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Interrelationships between yield strength, low-temperature impact toughness, and microstructure in low-carbon, copper-precipitation-strengthened, high-strength low-alloy plate steels

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ABSTRACT

Interrelationships between room-temperature yield strength and low-temperature impact toughness are examined for low-carbon, copper-precipitation-strengthened, high-strength low-alloy (HSLA) plate steels. Three steels, designated as HSLA-80, HSLA-80/100, and HSLA-100, are compared based on plots of yield strength versus 50% shear fracture-appearance transition temperature, followed by comparison of yield strength versus energy absorbed during Charpy V-notch testing at $-84\text{ }^{\circ}\text{C}$. Analysis of both approaches produced similar outcomes, indicating that either is acceptable for predicting the influence of microstructure on the combination of strength and toughness. Data from over 15 studies including over 160 data points are amassed into a single master plot. Strengthening for the highest-strength steels is associated with a strength-toughness vector with slope equal to -0.67 J/MPa . A grain-refinement vector is associated with a slope of approximately $+0.18\text{ J/MPa}$. Since austenite grain size variation was virtually nonexistent in this study, variation of effective grain size was related to the differences in crystal size and/or packet size for low-carbon martensite (finest), low-carbon bainite, and polygonal ferrite (coarsest). A detrimental effect of untempered, brittle, medium-carbon martensite islands was hypothesized. Tempering of this microconstituent during aging heat treatment reduces, but does not eliminate, the negative effect of these islands. Base microstructures of low-carbon martensite show a superior combination of strength and impact toughness, followed by low-carbon martensite with islands of stable austenite, low-carbon bainite, and polygonal ferrite. A vector approach to strength-toughness in HSLA-100 steels is used to clarify property differences from previous studies. Future developments for this class of steels should address grain refinement and changes in processing or alloying that avoid islands of medium-carbon martensite.

1. Introduction

From the middle 1980's to the early 1990's, several studies of low-carbon, copper-precipitation-strengthened, high-strength low-alloy (HSLA) plate steels were conducted [1–14]. This activity (and subsequent papers directly related to the original work [15,16]) was centered on the development of HSLA-100 plate steel, which was an extension of previous efforts regarding the development and implementation of HSLA-80 steel.¹ Several investigations of similar low-carbon, copper-containing steels have been published in the past ten years or so, with the goal of achieving higher strength levels [17–20]. Additionally, there has been a recent surge of interest in non-oriented electrical steels with copper additions for increased strength e.g., Refs. [21–23].

Copper as an impurity in steel is also of great concern for reactor pressure vessels (RPVs) because of its precipitation and/or clustering

which produces an embrittlement effect during service [24–26]. Related to the experimental work on RPVs, recent modeling efforts have been published that are concerned with the interaction between copper precipitates and dislocations in body-centered-cubic iron [27].

The goal of using a combination of copper at levels exceeding one mass percent in steel, a low carbon content (less than 0.07 mass percent carbon), and substantial substitutional alloy content (e.g., Ni, Mo, etc.) is to produce high strength without the negative effects of carbon-containing microconstituents. These steels are processed with HSLA steel technology, which includes clean-steelmaking practices, additions of microalloying elements (notably niobium), and finish rolling at low temperatures. The latter two items result in fine austenite grain sizes in steel plates and forgings. As a result, HSLA-80, HSLA-100, and similar steels of high strength also possess excellent low-temperature toughness and, because of low carbon content, weldability is improved notably compared with steels of the same strength but with higher carbon

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¹ The designations HSLA-100 and HSLA-80 refer to high-strength low-alloy steels with minimum yield strength of 100 ksi and 80 ksi, respectively.

Table 1
Chemical compositions of alloys (in mass pct).

Reference	Designation	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Al	N	Nb
[3,4]	HSLA 80	0.05	0.50	0.009	0.002	0.28	1.12	0.88	0.71	0.20	–	–	0.035
[3]	A710 Modified	0.06	1.45	0.012	0.002	0.35	1.25	0.97	0.72	0.45	–	–	0.040
[3]	HSLA-80/100	0.05	1.00	0.009	0.001	0.34	1.23	1.77	0.61	0.51	–	–	0.037
[3]	HSLA 100	0.04	0.86	0.008	0.002	0.27	1.58	3.55	0.57	0.60	–	–	0.033
[3,8,33]	HSLA 100	0.06	0.83	0.010	0.002	0.37	1.66	3.48	0.58	0.59	0.028	0.008	0.028
[7,34]	HSLA-100	0.083	0.85	0.012	0.005	0.29	1.57	3.57	0.55	0.64	0.018	–	0.036
[10]	HSLA-100	0.047	0.85	0.010	0.005	0.22	2.00	3.59	0.57	0.60	–	–	0.025
[11]	HSLA-100	0.036	0.91	0.008	0.005	0.24	1.60	3.59	0.59	0.59	0.022	0.0097	0.025
[12]	Cu bearing HSLA	0.04	1.10	0.007	0.003	0.36	1.83	1.92	0.62	0.64	–	–	0.04
[19]	Experimental	0.041	0.89	–	–	0.25	1.54	3.51	0.49	0.59	0.033	–	0.050
[31]	A710	0.038	1.27	0.009	0.002	0.29	1.21	2.04	0.56	0.39	0.040	–	0.051
[32]	A710 Modified	0.043	1.48	0.008	0.001	0.34	1.20	1.03	0.79	0.48	0.024	0.005	0.063

content. Interrelationships between the processing, microstructures, and properties of HSLA steels are summarized in numerous research papers, conference proceedings, and books; three excellent sources of information [28–30] among many are provided for the interested reader. Of particular importance to the present work are the so-called embrittlement vectors that have been used to quantify the propensity for cleavage fracture associated with various strengthening mechanisms other than grain refinement.

