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STUDY ON SOLID-PHASE WELDING OF FINE-GRAINED HYPEREUTECTOID STEEL WITH 40Cr STEEL

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Abstract. In this study, we have attempted the solid-phase welding of superplastic ultra-high carbon steel that has a carbon content of 1.4 wt.% (UHCS-1.4C) with 40Cr steel. The UHCS-1.4C was preprocessed into ultrafine grain and fully spheroidized microstructure through a controlled rolling and divorced eutectoid transformation. And the 40Cr steel was also preprocessed into fine grain through salt-bath cyclic quenching. The welding was performed at 1053 – 1093K, under compression strain rate rage of 10^{-3} – 10^{-1} s^{-1} and compression strain rage of 0.1 – 0.2. The ultimate tensile strength of the welded specimen increases with increasing welding time and with decreasing compression rate, and becomes approximately the same as that of 40Cr steel for a welding time above 600 s and a compression strain rate of 10^{-3} s^{-1}. The carbon content of 40Cr increases, while that of UHCS-1.4C decreases in the region near the interface. Considering from these result, the carbon in UHCS-1.4C diffuses into 40Cr. The fracture surface of the joints consists of sags and crests, which reveal a metallurgy bonding. The results indicate that UHCS-1.4C can be suitably used for solid-phase welding with 40Cr steel in a short-duration.

1. INTRODUCTION

Ultrahigh carbon steels (UHCSs), which are hypereutectoid steels, have unique mechanical properties, such as high strenths and superplasticity. Superplastic materials are characterized by their high strain-rate sensitivity index (*m*) and their deformation on resistance to neck growth. A proper thermo-mechanical treatment leads to superplasticity by forming a structure composed of a homogenously distributed carbide particles within the fine-grained ferritic matrix in UHCSs. These steels, which cannot be readily formed at room temperature due to their high carbon content, became industrial materials after it was learned that they showed superplasticity at some certain temperatures and superplastic forming techniques were developed [1-4]. Joining this kind of steels, or joining them with other steels (for example 40Cr steel), has gained importance after their industrial applications as structural materials [5]. Though fine-grained hypereutectoid steels can be formed easily at the superplasticity temperature, the superplastic microstructure disappears and high carbon content causes cracking when they are joined with the conventional welding methods [6,7]. The main goal should be protecting the superplastic microstructure as much as possible and preventing cracking in the welding of superplastic high carbon steels. Since the structure of HAZ completely changes during fusion welding, pressure welding is one of the solid-phase bonding methods that seems proper for joining UHCSs [8-11]. Therefore, in this study, first we manufactured a fine-grained hypereutectoid steel with thermo-mechanical processes. Second, the possibility of joining of UHCS/40Cr by pressure welding was examined. This included examination of the joining characteristics of UHCS/40Cr welded

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Table 1. Pressure welding parameters used in the present work and ultimate tensile strength.

Specimen No.	Bonding temperature [°C]	Compression strain rate	Tensile strength [Mpa]
P_1	820	0.001	578
P_2	800	0.001	611
P_3	780	0.0005	490
P_4	780	0.001	627
P_5	780	0.01	617
P_6	780	0.1	549

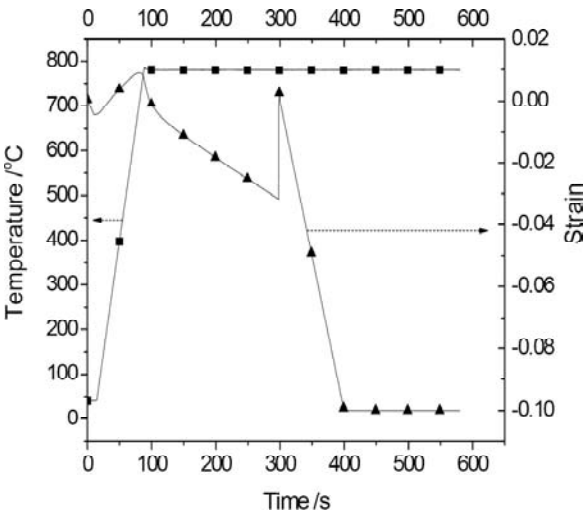

Fig. 1. An example of the welding procedures, T = 780 °C, $\dot{\varepsilon}$ = 0.001 s^{-1}.

