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NEW TYPE STEEL HAVING SUPERIOR BRITTLE CRACK ARRESTABILITY AND ITS APPLICATION TO IMPROVE STRUCTURAL INTEGRITY

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ABSTRACT

Studies on the crack arrestability of steel have revealed that the shear lips formed at the surface of steel when brittle cracks propagate offer great resistance to the further propagation of these cracks. This knowledge led to the development of steel (SUF steel) having ultra fine grains at the surface and in the subsurface region (surface layers) that promote the formation of shear lips. Plates of SUF steel have extremely high crack arrestability and do not require any special alloy additions. It is expected that the use of such plates for ship structures will remarkably increase the structural integrity.
In this paper, new type steel plate having extremely high crack arrestability is introduced. Large-scale fracture model tests were conducted to determine the effect of the use of SUF steel plates in a ship structure as a crack arrestor. Furthermore, required value of crack arrestability to prevent long brittle crack propagation is discussed.

KEYWORDS

Brittle fracture, Crack propagation, Steel, Ship, Structure integrity, Crack arrest, Cleavage fracture

INTRODUCTION

Brittle fracture is one of the major causes of serious damage to structures, such as ships, when they have an accident. Damage increases vastly if brittle fracture occurs and propagates as a result of such disasters as collisions and groundings of ships, although the number of ship accidents due to brittle fracture has recently been reduced greatly. Such catastrophic expansion can be averted by preventing the propagation of brittle cracks. Therefore, the structural integrity of ships will be increased by the use of steel having a property to prevent the propagation and expansion of brittle fracture that might result from disasters (i.e., crack arrestability) for important members of structures.
In this paper, new type steel plate having extremely high crack arrestability is introduced and required crack arrestability to prevent large scale fracture is discussed.

CONCEPT OF IMPROVING CRACK ARRESTABILITY

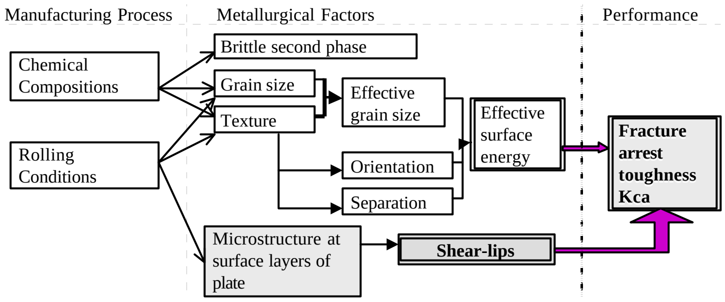

Figure.1: Controlling factors of brittle unstable crack arrest toughness

Figure 1 shows the controlling factors for crack arrestability. Nickel-containing steel plates are used for applications requiring high crack arrestability. Grain refining technique has also been investigated to improve crack arrestability without adding special alloy elements. TMCP process has provied steel plates with fine grain microstructures. Further effective technologies to improve crack arrestability were derived from the mechanisms of unstable brittle crack propagating behavior. The effect of shear-lips on crack propagation behavior is one of the major factors to improve crack arrestability [1]. Shear lips are formed in the surface regions of steel plate when brittle cracks propagate. They can offer great resistance to the further propagation of these cracks. This knowledge led to the development of the new type steel plate, SUF steel (steel having Surface layers with Ultra-Fine grain microstructures) [2]. Shear lips are developed in the ultra-fine-grained layer region when brittle cracks propagate. Because the plastic deformation and ductile fracture, which accompany with shear-lips, prevent the propagation of brittle cracks, SUF steel plates have excellent crack arrestability.

