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Stainless steel lined composite steel pipe prepared by centrifugal-SHS process

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The tension properties, thermal expansion coefficient, microstructure and the causes of crack formation of the stainless steel layer in the composite pipe made by centrifugal-SHS process were investigated. It was shown that the tensile strength is 316 MPa and the percentage elongation is 5–8%. The nonmetal inclusions make the stainless steel brittle. In the brittle stainless steel layer the crack is caused by the thermal stress. The stainless steel mainly composed of austenite phase which grows in columnar grain in the radial direction of a carbon steel pipe and a thin ferrite layer was distributed between the austenite phases. The intermetallic compound AlNi precipitates in the ferrite phase and sigma-phase precipitates at the phase boundarie between the austenite and ferrite. © *2000 Kluwer Academic Publishers*

1. Introduction
Centrifugal-thermit (C-T) process, which can be called as centrifugal Self-propagating High-temperature Synthesis (centrifugal-SHS) also, has been employed to make ceramic lined composite steel pipes [1–3]. Recently, a type of stainless steel lined composite pipe has been explored using same technique [4, 5]. The stainless steel layer lined shows a characteristic of ultra-low carbon, since content of carbon in raw powders is very low. Good corrosion resistance could be achieved. With considering low cost, the stainless steel lined composite pipe should find wide use in chemical industry as well as in metallurgy and petroleum industry.

Requirements for producing a perfect such composite steel pipe include composition adjustments of stainless steel line and elimination of microstructure defects such as porosity, inclusions and cracking. In this paper, an improved mechanical property by chemical composition control of stainless steel melts is presented. Microstructure of the composite steel pipe has been investigated. Possibility of cracking formation is discussed and method of eliminating cracking is given.

2. Experimental
A thermit powder mixture was prepared by blending Al, Fe_2O_3, Cr_2O_3, CrO_3 and NiO powders, which were weighted according to following chemical reaction Equations 1 to 4. In order to improve fluidity of molten steel a certain amount of CaF_2 powder was used.

$$Fe_2O_3 + 2Al = 2Fe + Al_2O_3 + 836\ \mathrm{kJ} \quad (1)$$
$$Cr_2O_3 + 2Al = 2Cr + Al_2O_3 + 530\ \mathrm{kJ} \quad (2)$$
$$CrO_3 + 2Al = Cr + Al_2O_3 + 1094\ \mathrm{kJ} \quad (3)$$
$$3NiO + 2Al = 3Ni + Al_2O_3 + 928\ \mathrm{kJ} \quad (4)$$

A low carbon steel pipe with an outer diameter of 76 mm and wall thickness of 4 mm and a length of 100 mm was mounted on a centrifuge machine. The low carbon steel pipe was loaded the thermit powder mixture, which was immediately ignited by a tungsten filament, once a given rotation velocity of the centrifuge machine was reached. Combustion reactions shown as the Equations 1 to 4 occurred. During the reactions, all the oxides were reduced by molten Al, resulting in formation of metal Fe, Cr, Ni and alumina. Combustion temperature was so high that all reacted products became liquid state. By means of the centrifugal force field, the liquid state metals of Fe, Cr, Ni with a density higher than that of alumina and other additives went to the inner surface of the low carbon steel pipe. They formed stainless steel lined layer with a normal composition of 12–14%Cr, 14–16%Ni, 70–74%Fe. Slag layer contained alumina, meanwhile, was far away the inner surface of the low carbon steel pipe and covered the stainless steel lined layer due to their low densities. Tensile strength and 0.2% yield stress of the resultant stainless steel lined layer was examined using Material Test System (MTS). Thermal expansion curves of both the stainless steel lined layer and the low carbon steel pipe were characterized by GLEEBLE Thermal Stress-Strain Simulator Fracture morphology and microstructure of the stainless steel lined layer were observed by means of scanning electron microscope (SEM) and transmission electron microscope (TEM).