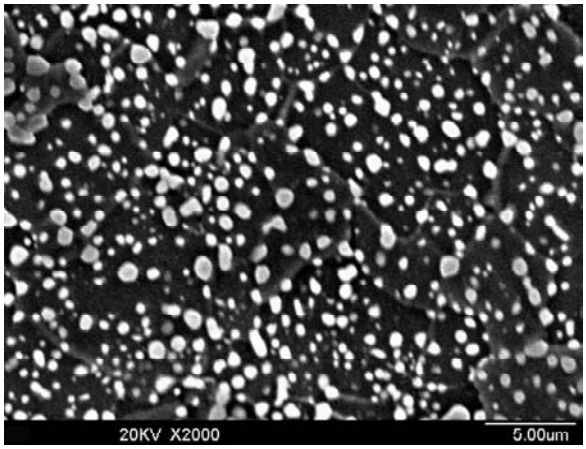

Fig. 2. SEM micrograph of the UHCS-1.4C after spheroidizing at 815 °C / 20 min, 1 C/min cooling to 750 °C, shown carbide particles distributed in ferrite matrix.

joints using different combinations of welding parameters.

2. MATERIALS AND EXPERIMENTAL PROCEDURES

2.1. Materials and specimen preparation

The materials used in this work were a UHCS and a cyclic quenched 40Cr steel. The UHCS was prepared by induction melting and casting into an ingot of 170 mm in diameter and 240 mm in length. The final chemical composition (in wt.%) of the steel was: 1.41C, 1.60Cr, 1.50Al, 0.35Si, 0.42Mn, and the balance Fe (UHCS-1.4C). The ingot was hot-forged into billets of 50×50 mm cross section and then hot-rolled into bars of 18 mm in diameter. The bars employed a controlled cooling divorced eutectoid transformation (CCDET) process, which involves 20 min soaking at 815 °C (slightly above the A_1 temperature), cooling to 750 °C at a rate of 1 °C per minute, and air cooling [12].

2.2. Pressure welding tests

All the pressure welding tests were carried out using a computer controlled thermo-mechanical simulator—Gleeble 1500D. Cylindrical samples of ϕ15×25 mm were prepared from UHCS-1.4C and 40Cr steel bars. The surface preparation of each sample before welding involved grinding to an 800-grit finish, followed by degreasing with acetone, which ensured grease- and dirt-free surfaces. Pressure welds were obtained under different parameter combinations (pressure, bonding temperature, forging rate). The experimental conditions used are summarized in Table 1, with prepressing stress is 56.6 Mpa and total true strain is -0.13. An example of the procedures is given in Fig. 1.

2.3. Examinations

The joints were cut perpendicular to the bond interfaces, using a linear cutting machine, and the cross-sections of these joints were metallographically polished using 2 mm of diamond

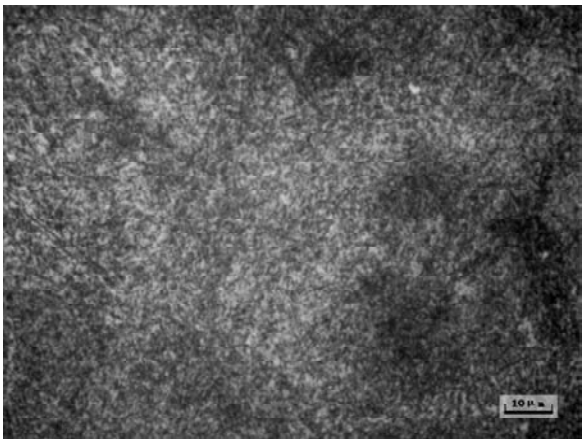

Fig. 3. Optical microstructure of cyclic quenched 40Cr steel shown fine microstructure.

