Construction and Building Materials 151 (2017) 827–839

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effects of strength-weakening oriented heat treatment on structural steel and its application on steel plate shear walls

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HIGHLIGHTS

- Effect of a high temperature heating and slow cooling process on structural steel were studied.
- The heating and controlled slow cooling method can reduce the yield/ultimate strength.
- The influencing pattern of heat-treating factors were studied and compared.
- Optimum heat-treating process were selected for each steel type.
- The application potential of steel strength weakening method on steel plate shear wall was explored.

ARTICLE INFO

Article history:
Received 13 August 2016
Received in revised form 20 April 2017
Accepted 16 June 2017

Keywords:
Strength weakening oriented heat treatment
Structural steel
Material tension test
Strength reduction
Steel plate shear wall

ABSTRACT

Low-yield point steels began to be widely used for energy dissipation in seismic design. Traditional aseismic designs often utilize section-cutting measurements to induce plasticity to be happened at designed location. But this paper investigated local steel strength-reduction measurement through controlled heat treatment that features high temperature heating and slow cooling process. A series of parametric heat treating process were applied and corresponding material tests were performed on Q235B carbon steel, low-alloy Q345B and Q390B steel, and Q235-grade angle steel. Results showed that the ultra-high peak temperature heating method (above 800 °C) and slow cooling treatment method can effectively reduce the yield and ultimate strength of all those tested steel types. No obvious reductions were presented on the elastic modulus, and the steel ductility even presented slight increase after heat treatment. The peak temperature served as the primary influencing factor; meanwhile, the cooling rate and holding time also influenced the strength reduction, which influencing extents were related to the steel type. The locally strength-weakening concept and heat treatment were then applied on the steel plate shear wall. Results showed that an appropriate local strength-weakening design can produce better lateral strength and ductility than traditional designs and all section low-yield point steel plate designs.

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1. Introduction

In current seismic resistant design, passive energy dissipation method is a generally used concept that energy dissipation device or region can be incorporated into structures to absorb a portion of input energy, thus reducing the energy dissipation demand on primary structural members and minimizing possible structural damage [1–3]. For moment-resisting frames, a good solution for passive energy dissipation is to induce the plastic hinge formulation at beam parts or away from joint region, with reduced beam section design [4–6]), or openings at beam web [7]. Another well-known passive dissipation solution uses damping devices in the building to absorb seismic energy when subjected to strong earthquake loads, like buckling restrained braces and some low-yield point shear walls [8]. The major approaches for energy dissipation generally needs special designs to induce plasticity development or energy dissipation developed at desired locations. And these goals are often realized by artificially creating a locally weakened region, which can enter the plastic state early before any large deformation demand happening at the key structural components. These designed weakening regions are mainly achieved through section reduction method. For example, in buckling restrained brace, the steel core is the key energy dissipating part, which often takes reduced section or perforated designs to induce early plasticity

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http://dx.doi.org/10.1016/j.conbuildmat.2017.06.096
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development within the restrained region [9]. Similar measurements were also utilized in shear walls [10] and moment connection designs [11].

In recent years, low-yield strength steels have been widely used for energy dissipation [12,13]. But at present the production of low-yield point steel are generally conducted at steel mills, and related steel product are still at a relative expensive price state. Besides, the low yield point steel is often incorporated into structures or connected to the high strength parts or steel members through welding. However, this connecting often induces cracks and damages, or fails to exert the energy dissipation ability due to early welding fractures [14]. In recent years, Hassan [15] proposed a novel heat treatment technique that can achieve local strength weakening at existing steels, and this measure was then applied in his exploring research on US connections: The innovate heat treatment involved heating a part of beam flange with ultra-high temperature and controlling the cooling process at a slow rate. After the heat-treating process, steel strength in the locally heat-treated region was reduced, creating a regional soft area that can act as a ductile fuse in the beam. The local strength-weakening concept and the effect of the heat treatment measurement were then validated through a series of joint tests and simulations [16,17]. Current paper investigates the effects of this strength-weakening oriented heat treatment on generally used types of structural steels in China. Four types of steels were tested here which are hot-rolled Q235B, low-alloy Q345B, Q390B steel, and Q235-grade angle steel (AG235).

