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Influence of Co and Al on pearlitic transformation in super bainitic steels

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Abstract

The effect of cobalt and aluminium on the austenite-to-pearlite transformation in a super-bainitic steel was investigated. The experimental work showed that the transformation rate of pearlitic and the volume fraction of pearlite both were increased by adding about 4 wt. % Co and 1.5 wt. % Al to the parent super-bainitic steel. The addition of cobalt and aluminium to super-bainitic steels desirably accelerated the growth rate of pearlitic microstructure, and undesirably reduced the interlamellar spacing of pearlite; resulting in a hardness higher than that of the parent steel in the pearlitic condition. Nevertheless, the accelerated pearlitic reaction, as a softening process of the super-bainitic steels prior to machining/forming, may make the commercial use of these steels more viable.

Introduction

Various high strength steels with extremely fine carbide-free bainitic structure (super bainite) have been developed in the recent years [1-6]. The super-bainitic microstructure is normally obtained by the isothermal transformation at temperatures in the range of 200 to 300 °C. Due to the low temperature transformation, it may take up to several days to achieve a fully bainitic microstructure [3-7]. Such a lengthy thermal cycle restricts the industrial application of these steels severely. Previous work showed that the addition of Co and Al accelerates the bainitic transformation and hence shortens the austenite-to-bainite transformation time [8].

Another drawback in the commercial use of super-bainitic steels is their poor machinability and formability. The hardness of fully hardened super-bainitic steels can reach up to 700 HV, depending on the microstructures of nano-size bainitic ferrite laths (20~65 nm) and amount of retained austenite [2-3]. Clearly, such a high hardness makes machining and/or forming the super-bainitic steels extremely difficult. Therefore, a softer microstructure (e.g. pearlite) is desirable prior to machining, followed by a suitable heat-treatment to restore the bainitic microstructure in the final component. The effect of cobalt and aluminum on the rate of pearlitic transformation and final microstructure of a re-austenitised bainitic steel was investigated in this work.

Experimental

Two bainitic steels one with and the other without addition of 3.87 wt. % Co and 1.37wt. % Al were prepared by vacuum induction remelting method. Table 1 shows the chemical composition of these steels. After homogenisation at 1200 °C for 48 h in a sealed quartz tube containing pure argon, the samples were air-cooled. All samples were austenitized at 1000 °C with a holding time of 30 min,

followed by the isothermal transformation at temperatures between 500 and 700 °C for different times before being quenched in water.

A number of metallographic samples were ground and polished using the standard techniques and etched in 4 vol.% nital solution. Optical microscopy and scanning electron microscopy (SEM) were used to examine the microstructures. The volume fraction of pearlite (f_V) was measured by *the standard point-counting technique* [9]. The interlamellar spacing of pearlite was measured by *circular test line method* [10]. The mean true spacing (σ_0) was calculated from the mean random spacing (σ_r) using the equation $\sigma_0 = 0.5\sigma_r$ [11]. Ten Vickers hardness tests and ten measurements of the interlamellar spacing were conducted on each sample and the corresponding average values are reported in this work.

Results and discussion

The optical and SEM micrographs of pearlitic microstructure of two alloys both isothermally transformed at 650 °C for 1 hr are shown in Fig. 1. Alloy 1 (containing Co and Al) has a fully pearlitic microstructure whereas the parent Alloy 2 consists of both pearlitic and martensitic grains. The presence of martensite in Alloy 2 proves the sample had contained some austenite before it was quenched, hence, the pearlitic transformation was not completed within 1 hr at 650 °C. The microstructures of the same alloys, isothermally transformed at 650 °C but within much shorter times are shown in Fig. 2. It is clear that the pearlitic transformation of Alloy 1 started in less than 180 s (Fig. 2a) whereas pearlite is absent in Alloy 2 even after a 600 s holding time (Fig. 2b). When Alloys 1 and 2 were held at a higher temperature and for a longer time (700 °C for 5 h), a visible amount of pearlite was observed in Alloy 1 - see Figs. 3a and 3b. However, the pearlitic

transformation did not commence in the parent Alloy 2 which can be judged by the presence of allotriomorphic ferrite and a large amount of martensite - see Figs. 3c and 3d.