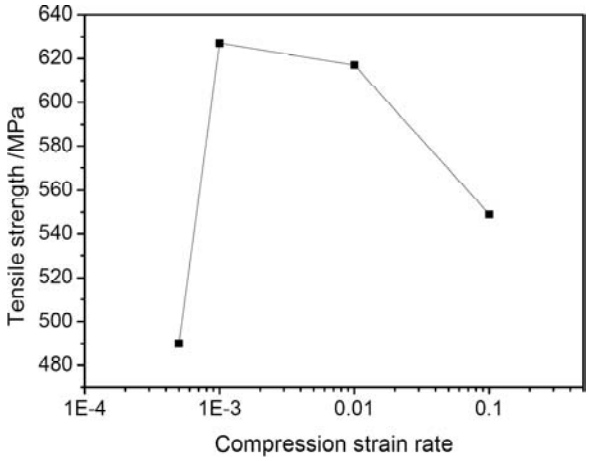

Fig. 4. Ultimate tensile strength *vs.* compression strain rate.

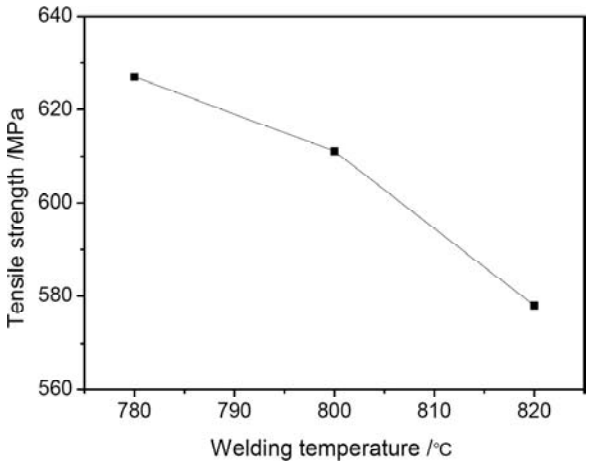

Fig. 5. Ultimate tensile strength *vs.* welding temperature.

paste as final polish and cleaned in an acetone bath. In order to study the microstructure and elemental analysis of the interface zone thus evaluating the quality of the joints, conventional characterization techniques such as scanning electron microscopy (SEM) and tensile tests were employed. Fractography was also employed in the evaluation of the fractured surfaces.

3. RESULTS AND DISCUSSION

3.1. Microstructure

The SEM micrograph of the UHCS-1.4C after hot working and CCDET processing is shown in Fig. 2. The spheroidized ferrite grain size measured by linear-intercept method is 4 to 5 μm. The carbide particals size was 0.3 to 0.7 μm. The carbides at grain boundaries were mainly the undissolved pro-eutectoid cementite and the carbides in the interiors of grains were mainly precipitated during the CCDET processing. The optical microstructure of cyclic quenched 40Cr steel is shown in Fig. 3, a fine microstructure obtained.

3.2.Tensile test results

Results of the cold tensile tests after solid-phase welding are given in Table 1. The results shows that the solid-phase welding of both steels can be carried out under the condition of suitable pressure welding parameter, and the strength of the joint is up to 630 MPa. Ultimate tensile strength of the joint are plotted against the compression strain rate in Fig. 4. The ultimate tensile strengths decreased from 627 Mpa to 549 MPa as increasing compression strain rate from 0.001 to 0.1. On the contrary, the joint obtained by slower compression strain rate, 0.0005, is low strength of 490 MPa. Fig. 5 shows the influence of welding temperature on the ultimate tensile strength of joint. The ultimate tensile strengths decreased from 627 MPa to 578 MPa as welding temperature from 780 °C to 820 °C.

The observation to the welding joint of 40Cr/ UHCS-1.4C demonstrates that welding joint almost without any welding defection can be acquired by adopting proper welding process parameters (Fig. 6a), otherwise the joint area tends to generate welding defection like mechanical bonding area, interface micro-void and so on (Fig. 6b). It can be seen that the carbide contents of the interface between both materials change. The carbide content of 40Cr increases, while that of UHCS-1.4C decreases in the region near the interface. Considering from these result, the carbon in UHCS-1.4C diffuses into 40Cr. Noteworthy is the grain in the UHCS-1.4C steel side near the interfacial zone of joint is still primarily equiaxed after welding. This