SUF STEEL PLATE

Figure 2 shows the macrostructure of the SUF steel plate together with the microstructures of the surface layers and midsection regions. The ultra-fine-grained region is the black layer observed at the surface of the steel plate, as shown in Fig.2. The average value of grain sizes in the surface layers is less than two micrometers. The distribution of the average grain size in the thickness-direction is also shown in Fig. 2. In the surface layer, the grain sizes are relatively homogeneous. The grain size changes significantly at the border of the surface layers and the mid-thickness of the plate. Charpy impact test results for SUF region suggested that remarkably lower brittle-ductile transition temperature is obtained in 'SUF' than in mid-thickness', although the chemical composition of the SUF steel plate is the same as that of ordinary steel plates without any special alloy elements. The tensile strength of the SUF steel plate is comparable to that of the 490 N/mm^2 class steel. Mechanical properties and welding performance of SUF steel satisfy the requirements of KE36 (EH36) class steel according to the NK (IACS) standard [3].

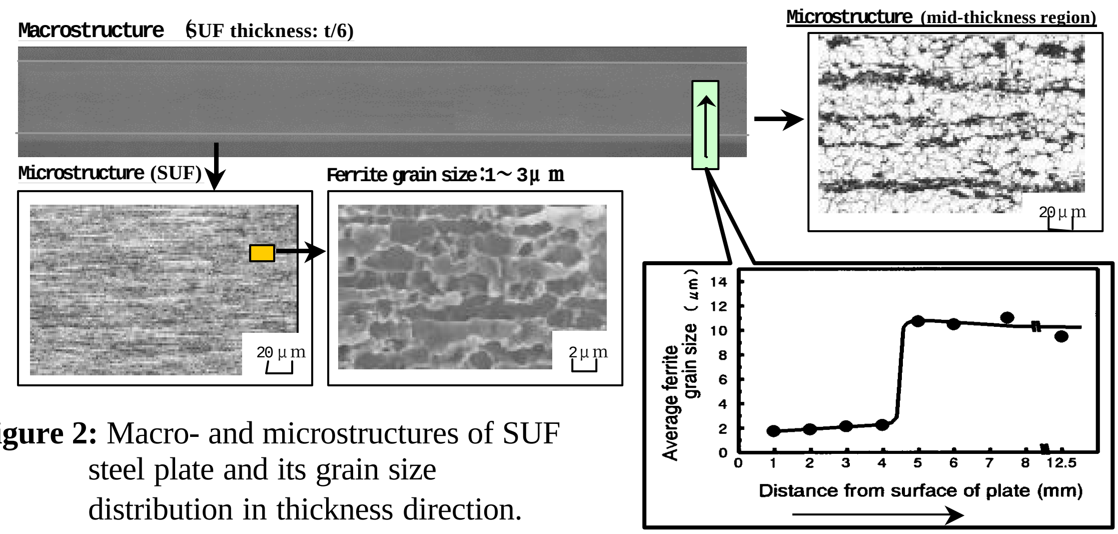

Figure 2: Macro- and microstructures of SUF steel plate and its grain size distribution in thickness direction.

CRACK ARREST TESTING AND RESULTS

Standard ESSO test

The standard temperature-gradient ESSO test was conducted to evaluate the crack-arrest toughness, the critical stress intensity factor for stopping the crack: Kca, of SUF steel and conventional EH36 steel. Figure 3 shows the fracture surface of the SUF steel plate used for the temperature gradient type ESSO test which evaluates crack arrestabilty. The inside of the plate was fractured brittlely, while the surface regions of the plate were not fractured brittlely but ductilely. The surface regions fractured ductilely with plastic deformation are called shear-lips, and these have a braking effect on unstable brittle crack propagation and further enhance the crack arrestability of the steel plate.

The results of standard ESSO test for SUF steel plate and of conventional steel plate (EH36 steel plate) are shown in Fig. 4. Both plates have equivalent chemical composition and the same 25mm thickness. Furthermore, the crack arrestability of the steel plates subjected to a plastic tensile strain of approximately 10% [4] was evaluated. It is clear from Fig. 4 that plastic pre-straining deteriorates crack arrestability. For the EH36 steel plate, the temperature indicating Kca=4000 $N/mm^{1.5}$ is about -40°C when plastic pre-straining is not given, however, the temperature rises to above 0°C when a 10% plastic tensile strain is given. On the other hand, although crack arrestability of SUF steel plate is also impaired by plastic pre-straining, SUF steel plate with 10% plastic tensile strain has higher crack arrest toughness (Kca) than that of EH36 steel plate without plastic pre-straining.

