Solid-state bonding of superplastic ultra-high carbon steel and structure steel with an interlayer

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Abstract. Solid-state bonding between two superplastic steels—ultra-high carbon steel (UHCS) and a structure steel (commonly referred to as 40Cr in China; yet contains only 1 mass% Cr)—was investigated. Industry-grade pure iron sheet was used as an interlayer and the bonding was carried out at the superplastic deformation temperature $T = 750 \, ^\circ \text{C}$. For a pre-pressing stress of $P = 56.6 \, \text{MPa}$, the initial strain rate was $1.5 \times 10^{-4} \, \text{s}^{-1}$, and for a bonding time of $t = 10\, \text{min}$, the joint tensile strength reached up to 702 MPa, a value 35% higher than what could be obtained without an interlayer. The bonding strength reached the tensile strength of 40Cr base metal through the same thermal-stress cycling. Based on the results, it was concluded that the weldability of 1.6 mass% C-UHCS / 40Cr steel was improved by using a pure iron interlayer.

1. Introduction
Fine-grained ultra-high carbon steel (UHCS) has excellent mechanical properties such as high strength, hardness and wear resistance. It can be hopefully developed as a novel resource-saving and economical engineering material. However, the presence of large volume of carbide and several alloying elements adversely affect its weldability through normal fusion welding methods, thus greatly restricting its application [1, 2].

Fine-grained superplastic materials can be readily bonded in the solid state [3, 4]. By taking advantages of the superplasticity, great progress has been made in the field of solid-state bonding of materials with poor weldability [5, 6]. However, the relatively low deformability and the issue of harmful eutectic structure at the bonding interface due to the alloying elements, prevent obtaining high-quality joints [2, 7, 8]. Developing an effective approach for bonding such a material with poor weldability is, therefore, imperative.

In this study, an appropriate interlayer material was designed for solid-state bonding of superplastic UHCS and a structure steel. The effect of the interlayer on the interfacial behaviour was investigated. This novel diffusion bonding method, based on the superplasticity and the use of an interlayer, is discussed.

2. Interlayer design
The use of an appropriate interlayer material is necessary for obtaining better joints. Previous studies on diffusion bonding of UHCS have elucidated the associated problems that seriously affect the
bonding quality, as characterized by the low bonding ratio caused by the poor deformability and the presence of harmful eutectic microstructure at the interface.

The first consideration for a material to be used as an interlayer for solid-state bonding of UHCS is that it should be an iron-based material in order to match the base metals. Then, it should have low yield strength to facilitate interfacial deformation at both bonding interfaces. Additionally, it also should have only a few alloy elements to prevent the enrichment of alloy element and avoid the formation of detrimental low-melting eutectic structure at the bonding interface. Based on these criteria, industry-grade pure iron was selected as the interlayer material for the present study.

3. Experimental
The materials used in the present study were 1.6 mass% C-UHCS and the structure steel 40Cr, which contains 1 mass% Cr (40Cr is the standard nomenclature for such a steel in China). The chemical compositions are shown in Table 1. The 1.6 mass% C-UHCS was manufactured via vacuum melting, hot rolling, and a spheroidizing treatment in that order, and was comprised of fine globular cementite and ferrite. The 40Cr steel, obtained via two quenching in salt bath at 820°C followed by a low-temperature tempering treatment at 200°C, consisted of small lath martensite. Both fine-grained steels could show good superplasticity. As the interlayer is required to be as thin as possible, a sheet of pure iron was rolled to a thickness of 50 μm. The microstructure of the steels and the interlayer were as shown in Figure 1. The 1.6 mass% C-UHCS and 40Cr steel were machined into φ15×25 mm samples.