Fig. 4 shows that the volume fraction of pearlite increased with increasing the isothermal transformation temperature in the range of 500 to 650 $^{\circ}$C for both alloys, and the rate of transformation was higher for Alloy 1 containing Co and Al than in the parent Alloy 2. As expected from the transformation rates of Alloys 1 and 2, the interlamellar spacing of Alloy 1 was much smaller than that of the parent Alloy 2, i.e. 62 and 134 nm respectively - see Fig. 5. The results of the hardness tests and interlamellar spacing measurements, shown in Fig. 6, are consistent with the observed microstructures of Alloy 1 and Alloy 2. For instance, Alloy 1 with a smaller lamellar spacing had a higher hardness than the parent Alloy 2 (i.e. 450 as to 378 HV1 with the same transformation temperature of 600 °C). Using a higher transformation temperature (i.e. 650 °C) reduced the hardness of both steels (356 and 321 HV1). It is expected that the hardness varied linearly with the reciprocal of interlamellar spacing.

The outcome of calculated TTT curves using *MUCG 83.Mod* software [12] is consistent with the experimental results, confirming the effect of Co and Al on the starting and ending times of the pearlitic transformation in bainitic steels. Capdevila et al. used a neural network model to assess the effect of various alloying elements on the interlamellar spacing of pearlite [13]. The model which was based on Takahashi equation [14] showed that the austenite-stabilising elements such as Mn and Ni increase the interlamellar spacing of pearlite. Both aluminium and cobalt increase the free energy change on the transformation from austenite to ferrite, so these elements are "ferrite stabilisers" and hence expected to reduce the interlamellar spacing of pearlite. In other words, the presence of Co

and Al destabilises super-cooled austenite, and thus shortens the starting time of the pearlite transformation. Fig. 7 shows that the addition of Co and Al shifts the C-curve to the left in the TTT-diagram and also reduced the transformation temperature range [15].

It was concluded that the addition of Co and Al to a super-bainitic steel can substantially accelerate the pearlitic transformation leading to a smaller interlamellar spacing and higher hardness than that of the parent alloy in fully pearlitic condition (35 to 70 HV1 harder than the parent alloy in pearlitic condition depending on the transformation temperature). In summary, the addition of Co and Al would be a "trade-off" process, i.e. having a faster reaction at the expense of slightly higher hardness. Substantial reduction in the hardness of super-bainitc steels by pearlitic transformation (e.g. from 700 HV down to 320 HV) would clearly facilitate machining and forming of these steels.

Conclusions

The pearlite isothermal transformation in a super-bainitic steel at the temperatures between 500 to 700°C was investigated and the following conclusions were made:

(1) The volume fraction of transformed pearlite in a super-bainitic steel containing Co and Al was larger than that of the parent steel. It is clear that the addition of Co and Al to the bainitic steel accelerated austenite-to-pearlite isothermal transformation.

(2) A fine pearlitic microstructure was obtained during the isothermal transformation for the alloy containing Co and Al and the interlamellar spacing of pearlite was considerably reduced compared to the parent alloy without Co and Al. Expectedly, the hardness of the Co/Al containing steel was higher than that of the parent steel (e.g. about 35 in Vickers scale when transforming at 650°C).

(3) Substantial increase in the transformation rate of austenite to pearlite (as a pre-machining softening process) by addition of Co and Al is desirable but it comes at the cost of increasing the hardness. The use of Co/Al containing bainitic steels may prove beneficial depending on the size/shape of the final products and manufacturing process.

Acknowledgements

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**Table 1** Chemical composition of investigated alloys, wt.%

