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Influence of grain size distribution on the Hall–Petch relationship of welded structural steel

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ABSTRACT

The strength of polycrystalline metals increases with a decrease in grain size according to the Hall–Petch relationship. However, heterogeneous microstructures deviate from this relationship depending on the distribution of grain sizes. This paper introduces a rule of mixtures based approach for determining the characteristic length of the microstructure for heterogeneous weld metal. The proposed grain size parameter, the volume-weighted average grain size, is measured experimentally for nine structural steel weld metals and two base materials. The weld metals are found to have a large variety of grain size distributions that are noticeably broader than those of the base material due to differences in phase contents. The results show that the volume-weighted average grain size is able to capture the influence of grain size distribution on the strength of welded structural steel. Based on the experimental results, a modified Hall–Petch relationship is formulated for the strength prediction of heterogeneous microstructures. The modified relationship is also found to be applicable to data from the literature.

1. Introduction

New lightweight solutions are needed to improve the energy efficiency of steel structures. Further development of the steel structures requires the utilisation of new materials and advanced production technology. In this development work, one of the fundamental issues is to understand the relation between microstructural quantities and material properties. This is especially challenging for advanced joining methods such as laser welding, where the properties of the narrow joint differ significantly from those of the base material [1–5].

In general, the mechanical properties of metallic materials have shown to correlate with the microstructural dimensions, most commonly with the average grain size. Based on the work of Hall [6] and Petch [7], a relationship was found between grain size and the mechanical properties of steel. For yield strength the relationship is formulated:

$$\sigma = \sigma_0 + kd^{-1/2}, \quad (1)$$

where σ_0 is the lattice friction stress required to move individual dislocations, k is a material-dependent constant known as the Hall–Petch slope, and d is the average grain size [8]. The work of Hall and Petch was focused on the lower yield point and the cleavage fracture stress of mild steel, respectively. Since then, the Hall–Petch relationship has been applied to a large variety of materials and material properties, such as hardness, stress–strain properties and fatigue [9–15]. As the Hall–Petch relationship is related to the measure of grain size, the correct definition of the effective grain size is crucial. Typically the average grain size is used to describe the microstructure [16], but its suitability for heterogeneous microstructures is questionable. Several investigations [8,16–21] have shown that the grain size distribution has an effect on the mechanical properties. For example, Berbenni et al. [20] showed that for a given average grain size, broadening of the grain size dispersion reduces the strength of the material.

To consider the influence of grain size distribution, Kurzydlowski [22] proposed an alternative approach, where the strength of different grain sizes was estimated by applying a weighting factor equal to the volume of the grains. This approach was further developed by Raeisinia and Sinclair [23]. They proposed a new geometric grain size parameter, the representative grain size, which eliminates the influence of grain size distribution on the Hall–Petch relationship. The fundamental assumptions of this approach are that all grains have the same shape and that the grain size distribution is log-normal. The same assumptions have been used in various numerical simulations of fictitious grain size distributions [16,24–27]. However, the previous studies [8,16–21,24,27] are focused on single phase base materials and do not cover heterogeneous weld metals.

The objective is to study the grain size distribution of weld metals and its influence on the Hall–Petch relationship. Furthermore,

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methods for the characterisation of the grain size distribution are extended to be applicable for weld metal microstructures. The microstructures of nine structural steel weld metals and two base materials are characterised using electron backscatter diffraction (EBSD) and optical microscopy. Because of the narrow welds, micro-indentation is applied for mechanical testing. Based on the experimental results, a modified Hall–Petch relationship is introduced for the strength prediction of heterogeneous microstructures. The study utilises stereological methods for estimating the volume fraction of grains from their surface area fractions. The investigation is limited to the transverse cross-sections of the material and thus the effects caused by grain shape three-dimensionality are omitted.

2. Definitions

Based on the role of grain boundaries as an effective barrier to the movement of dislocations, the grain size dependence of yield strength can be explained by the pile-up of dislocations at grain boundaries [6]. The pile-up causes an additional stress, which allows the deformation to be transmitted to the next grain. The additional stress is in relation to the number of dislocations in a pile-up, which is limited by the length of the slip band that can be identified with the average grain diameter [6]. Other theories have also been proposed for the grain size dependence, such as the dislocation density model [28–30] and the geometrically necessary dislocation (GND) model [31–33]. A review of the models is given by Zhu et al. [34] and Evers et al. [35]. Each model implies a different Hall–Petch slope k, but the mechanical properties are always scaled with the average grain diameter [34]. The average grain diameter, or in most cases the average grain size, is obtained from the experimental measurements [16,24]. The average grain size is defined as

$$d = \frac{1}{n}\sum_{i=1}^{n} n_i d_i, \tag{2}$$

where n is the total number of measurements and n_i the number of measurements corresponding to the grain size d_i.