3. Results and discussion
3.1. Microstructure
The micrographs of the cross section of the stainless steel layer are shown in Fig. 1. The measured thickness of the stainless steel layer was about 1.5 mm. The grains

of the stainless steel grow in columnar grains in the radial direction because the temperature gradient occurs in the radial direction predominantly during cooling. Thus the stainless steel grains grow fastest in the radial direction. This leads to the formation of the columnar grains.

Fig. 1b shows that there are some dendritic grains between the columnar grains. They are austenite phase mainly, characterized by TEM. At the grain boundary of austenite phase, a thin ferrite layer can be observed with TEM.

Fig. 2a,b show dislocation structures of the stainless steel layer caused by the thermal stress. In the austenite region, dislocation lines are flat, whereas in the ferrite region, some dislocation loops appear, in which exists precipitating phase of NiAl. The orientation relationship between the precipitate and ferrite matrix have

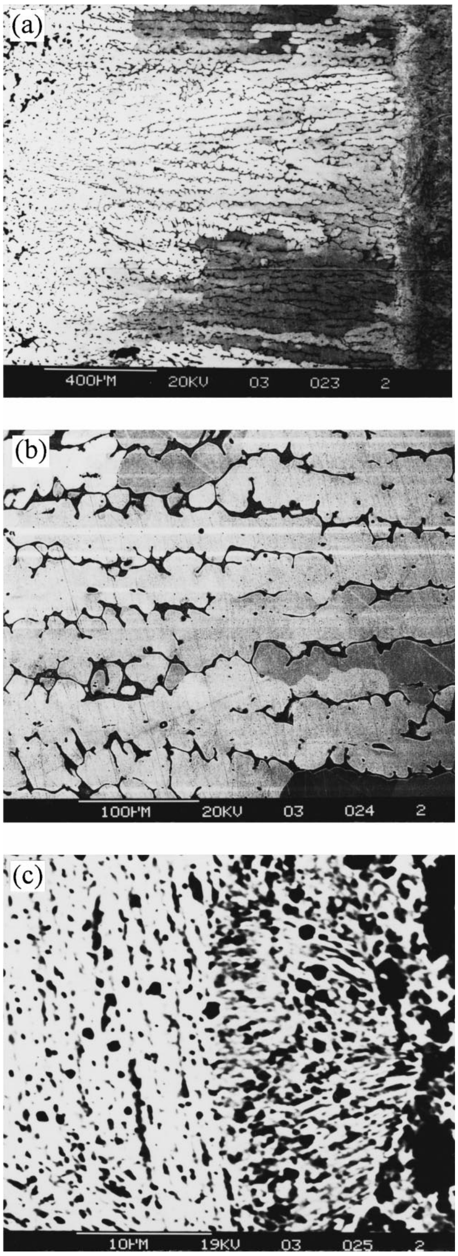


Figure 1 SEM back-scattered electron image of stainless steel layer. (a) Cross-section of the composite pipe, the left is stainless steel and the right is carbon steel, (b) the columnar crystal region, (c) the transition region between the stainless steel and the carbon steel matrix.

been determined to be

$$(110)_{\mathrm{AlNi}}//(110)_{\alpha-\mathrm{Fe}}$$
$$[001]_{\mathrm{AlNi}}//[002]_{\alpha-\mathrm{Fe}}$$

The sigma-phase (FeCr) precipitates at the phase boundary between the austenite and the ferrite as shown as Fig. 2c. The sigma-phase has a simple tetragonal lattice structure with the lattice parameter of $a = 0.8799$ nm, $c = 0.4556$ nm. The orientation relationship between the sigma phase and the ferrite phase is

$$(110)_{\sigma}//(110)_{\alpha-\mathrm{Fe}}$$
$$[002]_{\sigma}//[002]_{\alpha-\mathrm{Fe}}$$