The bonding faces of the samples and the interlayer sheet were polished and cleaned with acetone. The interlayer was placed between the 1.6 mass% C-UHCS and 40Cr steel samples. Bonding tests were carried out under ambient conditions without any vacuum or gas protection. The bonding temperature T was 750°C, the best superplastic deformation temperature of 40Cr steel. The UHCS was capable of exhibiting superplasticity well at this temperature [2, 5, 6]. The pre-pressing stress was 56.6MPa to have an intimate interfacial contact in the initial bonding stage. After a pre-pressing time of 20 minutes, the samples were bonded under a constant compression speed (initial strain rate $\dot{\varepsilon}_0 = 1.5 \times 10^{-4}$s$^{-1}$) for several values of bonding time t.

| Steel    | Fe | C  | Si  | Mn | Cr  | Al  | S   | P   | Nb  | V   | Ti   |
|----------|----|----|-----|----|-----|-----|-----|-----|-----|-----|------|
| UHCS     | Bal.| 1.60 | 0.49 | 0.44 | 1.54 | 1.66 | 0.0075 | 0.012 | 0.021 | 0.043 | 0.082 |
| 40Cr     | Bal.| 0.40 | 0.25 | 0.6 | 1.0 | -   | -   | -   | -   | -   | -    |
| Pure iron| Bal.| 0.02 | 0.008 | 0.02 | 0.01 | -   | 0.005 | 0.007 | -   | -   | -    |

**Figure 1.** Microstructures of fine-grained steels and pure iron interlayer. (a) globular pearlite in 1.6 mass% C-UHCS. (b) martensite in 40Cr steel. (c) cold-rolled microstructure of the pure iron interlayer.
The joint was machined into $15 \times 5 \times 3 \text{mm}$ tensile sample. The tensile test was performed at a crosshead speed of 0.3 mm/min at room temperature to evaluate the mechanical properties of joint. The microstructures and the fractures of joints were observed by scanning electron microscopy (SEM). The contents of alloying elements were analyzed by energy dispersion spectrum (EDS).

4. Results and discussion

Figure 2 shows the bonding strength of 1.6 mass%C-UHCS joints, depending on bonding time $t$ for the two cases of bonding with and without an interlayer ($\dot{\varepsilon}_0 = 1.5 \times 10^4 \text{s}^{-1}$, $T = 750 \degree \text{C}$). As seen in Figure 2, the joints with the pure iron interlayer exhibit higher strength than the direct bonding joints for the same bonding condition.

For direct bonding, the joint strength increased with bonding time and reached a maximum when the bonding time was 15min. As the bonding time increased further, harmful interfacial diffusion intensified, thus reducing the bonding strength [8]. By comparison, when bonding time was 10min, the maximal strength of joints with the pure iron interlayer reached 702 MPa, which is 35% higher than that of the directly bonded joints. The bonding strength can potentially reach the strength of base metal, which is the 40Cr steel, when it undergoes the same thermal cycle. As the bonding time increased further, the bonding strength reduced slightly due to grain growth and the deterioration in the microstructure of the interlayer. The pure iron interlayer significantly improved the bonding strength and high-quality joints were obtained with relatively short bonding times. These results are consistent with what was expected. The interlayer design and bonding method for superplastic 1.6 mass%C-UHCS are experimentally proved effective.

Figure 3 shows the microstructure of joints obtained through direct bonding and bonding with the interlayer. As shown in Figure 3(a), many voids are observed at the bonding interface. In contrast, there are few defects at both the bonding interfaces, as shown in Figure 3(b).

In the case of direct bonding, the unbonded areas are caused by the low deformability of the 1.6 mass%C-UHCS. Although the superplastic deformation of base metals contributes somewhat to the interfacial contact, the bonding time is relatively too short to obtain a high bonding ratio for UHCS. However, the bonding strength cannot be improved by just extending the bonding time, for the consequent excessively harmful interfacial reactions can also seriously affect bonding quality. Using a low-yield-strength interlayer affords acceptable joining between the interlayer and the both base metals. Interlayer thickness is about 40 μm after bonding, and a distinct deformation occurs in the pure iron interlayer. This deformation significantly facilitates interfacial contact with both the base metals, thus increasing the bonding ratio.