| Alloy	C	Si	Mn	Mo	Cr	Co	Al	P	S	V	Ni
1	0.78	1.60	2.02	0.24	1.01	3.87	1.37	0.002	0.002	–	–
2	0.79	1.59	1.94	0.30	1.33	–	0.013	<0.002	–	0.11	0.02
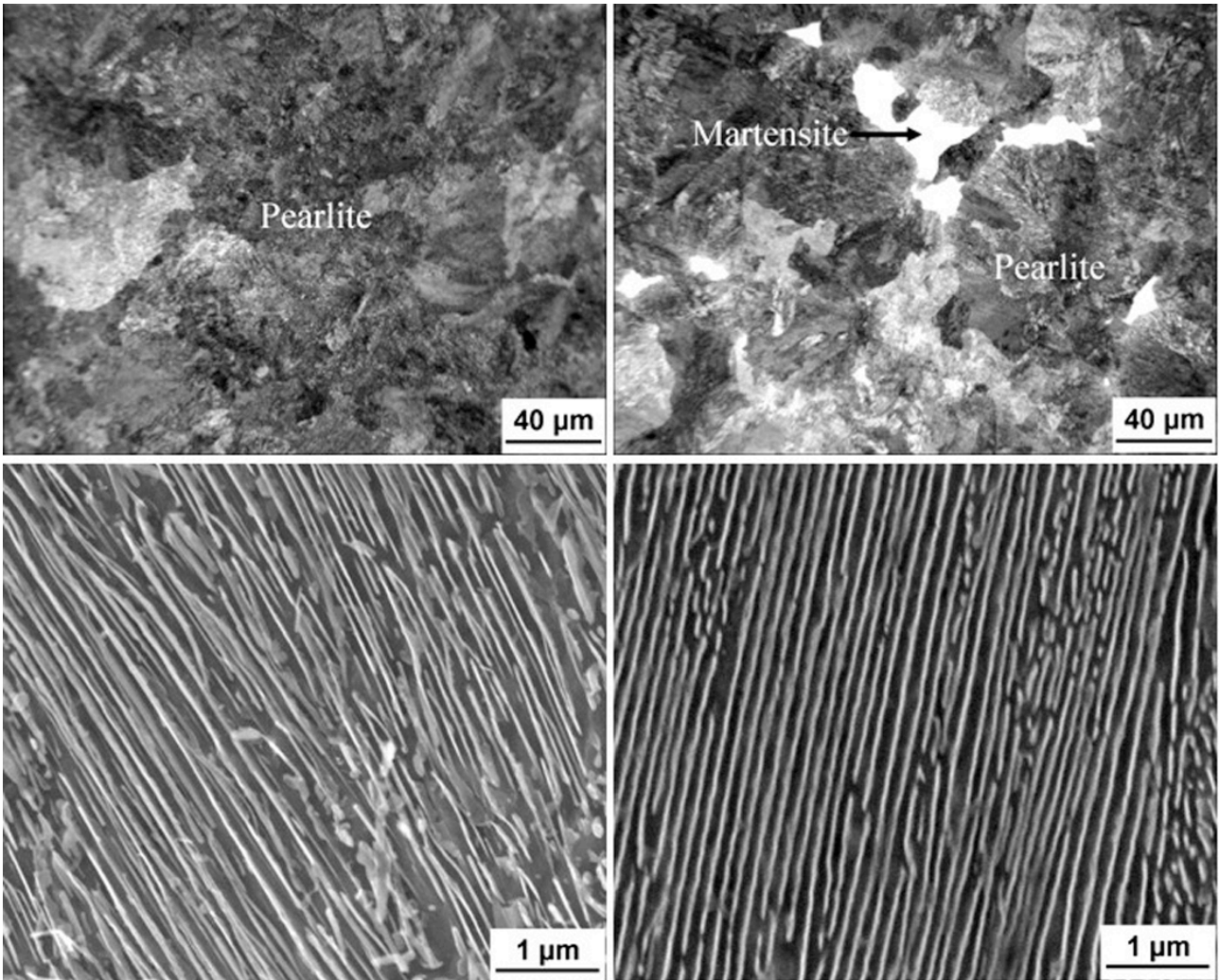
1　Optical (top) and SEM (bottom) micrographs of Alloy 1 containing Co/Al (left) and the parent steel Alloy 2 without Co+Al (right) after isothermal transformation at 650 °C for 1 h. Alloy 1 is fully pearlitic and its