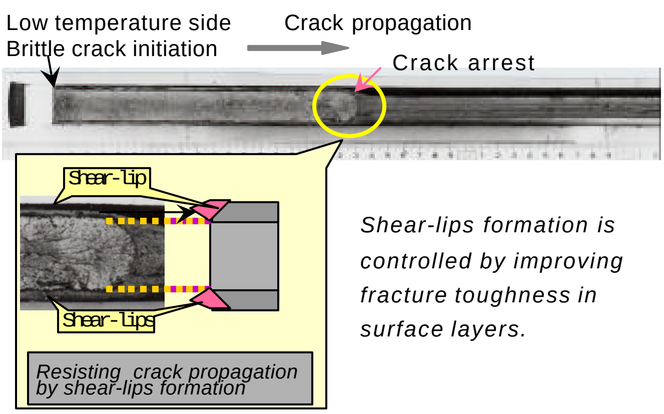

Figure 3: Fracture surface of standard ESSO test specimen for SUF steel plate

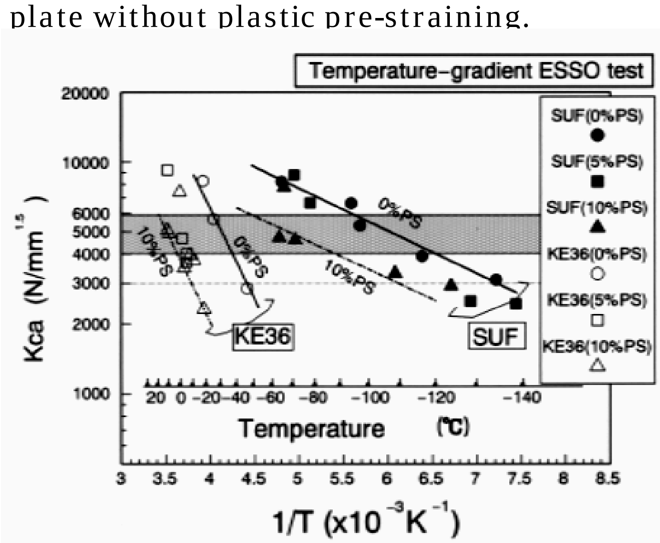

Figure 4: Results of temperature gradient type ESSO tests s

Effect of shear lips in improving crack arrest toughness

To confirm experimentally the effect of shear lips developed in the SUF region in improving the crack arresting performane of SUF steel plate, specimens of SUF steel plate were removed of the SUF portion by griding, and the Kca was evaluated by standard temperature-gradient type ESSO test. The ESSO test results of SUF steel plate specimens with the SUF retained on both sides (with SUF), with the SUF removed from one side (with 0ne-side UF), and with the SUF removed from both sides (without SUF) are plotted in Fig. 5. The chain linen in Fig. 5 shows the presumed Kca values of SUF steel plate calculated by adding the effect of shear lips in improving the Kca value as estimated by the Kraft model [5] to the Kca value of the specimens without SUF. The presumed Kca values of the specimens with one-side SUF are indicated by the dotted line in Fig. 5. The effect of shear lips in the SUF region can be explained fairly well by these rough approximations.

Ultra-wide plate duplex ESSO test

Crack arrestability against a large scale unstable brittle crack propagating at great speed was verified with the ultrawide plate duplex type ESSO test specimen shown in Fig. 6(a),. A conventional EH36 steel plate was used as an approach-plate through which the unstable brittle crack propagated, the SUF steel plate was used as the test plate. Figure 6(b) shows the appearance of the test specimen immediately after the test and the fracture surface. It was observed in this test that when the unstable brittle crack which had propagated through the EH36 steel plate reached the SUF steel plate, the unstable brittle crack was immediately arrested by the formation of shear-lips.