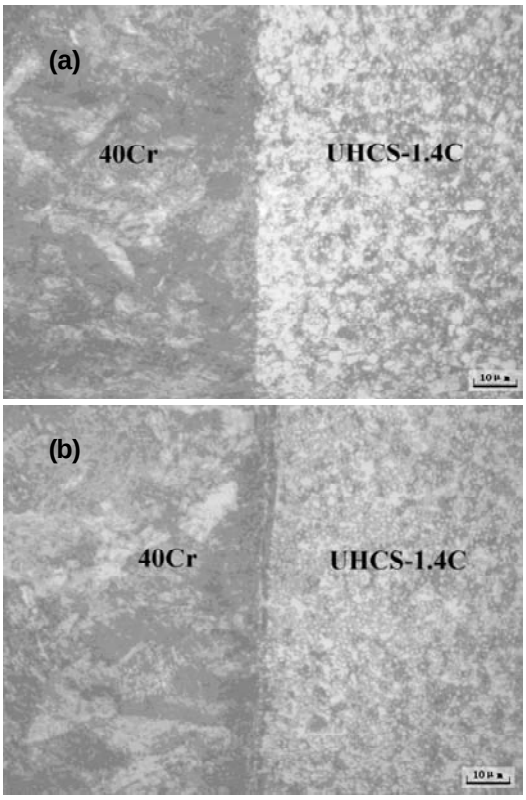

Fig. 6. SEM Photographs of the welded joint zone of 40Cr/UHCS-1.4C, a)Specimen no. P_4; b)Specimen no. P_6.

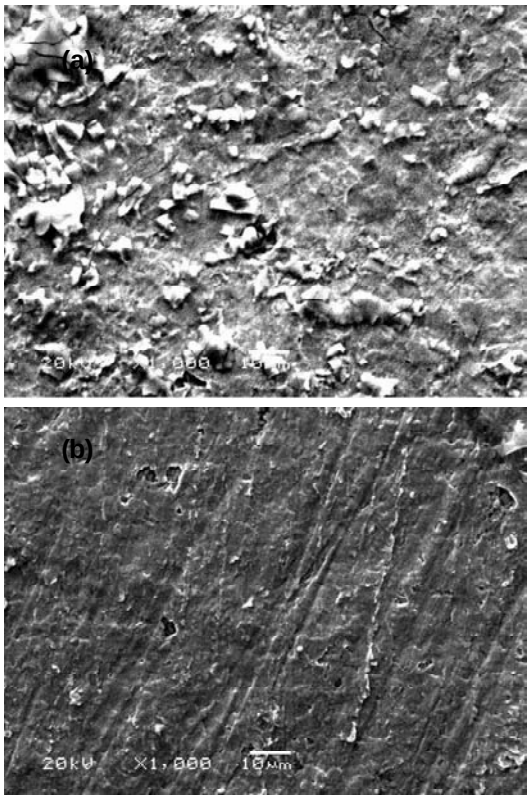

Fig. 7. Fracture surfaces of the welded joints of 40Cr/UHCS-1.4C, a)Specimen no. P_4; b)Specimen no. P_6.

indicates that the UHCS1.4-C will maintain superplasticity and prevent cracking during solide state welding with 40Cr.

Fracture surface near 40Cr steel side of welded joint "P_4" is shown in Fig. 7a. As seen from Fig. 7a, there are a lot of sags and crests in the fracture surface, and little trace of machining (here is grinding trace) in the 40Cr steel surface which is formed by grinding before welding. This means a good metallurgy bonding, and results in high strength. Fig. 7b shows the fracture surface near 40Cr steel side of welded joint "P_6". As seen from Fig. 7b, there are a little traces of machining, sags and crests in the 40Cr steel surface, which means a imperfect metallurgy bonding, and results in low strength.

4. CONCLUSION

The good welding joint of 40Cr with UHCS-1.4C can be obtained by pretreatments and by adopting proper welding process parameters. The ultimate tensile strength of the welded specimen increases with increasing welding time and with decreasing compression rate (in a rage of 10^{-3} – 10^{-1} s^{-1}), and the strength of the joint is up to 630 MPa. The fracture surface of the joints consists of sags and crests, which reveal a metallurgy bonding. Thus, we have confirmed that The UHCS-1.4C can be welded with in a short time using solid-phase welding.

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