Granular Product in a High Strength, Low Alloy Containing Molybdenum and Niobium

Y. B. Xu, G. J. Liu, and T. Y. Zhang

The formation and microstructure of the granular product and its effect on the mechanical properties of a high-strength, low alloy steel containing molybdenum and niobium have been investigated. It was found that the granular product "islands" are composed of both twinned martensite and dislocated martensite. The effect of the granular "islands" on the strength at room temperature and at 400 °C has been determined. The results showed that the strength increased and both the impact and fracture toughness decreased as the volume fraction of granular "islands" was increased. In situ fracture studies indicated that the three stages of the microfracture process of the specimen containing granular "islands" are the initiation of voids at interfaces between the granular "islands" and the bainitic ferrite matrix, followed by void growth and finally, coalescence by shear.

I. INTRODUCTION

Recent studies of a high strength, low alloy steel containing molybdenum and niobium showed that there was a granular product "island", one of the transformation products, which is quite different from upper and lower bainite in morphology, produced either by continuous cooling with an appropriate cooling rate, or by isothermal transformation after undercooling to a suitable temperature. This product is similar to those described by some authors using low carbon bainitic steels containing boron, and called the martensite-austenite (M-A) constituent or granular "islands" distributed in the bainitic ferrite matrix. Throughout the paper, the granular product will be referred to as the granular "islands". Investigations demonstrated that the microhardness of the islands (Hm ~ 400) is much higher than that of bainitic ferrite matrix (Hm ~ 150) and that the steel containing granular islands was found to have lower Charpy fracture energy and fracture toughness as well as higher tensile strength than those of steel without the islands.

This paper presents the results of studies concerning the fine structure and the mechanism of formation of granular islands as well as the influence of the islands on mechanical properties of a high strength, low alloy steel containing molybdenum and niobium.

II. MATERIALS AND METHODS

The steel used for the present study was made in a 11.4 ton open-hearth furnace. The ingots were press forged into plates of several thicknesses. The chemical composition of the steel is given in Table I.

All specimens, of 120 × 25 × 25 mm, which were cut from hot rolled plates, were normalized at various cooling rates after austenitizing at 950 °C for 10 minutes in order to obtain different volume fractions of granular islands. Cooling rate was measured with a chromel-alumel thermocouple. The volume fraction of granular islands was determined metallographically by the point-counting method using photographs. The heating cycle, microstructure, and the corresponding volume fraction of granular islands of each specimen are presented in Table II.

Specimens for optical microscopy were mechanically polished and then chemically etched in 2 pct nital. Observations by transmission electron microscopy were performed on a Philips 420 electron microscope operated at 100 kV, and included both replica and thin foil techniques. The thin foil specimens for TEM were chemically polished to a thickness of about 50 μm in a solution of 5 parts hydrofluoric acid and 95 parts hydrogen peroxide and then electropolished in a solution of 15 pct perchloric acid and 85 pct alcohol.

Microanalysis was conducted on a type H400EPMA instrument to compare the differences of the chemical compositions of the granular islands and bainitic ferrite matrix. In situ fracture microprocesses were observed on a Stereoscan type 4-10 SEM. J-integral and crack opening displacement were determined by using the multiple specimen method.

III. RESULTS

A. Microstructure

A photograph of the normalized specimen is shown in Figure 1. It can clearly be seen from this picture that the microstructure is composed of the granular islands (indicated by arrow) and the bainitic ferrite matrix. This mixed microstructure, which is quite different from upper and lower bainite in appearance, is usually designated as granular bainite.

In order to study the fine structure of the granular islands, thin foil studies for the normalized specimen were carried out at high magnification. Figure 2 shows a bright-field electron micrograph of an island indicating the fine structure.

A series of observations showed that two types of granular islands in morphology were found. One is twinned martensite in which the microtwins are very fine and parallel to each other as shown in Figure 3. Obviously, this is a feature characteristic of twinned martensite. In general, the plane of twinning belongs to the {112} family, and the direction of
slip is (111). The microtwins are often observed when the orientation of the foil is (110) or (113). The other, which is called dislocated martensite, has a significant high dislocation density as shown in Figure 4.

The thin foil observations also showed that the bainitic ferrite matrix was characterized by a substructure with high dislocation density (Figure 5). No evidence of martensite laths and remaining austenite was observed during the course of study.