interlamellar spacing is considerably smaller than that of the parent Alloy 2.
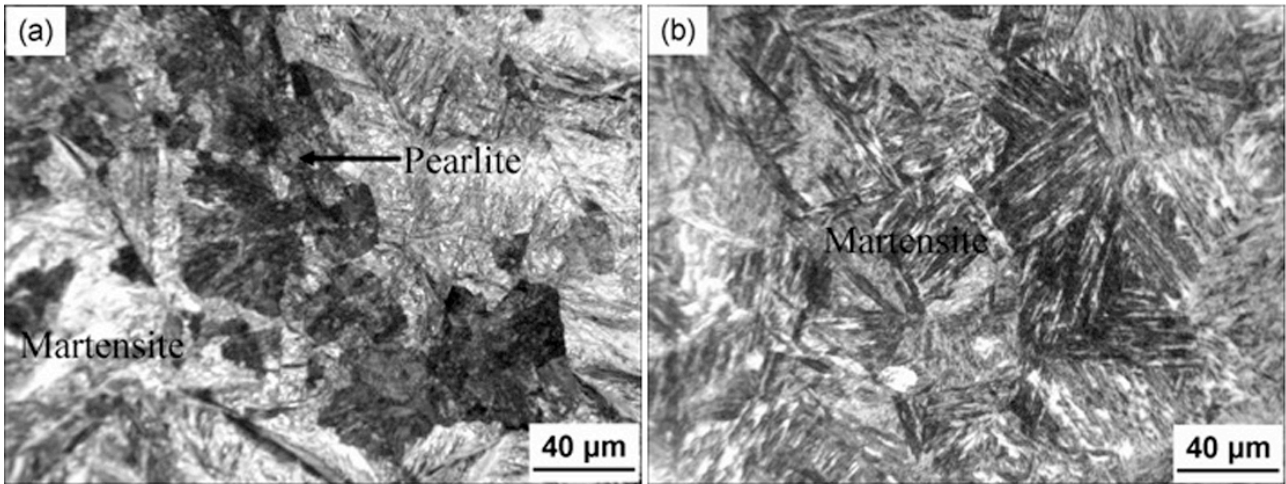
2 Optical micrographs show isothermal transformation of Alloy 1 containing Co and Al (a) resulted in pearlite formation within 180 s whereas pearlite is still absent in parent Alloy 2 (b) despite using much longer time of 600 s (transformation temperature was 650 °C for both alloys).
