

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grain boundaries deteriorate the mechanical properties of the material [17]. However, there are also non-metallic inclusions, which depending on the type and size, may further degrade spring steel properties [18–20].

In the case of tool steels microstructure refinement and properties improvement can be achieved through utilization of electro-slag remelting (ESR) [21]. Uniform, relatively rapid solidification in ESR with highly reactive slag leads to an improvement in the chemical uniformity and uniformity of macrostructure, greatly improved cleanliness and reduced segregation tendency, removal of exogenous oxide inclusions and substantial sulfur reduction [21]. Microstructural features such as the eutectic cell size and the eutectic carbide particle size are also reduced. These features, besides other, result in improved hot workability and better ductility and fatigue properties of tool steels [22].

The aim of the current research work was to investigate the possibility of refining spring steel microstructure by utilizing electro-slag remelting and to determine its effect on the mechanical and dynamic properties of commercial 51CrV4 spring steel.

2. Experimental

2.1. Material and heat treatment

The material used in this investigation was commercial 51CrV4 spring steel from Štore Steel d.o.o. produced by a conventional casting process. After casting of billets ($180 \times 180\ \text{mm}^2$) two spring steel charges were produced, aimed at evaluating the effect of electro-slag remelting (ESR). First charge, used as a reference and denoted CCC, was directly hot rolled in strips ($18 \times 90\ \text{mm}^2$) and soft annealed, while the other, denoted ESR, was first electro-slag remelted and then hot rolled and soft annealed under the same conditions as the first charge (CCC). Chemical composition of both charges is given in Table 1, where due to the protection of the trade secrets the level of Mo and Ni cannot be revealed.

Testing specimens (up to 16 for each property) were then taken from hot rolled and soft annealed stripes in the rolling direction and all were vacuum heat treated in a vacuum furnace with uniform high-pressure gas-quenching using nitrogen gas at a pressure of 5 bar. After heating (10 °C/min) to the austenitizing temperature of 870 °C, specimens were soaked for 10 min, gas quenched to a temperature of 60 °C, and then single tempered for 1 h at 300, 375 and 475 °C, respectively.

2.2. Mechanical testing

Influence of ESR on the mechanical properties of spring steel included tensile test, and measurement of hardness, fracture toughness and impact toughness. Tensile test at room temperature (21 ± 0.5 °C; ISO 6892-1) was performed on standard cylindrical specimens with a diameter of 10 mm and gage length of 50 mm using Instron 8802 tensile-test machine. Measurements involved yield strength $R_{p0.2}$, ultimate tensile strength R_m, elongation A_5 and contraction Z.

For fracture toughness measurement circumferentially notched and fatigue-precracked tensile-test specimens (Fig. 1), designated K_{Ic}-test specimens, were used [23,24], with the fatigue precrack of about 0.5 mm created under rotating-bending loading before the final heat treatment [25]. Using an Instron 8802 tensile-test machine and a cross-head speed of 1.0 mm/min load at fracture was measured and fracture toughness K_{Ic} calculated using Eq. (1) [26]:

$$K_{Ic} = \frac{P}{D^{3/2}}\left(-1.27 + 1.72\frac{D}{d}\right) \tag{1}$$

where P is the load at failure, D the outside non-notched diameter (10 mm), and d the diameter of the instantly fractured area. Eq. (1) is valid for $0.5 < d/D < 0.8$ and linear elastic behavior, as displayed by all investigated specimens.

Impact toughness was determined according to Charpy V-notch test (BS EN 10045-1) using a 300 J pendulum. Tests, carried out only for specimens tempered at 475 °C, were performed at room and sub-zero temperatures of 0 °C, −20 °C and −40 °C in order to reveal transition into brittle behavior. Finally, the Rockwell-C hardness (HRc) was measured on each cylindrical specimen using an Instron B2000 hardness machine and average values calculated. Up to six measurements were performed on each specimen.

2.3. Dynamic testing

Fatigue properties for CCC and ESR spring steel were determined at room temperature (21 ± 0.5 °C) under bending as well as tensile-compression loading. Bending fatigue testing was performed on a Rumul Cracktronic resonant machine using Charpy V-notch test specimens and a constant amplitude bending stress, ranging between 275 MPa and 430 MPa. The testing resonant stress frequency was 175 Hz using a sinusoidal waveform at a stress ratio R of 0.1. A criterion of specimen failure was a drop of inherent oscillation by more than 3%, where fatigue cracks occurred at a depth of up to 3 mm.

Fatigue testing under tension-compression loading was performed on polished hourglass-shaped fatigue specimens with a gauge length of 38 mm and a neck diameter of 7.5 mm. Room-temperature fatigue tests were conducted in an Instron 8805 test machine under the conditions of $R = -1$ and sine wave of 30 Hz. Maximum tensile stress was in the range between 500 and 780 MPa.

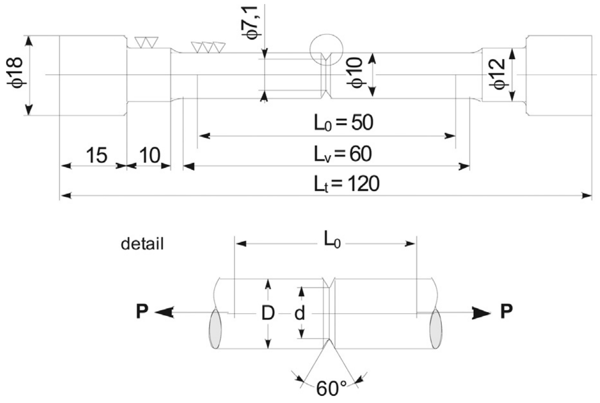

Fig. 1. Circumferentially notched and fatigue-precracked K_{Ic}-test specimen; all units in mm.

Table 1
Chemical composition of CCC and ESR spring steel charges (mass%).

Charge	C	Si	Mn	P	S	Cr	Al	Cu	V
CCC	0.54	0.33	0.97	0.012	0.007	1.10	0.006	0.17	0.17
ESR	0.53	0.29	0.94	0.010	0.003	1.07	0.025	0.18	0.16