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Microstructures and properties of sandwich plane laser-welded joint of hull steel

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ABSTRACT

It is necessary to develop new production and new processing strategies in order to make lightweight construction adapted successfully. In this paper, the fundamental mechanical properties of hull steel CCS-B sandwich plane laser-welded joint and base metals were presented. For the flat grooved specimens with various radiuses, with increasing of initial stress triaxiality, the relationships between the initial stress triaxiality and the equivalent strain to fracture are fitted using an exponential function. The microstructures, tensile properties and impact toughness values of base metals and weld metals at various testing temperature are compared and analyzed.

1. Introduction

The demand for lighter and safer structures has stimulated the need to study new materials and new structural configurations in ship structures. Now, more interests are concentrated on sandwich structures for ultra-light material systems, however, lots of sandwich structures mainly refers metallic faceplates joined by metal-containing cores, such as metallic foams or fiber [1–4]. Honeycomb sandwich and foam sandwich are widely used in traffic field. For example, the head crust of magnetically levitated train is made up of two large sandwiches with complex shape and joint, supported structures and the body crust is the same. Due to high speed (300–500 km/h), the aerodynamic pressure on train is large, especially when two trains encounter or go in to the tunnel, the worse problem may be occurred. Since when the sandwiches were in pressure field, it is necessary to study the stability of sandwich plates. Thus, the impact of sandwiches and the stability of sandwich with damage should be studied. Sandwiches with metallic foams or fiber cores make the weight loss indeed, while the strength cannot satisfy requirement. All-metal sandwich panels offer an option that can fulfill these requirements. These panels are composed of metal face plates separated by many metal cores, and the cores rank periodic in two face plates. The simplest core geometry of all metal sandwich structures is built from flat web plates perpendicular to the face plates [5]. Pyramidal cores and corrugated cores geometry of sandwich plane had been processed by Radford [6]. These special cores need specific equipment for production, but they usually result with the lightest panels. Naturally, during the production process or after welding of faceplates plates and core together, the steel sandwich panels can also be filled with some polymer, mineral or rock wool, concrete etc. to improve the behavior for specific targets [7].

Laser welding can manufacture these complex structures. Due to its high energy intensity and a deep penetration effect, laser welding offers a number of benefits for the production of all-metal and hybrid-metal sandwich panels. High pre-fabrication accuracy of the components, high welding speed and the possibility to connect internal stiffeners with the face sheets from outside have led to a wide application of laser welding in the construction of metal sandwich panels. In the past 20 years, some countries have started series studies about laser welded sandwich panels [8–18]. An approach to the structural analysis of patch-loaded, laser-welded web-core sandwich plates was presented in Ref. [8]. The accurate and fast linear elastic response prediction of webcore sandwich plates was analyzed. Moreover, the effect of the rotation stiffness of the laser-welded T-joint between the face and web plate were also discussed. In Ref. [9], impact damage of sandwich panels can be numerically simulated based on a suitable choice of material model for the sandwich core. Results indicated that residual indentation of the sandwich panel depended on the

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maximum impact force, which was determined by the size and structural properties of the panel as well as the projectile mass and striking energy. Ref. [10] indicated that all-metal sandwich panels, made by a process of laser welding faceplates to core-stiffeners have advanced cost/weight properties compared with the conventional structural applications of stiffened plates. However, optimal design of these advanced structures requires a fast simulation procedure that should have the same level of reliability compared to finite element calculations and natural tests, while being more time effective and less complex. It was shown that different polynomial functions together with design of computer experiments can contribute to such an aim by providing simple however reliable metal models. Ref. [11] investigated the possibilities for structural optimization of laser-welded sandwich panels with an adhesively bonded core and uni-directional vertical webs. Closed form expressions for the equivalent stiffness and elastic buckling strength of laser-welded sandwich panels have been discussed and numerically evaluated to demonstrate the effect of parameter variations on stress and deflection. Based on the optimization results, it is concluded that, within the span of production parameters and rule requirements, substantial improvements can be made with or without an adhesively bonded core. In Ref. [12], T-joint rotation stiffness in laser stake welded steel sandwich panels and influence of rotation stiffness on the response of a web-core sandwich beam were also investigated. These studies [13,14] indicated that the laser-welded metallic sandwich panels provide an opportunity for shipyards to reduce weight while enhancing performance in applications where an economical metallic solution is needed. By optimizing thickness, materials, geometry, and joint designs, the flexible sandwich panel designs can be tailored to a wide variety of shipyard applications that meet various performance requirements. In above optimized design and theory computations, ideal structures were considered. No studies considered the effects of laser welded joints on the stiffness, strength of the whole structure. However, in our studies, results have found that the effective bonding dimensions between face sheet and core sheet are less than that of ideal structures. Moreover, during the laser welding processes, the microstructures, properties of the welded joints have also changed. Therefore, it is very important to study the effect of laser welded joints on the whole structure. In order to systematically analyze the stiffness, deformation and failure behaviors of the laser-welded sandwich structures, the properties of laser-welded joints especially weld metal firstly need be characterized.