![Figure 2](image-url)  
**Figure 2.** Bonding strength dependence of $t$ ($\dot{\varepsilon}_0 = 1.5 \times 10^4 \text{s}^{-1}$, $T = 750 \degree \text{C}$).
The cold-rolled microstructure of the pure iron interlayer is easily recrystallized during bonding. The concentration gradient between the interfaces makes carbon diffuse from base metals into pure iron interlayer, and consequently, the microstructure and mechanical properties of interlayer are improved as the carbon content increases. High-quality joints of UHCS / pure iron / 40Cr are thus achieved. However, extending the bonding time causes grain growth in the interlayer, resulting in the deterioration of the joint microstructure, and as a result, the bonding strength reduces. This is also reflected in the bonding results in Figure 2.

The fractures of bonding joints, for both the cases of direct bonding and bonding with an interlayer, are shown in Figure 4. As seen in Figure 4(a), numerous intergranular cracks (Figure 4(a) A) can be observed at the interface with 40Cr. EDS analysis shows that alloying element enrichment of Al (1.19 wt%), Si (0.74 wt%) exists in the cracks. The interface and grain boundary are rich in Al, Si because they act as passages for interdiffusion. These cracks are formed near the interface owing to the formation of low-melting phase or eutectic structure under deformation stress and inner stress. Original grinding traces (Figure 4(b) A) and a few metallurgical bonded areas (Figure 4(b) B) can be observed on the UHCS side. The low bonding ratio and the numerous bonding defects seriously reduce the joint strength.

Figure 4(c), (d) shows the fractures of 1.6mass%C-UHCS / pure iron / 40Cr joint. Fracture occurs in the interlayer along the interface and also in some regions of the UHCS base metal (Figure 4(d) A). Pure iron interlayer enhanced interfacial contact, thus causing a significant increase in metallurgically bonded areas (Figure 4(c) A). The fractures in some areas of base metal are also consistent with the results from tensile testing of joints.

Figure 5 shows the distribution of alloying elements in the 1.6 mass%C-UHCS / pure iron / 40Cr joint. The interdiffusion of alloying elements clearly occurs at both interfaces. The Al and Cr content of the interlayer are far below those of base metals. A pure iron interlayer prevents the direct interdiffusion between UHCS and 40Cr, thus preventing the enrichment of the alloying elements, especially those responsible for low-melting-structure (phase)-forming elements. This transition region greatly reduces the formation possibility of harmful structures, and therefore, the excessive interfacial reaction is avoided. No intergranular cracks were observed at the interfaces after bonding with an interlayer. This result is well evidenced by Figure 4. In general, a pure iron interlayer can thus enhance the weldability of superplastic 1.6 mass%C-UHCS.
5. Conclusions

A pure iron interlayer facilitates proper interfacial contact during solid-state bonding of 1.6 mass% C-UHCS and 40Cr steel, reduces required bonding time, and prevents direct interfacial reaction of base metals, thereby preventing the formation of detrimental eutectic phase and structures in the joint. All these contribute to improving joint quality. A pure iron interlayer can be useful in solid-state bonding of dissimilar superplastic steels.
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References
[1] Furuhara T, Yamaguchi J, Maki T 2004 Iron Steel Institute Japan. 17 356
[2] Zhang ZL, Liu YL, Zhu JW, Yu G 2008 Mater. Sci. Eng. 483-484 64
[3] Maehara Y, Langdon T.G 1990 Mater. Sci. Eng. 128 1
[4] Nieh T.G 1997 Superplasticity in metals and ceramics (New York: Cambridge University Press)
[5] Zhang KK, Sun J, Wu ZW, Ma L, Qiu RF, Zhang ZL 2011 Transactions of the China Welding Institution. 32 5
[6] Zhang KK, Yang YL, Wang CS, Li HK, Xue J 2001 J. Mater. Sci Technol. 17 189
[7] Zhang KK, Yue Y, Zhang ZL 2010 Materials Science Forum. 287 177
[8] Zhang KK 2011 The national natural science funding project concluding report-Grant No. 50774029 (Beijing: National Natural Science Foundation of China)