The sigma-phase is often found in conventional casting stainless steel, such as 18/8 Cr-Ni and 18/8 Cr-Ni-Ti casting steel. Their grain sizes are larger, for example, in the 18/8 Cr-Ni casting steel, the grain size of the sigma-phase was 6.25 μm [6]. In the present stainless steel, however, the grain size of the sigma-phase is only 0.25 μm. In general, the sigma phase at grain boundaries can cause chromium impoverishment and loss of corrosion resistance. Smaller sizes of sigma phases may reduce consumption of chromium. The content of chromium near grain boundary may be higher comparing with the case of conventional casting stainless steel. Corrosion resistance of the stainless steel layer may be improved.

A transition region with a width of 10 μm, which consists of plate-type martensite, is observed between the stainless steel layer and the carbon steel matrix (Fig. 1c, Fig. 2d). The compositions of the transition region and carbon steel matrix are given in the Table I and Table II. The reason for forming the transition region is that the thin layer of the molten stainless steel which contact the carbon steel was diluted by the dissolution of carbon steel, the contents of alloying elements such as Cr, Ni are reduced, so that the Ms temperature is increased. The thin stainless steel layer transformed from austenite into martensite in the cooling process. On the other hand, the formation of the martensite transition region might be related to the thermal stress in the stainless steel layer, which accelerated the martensitic transformation and increased the Ms temperature.

3.2. Cracking of stainless steel layer

The Fig. 3 shows the thermal expand curves of the stainless steel and the carbon steel matrix. The thermal