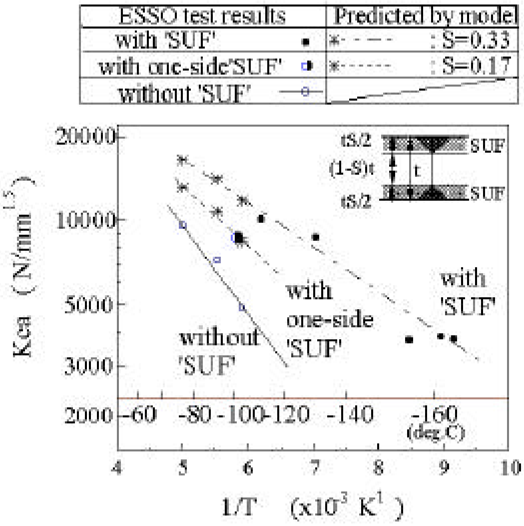

Figure 5: Effect of SUF on Kca

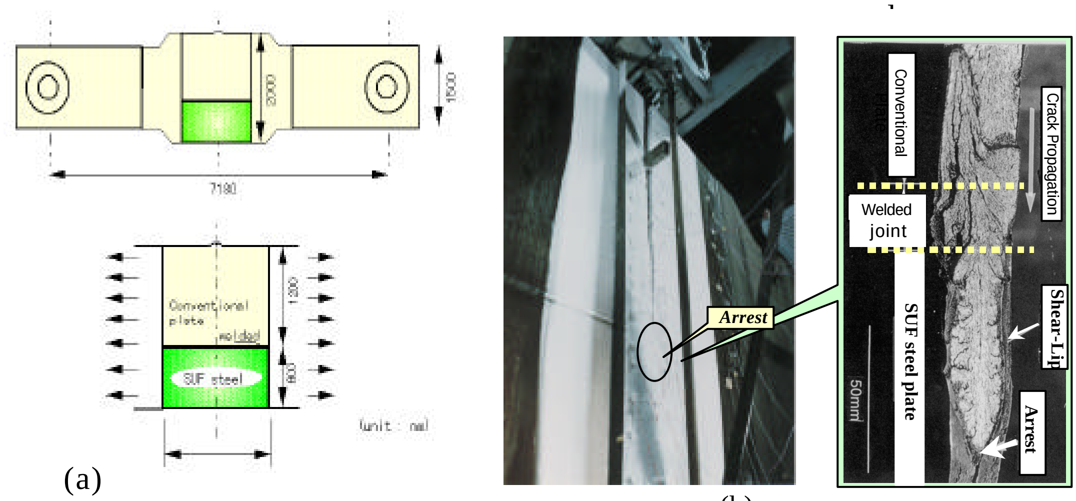

Figure 6: Ultra wide plate duplex ESSO test of SUF steel plate and its fracture surface.

REQUIRED Kca VALUE TO ARREST LARGE SCALE FRACTURE

When the crack length increases, the crack tip stress intensity factor (K) is reported to tend to saturate at a certain value of Keff (effective K) and not to reach the value of $K=\sigma\sqrt{(\pi a)}$ (which is calculated by linear fracture mechanics) [6]. One of the reasons is that the size of the plastic region formed at the crack tip is limited under its propagation. Then, a running brittle crack can be arrested if the following equation is satisfied: Keff≦Kca. However, it is not easy to calculate the Keff value since many factors like the dynamic effect of crack are involved. Therefore, the brittle crack arrest toughness required for the arrest of long cracks has been experimentally studied using large-scale crack arrest test.