Since the combination of high strength and excellent low-temperature toughness is a key component of HSLA plate steels, the purpose of this paper is to provide a summary of strength-toughness data from previous studies of low-carbon, copper-precipitation-strengthened plate steels and then to combine this information with more recently collected data from similar steels. This assessment strives to extend our understanding of key microstructure-property relationships in these steels with the goal of better understanding current trends and future developments for this class of steels.

2. Steel compositions and typical microstructures

Table 1 provides the chemical compositions (in mass pct.) of several low-carbon, copper-precipitation-strengthened steels that will be referred to in this paper [3–5,7–14,19,31–34]. The majority of the steels are designated in the original work as either HSLA-80, HSLA-100, or as intermediaries such as HSLA-80/100 Modified or A710-Modified steel. Common chemical-composition features of these steels include: (i) a low carbon content (typically < 0.07%C), (ii) a high level of copper (> 1%Cu) for precipitation strengthening, (iii) intermediate amounts of hardenability elements other than copper such as > 0.8%Ni, > 0.5% Mn, and oftentimes > 0.5%Cr, and > 0.2%Mo, (iv) a microalloying addition of niobium (approximately 0.04%Nb) to provide for grain refinement, (v) low levels of phosphorus and sulfur (< 0.015%P and < 0.005%S), and (vi) inclusion shape control.

The majority of data published for these steels has been for steel products with prior austenite grain sizes of about 10 μm . This common grain size for the steels described in Table 1 is typically obtained by a final austenitizing heat treatment at a temperature of about 900 $^{\circ}\text{C}$ or slightly higher.

Of the steels described by Table 1, each has a base microstructure (depending on alloy content and cooling rate) dominated by one or more of three common microconstituents: polygonal ferrite (PF), low-carbon bainite (LCB), sometimes referred to as carbide-free bainite,² and low-carbon martensite (M). Wilson et al. [3] examined four steels of this type and provided continuous-cooling-transformation (CCT) diagrams for HSLA-80, HSLA-100, and a steel of intermediate chemical composition, referred to as A710-Modified steel. In each case, the steels

² A number of other terms have been used to describe this microstructure, such as granular bainite and acicular ferrite. However, in this paper, the term low-carbon bainite has been adopted.

were austenitized slightly above 900 $^{\circ}\text{C}$ prior to cooling, and austenite grain size was approximately 10 μm . The CCT work and associated microstructural analyses of as-cooled specimens revealed that austenite transformed, over wide ranges of cooling rates, to predominantly polygonal ferrite in HSLA-80 steel, low-carbon martensite in HSLA-100 steel with 0.06%C, and low-carbon bainite in A710-Modified steel. The chemical composition of the latter alloy was intermediate to those of the two steels with the HSLA designation.

Light micrographs of the three base microstructures in the as-cooled condition are shown in Fig. 1 [5]. The microstructures commonly produced during cooling in HSLA-80 steels contain large amounts of polygonal ferrite, as indicated by Fig. 1a. A polygonal ferrite grain size of > 5 μm is common, although it depends on finish rolling parameters and cooling rate. During the formation of proeutectoid ferrite crystals from the parent austenite phase, carbon is rejected from ferrite into adjacent crystals of austenite which become highly enriched in carbon. After ferrite growth ceases, continued cooling to room temperature results in the decomposition of austenite to small amounts of upper bainite, lower bainite, and/or martensite, although some small regions of austenite are retained at room temperature. The dark features in Fig. 1a show islands of these latter microconstituents. Fig. 1a shows that the largest medium-carbon microconstituent islands are nearly the size of some ferrite grains. In the cases of islands that are predominantly untempered martensite, such features should be sites that initiate brittle fracture at low test temperatures.

Compared with HSLA-80 steels, many HSLA-100 steels have a very different microstructure which is predominantly martensite. In HSLA-100 steel, austenite transformation to polygonal ferrite and bainite at comparatively high temperatures is avoided, therefore martensite forms at low temperatures with the same carbon content as the parent austenite phase, e.g., 0.06%C. Some austenite (about five volume percent) is retained as thin films between laths of low-carbon martensite after cooling to ambient temperature. Fig. 1b shows a typical low-carbon martensite microstructure. The prior austenite grain structure is somewhat discernible, and packets of martensite laths are readily evident.

For steels with chemical compositions intermediate to those of HSLA-80 and HSLA-100 steels, the predominant microstructure observed has been described as low-carbon bainite (although a variety of other terms have been used). Fig. 1c shows an example of this microstructure. Coarse laths of bainitic ferrite (white and light gray regions) are evident, and a dark gray microconstituent between adjacent laths is apparent. Unlike low-carbon martensite shown in Fig. 1b, carbon is rejected from growing laths of bainitic ferrite into adjacent regions of austenite during cooling. As a result, the carbon-enriched austenite regions tend to be retained to room temperature or to transform to medium-carbon martensite at temperatures close to room temperature. The region labeled A in Fig. 1c shows one such region. As these gray regions frequently are mixtures of martensite and austenite, they are oftentimes referred to as the M/A constituent. Compared with Fig. 1a,

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