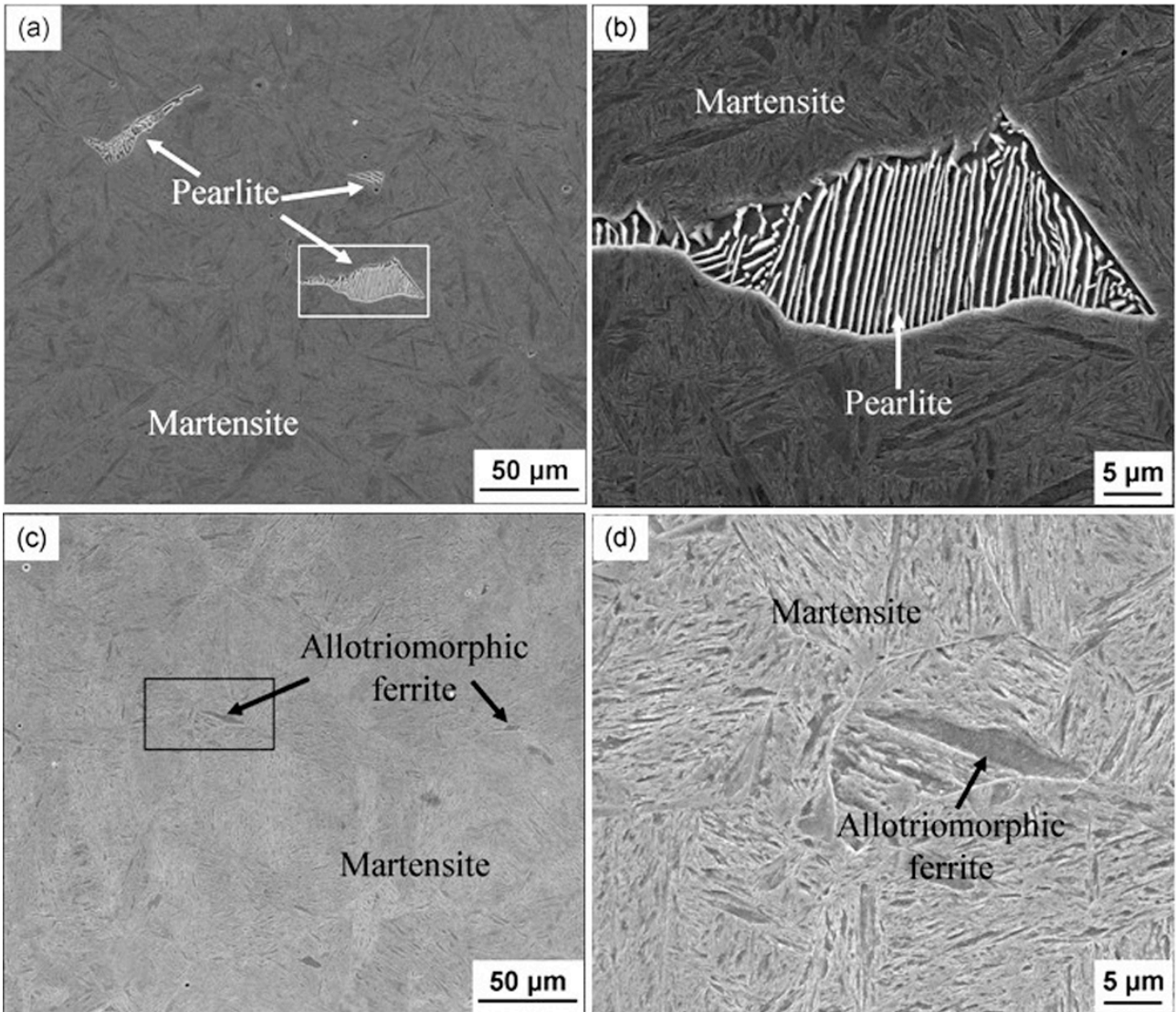
3 Scanning electron micrographs show the Alloy 1 with Co and Al (a&b) contains some pearlite colonies whereas the parent Alloy 2 (c&d) mostly consists of martensite (both alloys isothermally transformed at 700 °C for 5 h).
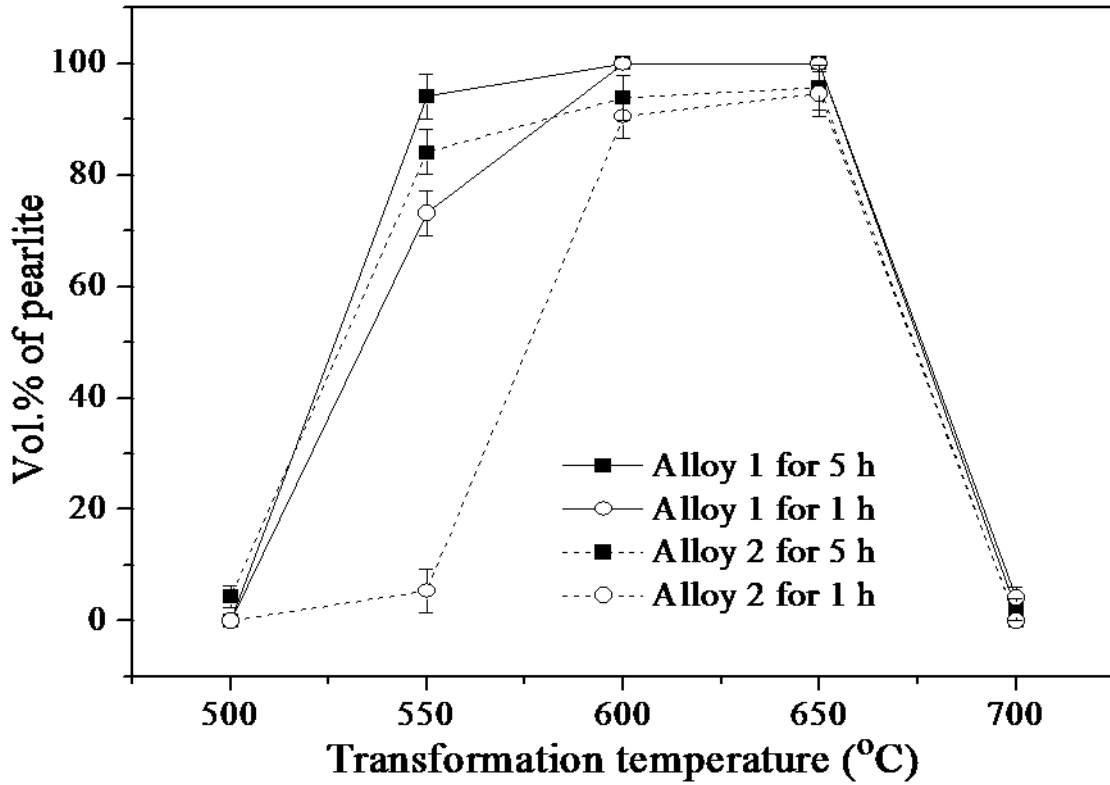
4 Amount of pearlite as a function of transformation temperature and time in Alloy 1 containing