Figure 7 shows the results of large-scale crack arrest test (ultra wide-plate duplex ESSO test) conducted with higher-strength hull structural steel plates (Grade EH36) generally used as materials of crack arrestor for ships [7]. In this figure, the brittle crack arrest toughness (Kca value) was obtained from standard test (temperature-gradient type standard ESSO test or double-tension test with a specimen width of 400 to 500 mm and a crack propagation region width of 150 to 250 mm) with relatively small effects on crack size and dynamic phenomenon.

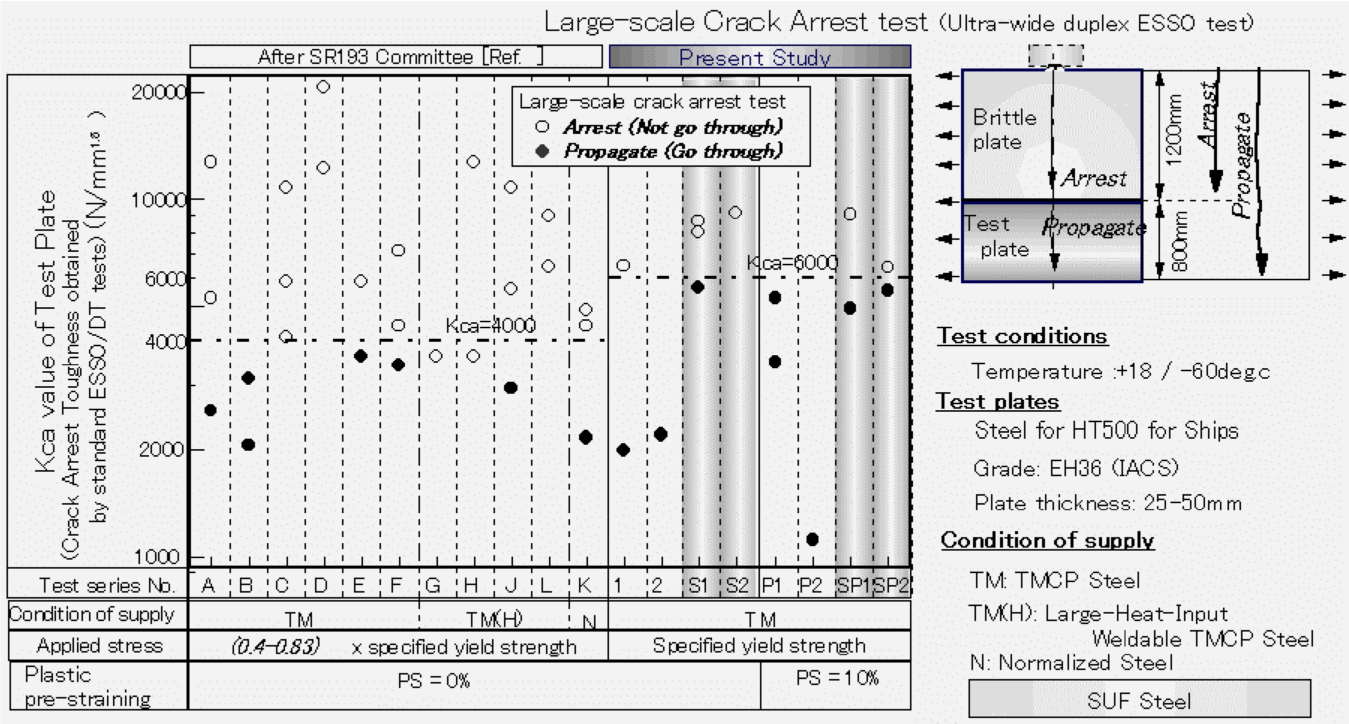

Figure 7: Results on large-scale fracture test, together with the results obtained by SR193 committee [7]

The study on crack arrestor by Dr. Kanazawa et al. [6], and the analysis reports on brittle fractures in actual ships [8] confirm that the propagation of long cracks can be arrested if the Kca value of the above standard test is 4000 to 6000 $N/mm^{1.5}$ or more. It is suggested that these research results approximately agree with the test results shown in Fig. 7.