TABLE I Composition of the transition region

Elements	Al	Si	Cr	Fe	Ni	Cu
Atom (%)	4.209	2.916	7.480	79.445	4.289	1.660

TABLE II Composition of the carbon steel matrix

Elements	Al	Si	Cr	Fe	Ni	Cu
Atom (%)	1.103	0.536	0.620	96.336	0.000	1.405

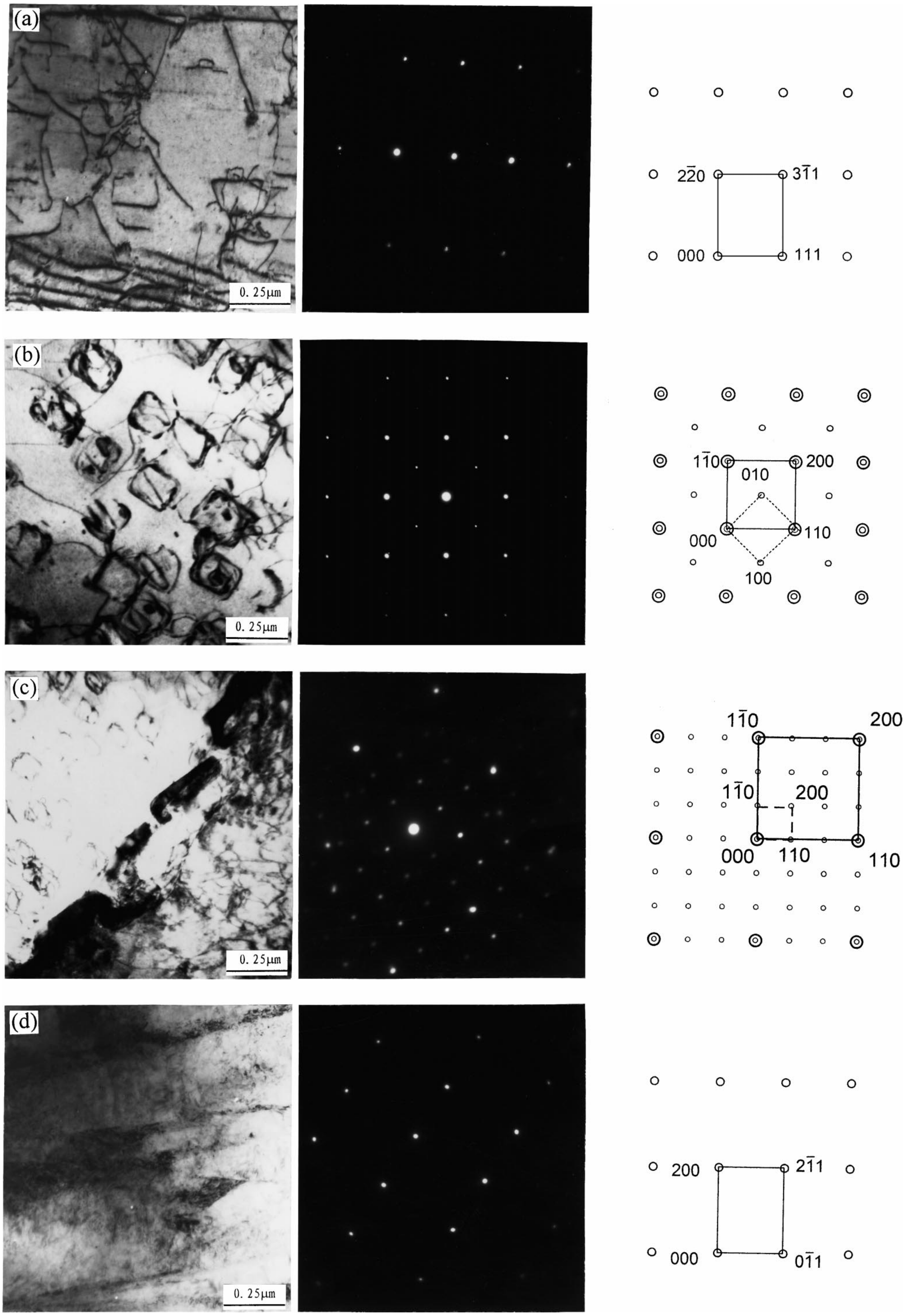


Figure 2 TEM micrograph and electron diffraction pattern of stainless steel layer (a) Austenite(γ-Fe), (b) Ferrite(α-Fe) + AlNi, (c) The precipitating phase (σ phase) at phase boundaries (d) Martenzite in transition region.

expansion coefficient can be calculated from the following formulae with $\Delta l = l \cdot \alpha \cdot \Delta T$ and $\varepsilon = \Delta l / l$

$$\alpha = \frac{\varepsilon}{\Delta T} \tag{5}$$

where l is the length of the test sample of the stainless steel or the carbon steel, Δl is the variation in the lengths of samples, ΔT is the intervals of temperature and ε is the strain. The calculated thermal expansion coefficients of the stainless steel and carbon steel are $23.61 \times 10^{-6}\ \mathrm{K}^{-1}$ and $13.48 \times 10^{-6}\ \mathrm{K}^{-1}$, respectively. It is obvious that the thermal expansion coefficient of the stainless steel is higher that of the carbon steel. Therefore, the stainless steel layer contracts much more

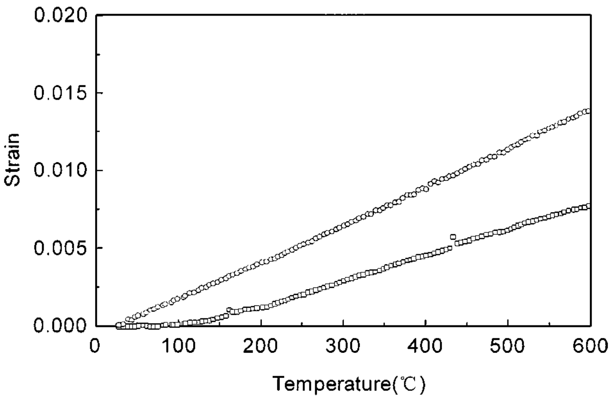
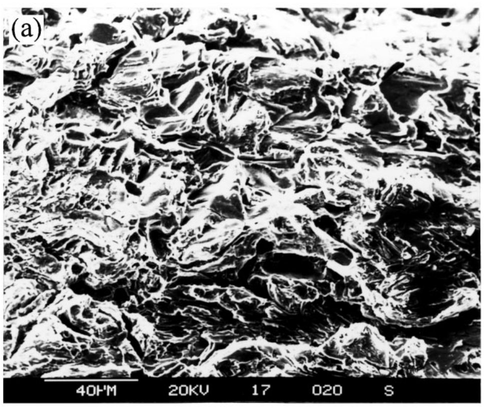