Co and Al and the parent Alloy 2.
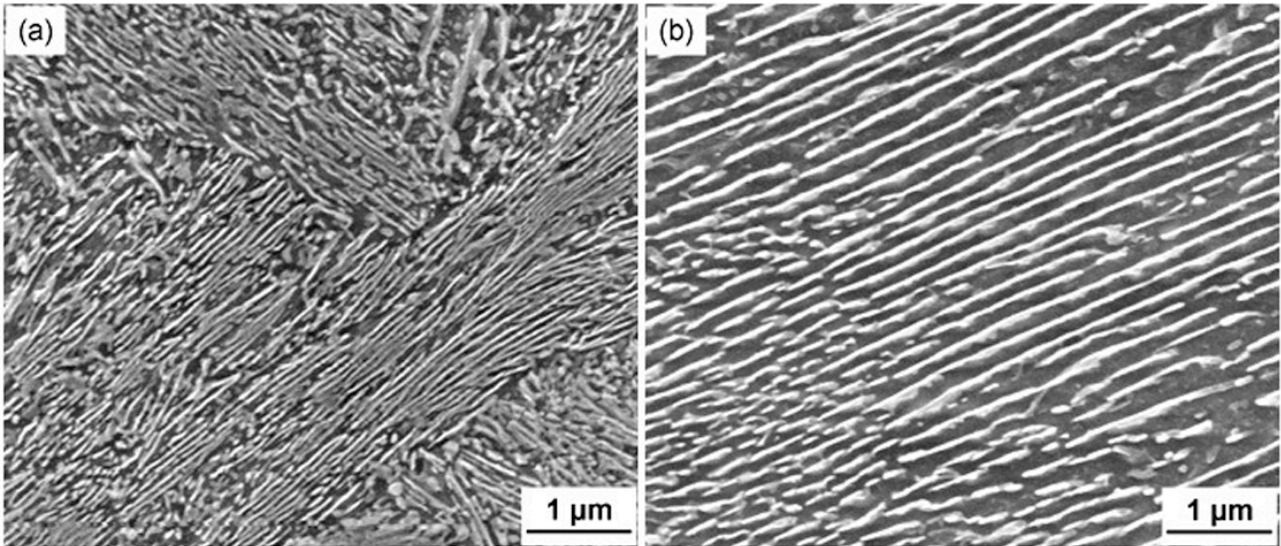
5 SEM micrographs show the pearlite formed at 600 °C within 5 hrs has a finer structure in Alloy 1 containing Co and Al (a) than the parent Alloy 2 (b).