In case of accidental conditions such as collision or grounding, where large plastic deformation is accompanied, the structure members seem to be subjected to the amount of plastic strain of 5 to 10 %, and to be loaded up to yield strength. Even in such situation, if Kca at design temperature is larger than 6000 $N/mm^{1.5}$, it is expected that crack propagation can be arrested.

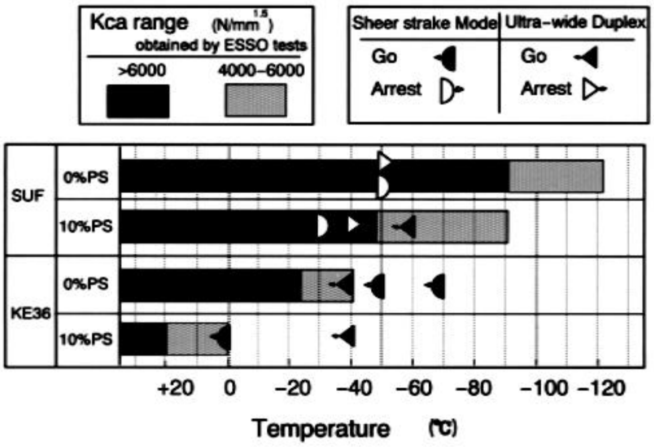

Figure 8: Summary of crack arrest arrestability for SUF steel plate and EH36 for reference.

The temperature regions where the SUF steel plate can maintain its crack arresting performance are shown in Fig. 8. The temperature region where the Kca value of the specimens obtained by the temperature-gradient ESSO test is not less than 6000 $N/mm^{1.5}$ is shaded dark. The temperature region where the Kca is 4000 to 6000 $N/mm^{1.5}$ is shaded light. The ultra-wide duplex ESSO test results and the large scale sheerstrake model fracture test results [3] are denoted by marks indicating "go (crack propagated)" and "arrest (crack arrested)" for specific temperatures. The lower limit temperature at which Kca = 6,000 $N/mm^{1.5}$ can be achieved is about 70 deg.C lower for the SUF steel than for the conventional EH36 steel. A plastic strain of 10% shifts the crack arrest performance of both SUF and conventional EH36 steels by about 40 deg.C toward the high end of the test temperature range. The lower limit temperature at which Kca is about 6,000 $N/mm^{1.5}$ is -50 deg.C for the SUF steel and about +15 deg.C for the EH36 steel. Therefore, SUF steel plate can be expected to be fully able to arrest long cracks when applied to ships operating in seas at the lowest temperature of 0 deg.C even under accidental conditions.

APPLICATION

SUF steel plates or equivalents, which have sufficient crack arrestability (Kca≧6000 $N/mm^{1.5}$) at the lowest service temperature even when 10% plastic strain is imposed, are authorized as high crack arrestability steel plates, and it has been decided to give the optional class-notation 'Higher crack arrestor' to ships in which these steel plates are used for important members [9]. SUF steel plates were applied for an LPG carrier for the first time in 1995, and for a bulk carrier in 1996, a tip carrier, a coal carrier and so on . The application of the SUF steel plate in large-scale steel structures requiring safety against brittle fracture, such as earthquake-resistant high-rise buildings and offshore structures, will contribute to higher structural integrity and the prevention of environmental problems such as tanker oil spills.

CONCLUSIONS

Focusing on that the shear lips formed at the surface of steel when brittle cracks propagate offer great resistance to the further propagation of these cracks, SUF steel plate having ultra fine grains in the surface layers has been developed. Large-scale fracture model tests were conducted to determine the effect of the use of SUF steel plates in a ship structure as a crack arrestor. It is expected that crack propagation can be arrested if Kca at design temperature is larger than 6000 $N/mm^{1.5}$, even in case of accidental conditions, where the structure members seem to be subjected to the amount of plastic strain of 10 %.

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