However, for heterogeneous microstructures it can be argued that the average grain size does not adequately represent the physical response of the material due to the broad grain size dispersion; see e.g. [20,21]. In a microstructure, the largest grains can be associated with low strength due to the length of the slip bands, causing them to yield first; see e.g. [36,37]. Furthermore, even a low number of large grains can occupy a significant material volume. To capture the influence of grain volume, a rule of mixtures approach is proposed for heterogeneous microstructures. The contribution of each grain to the strength of the material is considered to be proportional to the volume of the grain; see e.g. [17,22]. Thus, the volume-weighted average grain size is defined as

$$d_v = \frac{1}{V_T}\sum_{i=1}^{n} V_i d_i, \tag{3}$$

where V_T is the total volume of material and V_i the volume of grains corresponding to the grain size d_i. Because of the different definition, the volume-weighted average grain size is always larger than the average grain size. The two parameters are equal only when all the grains are the same size.

3. Experimental procedures

3.1. Test specimens

To investigate the grain size distribution and its influence on the Hall–Petch relationship, various material microstructures are examined. In addition to structural steel, the weld metals (WM) of conventional arc (CV), laser (LA), and laser-hybrid (HY) welded joints are included in the test series. The weld metals represent complex microstructures with a large variety of grain size distributions. Table 1 lists specimen nomenclature with the corresponding joint type and welding method. Transverse cuts in relation to the welding direction were used for the test specimens. The cut sections were mounted in an electrically conductive resin and grinded using P180-P4000 grit abrasive papers, followed by polishing with 3 μm and 1 μm diamond paste. For optical microscopy and hardness measurements, the specimens were etched with a 2% Nital solution, while polishing with colloidal silica in a vibratory polisher was used as the final step for scanning electron microscopy. The base material (BM) for the welded joints is a shipbuilding structural steel with minimum

Table 1
Test specimen nomenclature and the corresponding joint types and welding methods.

Specimen	Joint type	Welding method	Measurement location
BM.1	Plate, 6 mm	–	1.0–1.9 mm[a]
BM.2	Plate, 5 mm	–	0.75–1.35 mm[a]
CV.1	Butt joint, 3 mm	Arc	Toe, root
CV.2	Butt joint, 3 mm	Arc	Toe, root
CV.3	T-joint, 3/5 mm	Arc	Toe
HY.1	Butt joint, 3 mm	Laser-hybrid	Toe, root
LA.1	Butt joint, 3 mm	Laser	Toe
LA.2	Butt joint, 3/5 mm	Laser	Toe

[a] Distance from the surface of the plate.

Table 2
Mechanical properties and chemical compositions of test materials.

Specimen	Grade	Mechanical properties			Chemical composition											
		$R_{p0.2}$ (MPa)	R_m (MPa)	A (%)	C (wt%)	Mn	P	S	Si	Al	Cu	Ni	Cr	V	Mo	Fe
BM.1	GL D36	343	472	34	0.11	0.96	0.021	0.007	0.25	0.043	0.03	0.03	0.02	0.002	0.002	Bal.
BM.2	GL D36	400	533	33	0.18	1.39	0.019	0.019	0.24	0.031	0	0.02	0.03	–	0	Bal.
CV.1	S355J2	466	564	31.3	0.169	1.31	0.013	0.012	–	–	0.1	–	–	–	–	Bal.
CV.2	S355J2	466	564	31.3	0.169	1.31	0.013	0.012	–	–	0.1	–	–	–	–	Bal.
CV.3, 3 mm	S355J2	466	564	31.3	0.169	1.31	0.013	0.012	–	–	0.1	–	–	–	–	Bal.
CV.3, 5 mm	S355J0	432	521	30.3	0.177	0.811	0.023	0.015	0.016	0.032	0.013	0.012	0.018	0	0.001	Bal.
HY.1	GL D36	399	531	26	0.15	1.48	0.013	0.008	0.01	0.037	0.29	0.19	0.06	0	0.01	Bal.
LA.1	GL D36	414	567	24.7	0.1	1.25	–	–	0.002	0.045	0.014	0.014	0.004	0.016	0.031	Bal.
LA.2, 3 mm	S355J2	466	564	31.3	0.169	1.31	0.013	0.012	–	–	0.1	–	–	–	–	Bal.
LA.2, 5 mm	S355J0	432	521	30.3	0.177	0.811	0.023	0.015	0.016	0.032	0.013	0.012	0.018	0	0.001	Bal.