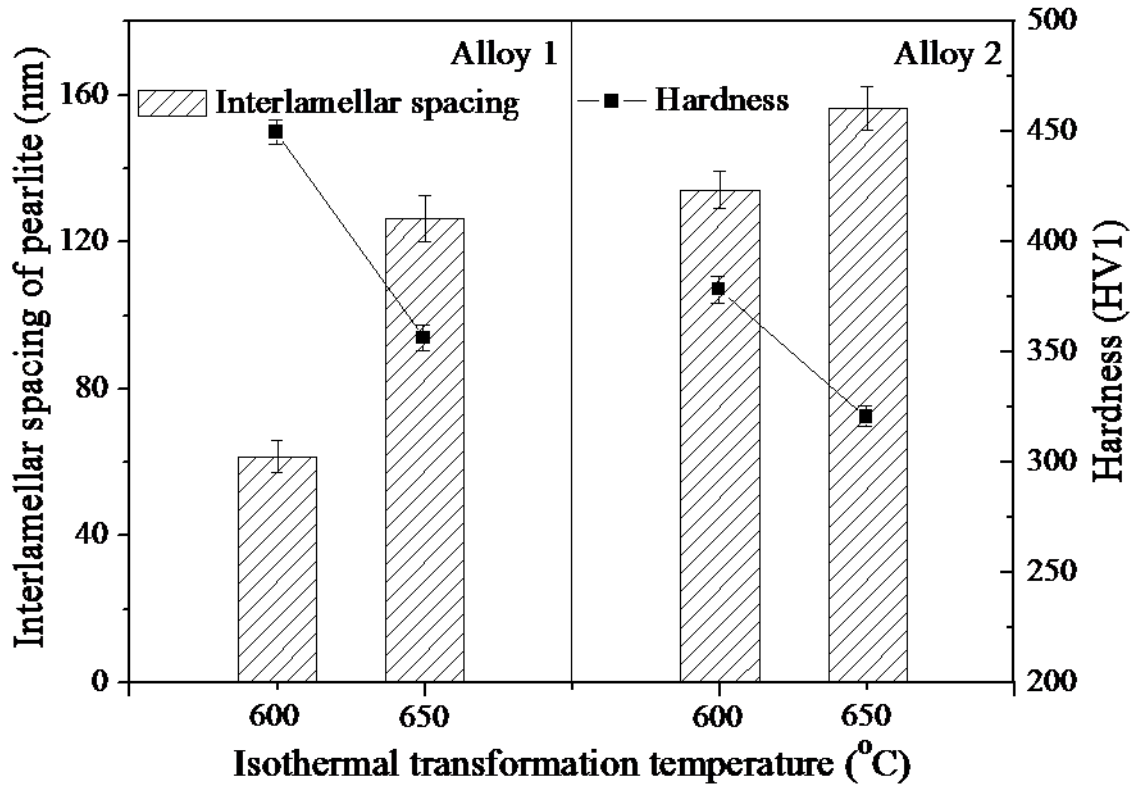
6   Measured interlamellar spacing and hardness of pearlite formed at different temperatures within 5 hrs.
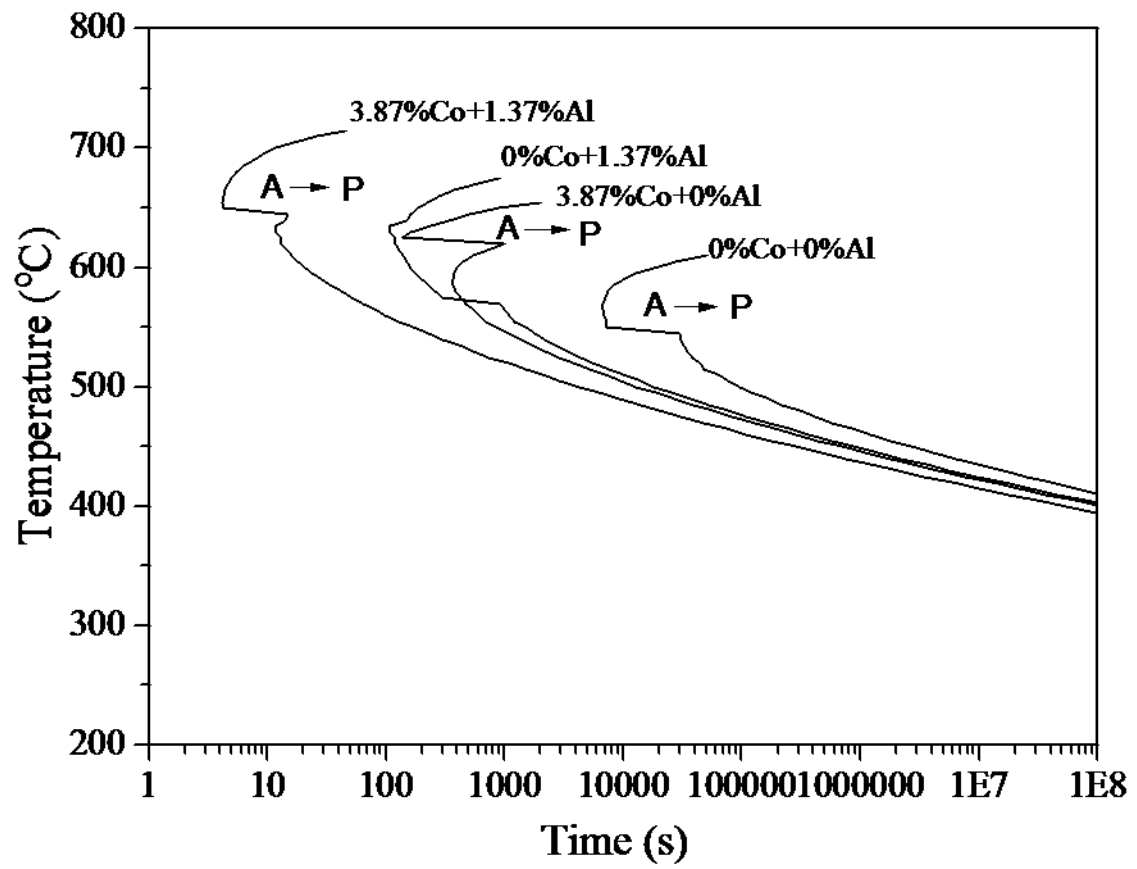
7　Effect of Co and Al on the TTT diagram of pearlite transformation [15].