2. Strength-weakening oriented heat treatment technique and material tests

2.1. Principles and effects of heat treatment

The microstructure of steel consists of a spatial arrangement of crystalline aggregates of different phases. These phases essentially control the final properties of any given steel, including the hardness, strength, ductility, etc. Then, diverse steel properties are made possible by modifying the decomposition of a high temperature d-ferrite phase to high temperature austenite phase and the decomposition of austenite phase to a low temperature a-ferrite phase, through changing the composition and cooling rate [18]. The heat treatment method used in current study uses controlled heating and cooling processes to modify the microstructure and to reach the desired steel performance. When heating steel above the critical temperature (i.e., austenite formation temperature, which is decided by chemical composition), the austenite phase nucleates at the ferrite-cementite boundary and then consumes the cementite to grow into ferrite through diffusion-controlled growth with further heating. After the completion of austenite formation, further heating would lead to continued grain growth of austenite. In the subsequent annealing process, if the steel is cooled slowly, the austenite would transform to pearlite, obtaining a stress-relieved pearlite-ferrite structure that has relatively low strength but good ductility. Otherwise, if the steel is cooled very rapidly, a harder and stronger martensitic structure would be formed with the metastable phase of carbon dissolved in iron [19].

Metallurgy engineers general aim to produce getting high-strength steels. Thus, studies on the applications of non-equilibrium cooling or quenching have been extensively conducted [20,21]. However, the present study uses another treatment method: a process that involves locally heating the existing steel to a high temperature and afterward slow cooling process to induce the formation of a coarse grain and low-strength pearlite-ferrite microstructure. The heating procedure is expressed in Fig. 1. Firstly, the steel specimens were heated to an elevated temperature, T_u, with heating speed of V_h. The peak temperature was held for t_h period, followed by a controlled slow cooling process at a rate of V_c. Here, T_c refers to the terminate temperature of controlled cooling, below which the specimen was naturally cooled to room temperature through air cooling. The heating process was accomplished in an electric furnace (Fig. 2) that abovementioned factors can be settled and well controlled.

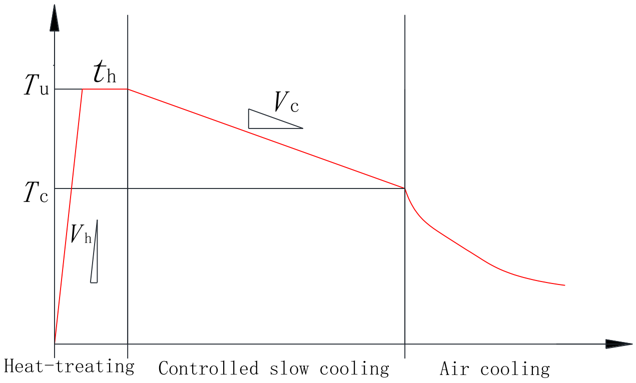

Fig. 1. Heat treatment process.

2.2. Specimen testing plan

Tensile coupon tests were conducted to obtain the influencing pattern of heat-treating measurements on mechanical properties of different structural steels. Test specimens were cut along the rolling direction of steel plates. The shapes and dimensions are in accordance with GB/T 228.1-2010[22], and are given in Fig. 3. The generally used thickness range for each steel type and specimen identification were considered during the test. Therefore, different coupon thicknesses, d, were adopted for each steel grade: $d(Q235) = 16\text{mm}$, $d(Q345) = 12\text{mm}$, $d(Q390) = 14\text{mm}$, $d(AG235) = 10\text{mm}$. However, due to manufacturing errors, the real dimension may have small variations around the designed value. Then before the tensile tests, the real dimensions were obtained as the average of three times measurements within the gauge length.

Fig. 1 gives the heating process that contains several key controlling parameters. Previous studies revealed that the influence of heating speed can be ignored if the heating time is long enough to ensure an evenly distributed temperature inside steel samples [21]. Then in present study the heating speed V_h was set to 10 °C/min for all tensile tests. The investigated parameters were peak temperature T_u, holding time t_h, cooling speed V_c, and terminate temperature T_c. A series of pre-stage exploratory tests on Q345B steel indicated that the heating process with 1050 °C/min, 15-min holding time, and 0.33 °C/min cooling speed to 500 °C can lead to an obvious strength-reducing effect [17]. The aims of the present study are to comprehensively investigate the effect

Fig. 2. Electric furnace.

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