Figure 3 Thermal expand curve of the stainless steel and carbon steel (□-carbon steel, ○-stainless steel).

than the ceramic layer and the carbon steel during cooling, resulting in the tensile stress remaining in the stainless steel layer.

The calculated tensile stress is 513 MPa which is above the tensile strength of the stainless steel layer, so that the thermal stress is high enough to cause the stainless steel layer to crack if it would not be relaxed by plastic deformation [4]. Besides, if the partition of the ceramic and metal was not completed, the ceramic (Al_2O_3) would remain in the stainless steel as brittle inclusions, which would decrease plasticity of the steel and cause stress concentration and brittle fracture (Fig. 2a). The formation of the inclusions has a bearing on characteristics of the C-T process. As well known, in the process of conventional centrifugal casting, the duration of slag making are sufficient to remove



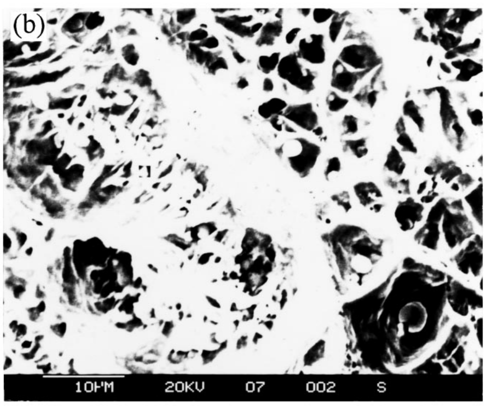


Figure 4 Fracture micrograph of the stainless steel layer.

TABLE III Mechanical properties of stainless steel layer

Materials	Tensile strength (MPa)	0.2% proof stress (MPa)	Elongation (%)
Before improvement	501	—	0
After improvement	316	265	5–8

the inclusions. In the C-T process, however, the molten products are fast produced lasting only 10–60 s. There is no enough time to allow oxide inclusions to remove out off molten steel. It is necessary to prolong the duration of molten products and to increase the fluidity that facilitates the partition of metal and ceramic. The present experiments show that the time for keeping liquid state of molten products could be increased by preheating the carbon steel pipe before C-T process. In addition, improved the fluidity of the molten products by introducing CaF_2 into thermit is helpful to reducing the inclusions. The CaF_2 also acted as desulphurzer and dephosphorizer. After the improvement of process, the inclusions in the stainless steel were significantly reduced. The elongation of the stainless steel layer was increased from 0% to 5–8% and the crack is not observed in the plastic stainless steel. Fig. 4b is fracture micrograph of tensile tested specimens. There are a lot of dimples on the fracture surface which is the characteristic of toughness fracture. The improved mechanical properties of the stainless steel are given in Table III. Obviously, the stainless steel was changed from brittle material to plastic.

4. Conclusions

1. The stainless steel layer produced by C-T process mainly composed of austenite phase which grows in columnar grains. A thin ferrite layer is distributed at the boundary region of the austenite grains.

2. The intermetallic compound AlNi precipitates in the ferrite phase and sigma-phase precipitates at the phase boundaries between austenite and ferrite. A martensitic transition region exists between the stainless steel layer and carbon steel matrix.

3. The crack in the stainless steel layer can be avoided by reducing inclusions in the stainless steel layer and increasing its plasticity.

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