The fracture mode of this steel at room temperature is still ductile fracture [15]. Prediction of ductile fracture of metals in engineering structures is a topic of great importance in the automotive, aerospace and military industries. Equivalent strain to fracture is widely used to define the material ductility. Many theoretical analyses and experimental results have shown that the material's fracture strain is not constant but changes under different loading conditions [16–18]. During performance processes, various loading modes, such as tensile, shear and bending may be loaded at laser beam welding sandwich plate. Moreover, when impact or bending loading modes are performed at sandwich plate structures, various stress states are produced at various regions. A common used type of test for ductile fracture calibration is the tensile test on axisymmetric un-notched and notched flat specimens, according to Bai Yuanli's formula to calculate the stress triaxiality, which covers the stress triaxiality range greater than 1/3, so it is necessary to characterize the fundamental mechanical proprieties of weld metal and base metal with different stress states and charpy toughness.

2. Materials and experimental procedures

2.1. Materials

The base metal used in this paper is low alloy and high strength hull steel CCS-B, Table 1 shows its main chemical composition.

Laser beam keyhole welding is used to join the face plates and the web planes, welding parameters are listed in Table 2. The thickness of the face and web plates are 4 mm. The dimensions of optimized sandwich structures are listed in Table 3 and Fig. 1.

2.2. Experimental procedures

To analyze stress conditions and failure modes of bending or impact loading for the laser beam welding sandwich planes, the basic properties such as tensile properties, equivalent strain to fracture with various stress conditions and charpy toughness must be characterized.

To demonstrate the basic tensile properties of the base metal, the welded joints and the weld metal, the tensile specimens with various locations were machined. Tensile properties of base metal and weld metal were measured by the universal test machine SHIMACZU AG-10TA at room temperature. Dimensions of tensile specimens of ship steel CCS-B base metal and the welding joint are presented in Fig. 2. Because the ship steel CCS-B base metal were provided by rolling mode, the two type tensile specimens were designed. One specimen was machined along the rolling direction, and the other specimen was machined perpendicular to the rolling direction. To characterize the tensile properties of true weld metal and the welded joints, two types of tensile specimens were cut from different locations of the welded joint. Sampling schematics of tensile specimen in weld metal and the welded joints are shown in Fig. 3. The tensile direction of one specimen was designed along the length direction of weld metal, i.e. full weld metals were located in the range of the gauge of the tensile specimens, as shown in Fig. 3(a). Thus, the measured tensile properties present the true properties of the weld metal. However, the weld metal of the other tensile specimen was only located in the middle of the gauge as shown in Fig. 3(b), in fact, the specimens indicate the tensile properties of

Table 1
Main chemical composition of hull steel CCS-B.

C	Mn	Si	P	S	Cu	Ni	Cr	V	Ti
0.13	0.68	0.21	0.025	0.016	0.04	0.03	0.02	0.002	< 0.0005

Table 3
Dimensions of laser welding sandwich plane structure.

h (mm)	a (mm)	n	L_1 (mm)	t (mm)	L (mm)	b (mm)
40	78	15	24	4	1200	500

Table 2
Welding variables of hull-steel CCS-B.

No.	Welding method	Welding power (KW)	Welding speed (mm/min)	Shielding gas	Gas flow (L/min)
Parameter	Laser-welded	12	2000	Ar	30