

# Hot Workability of High Strength Low Alloy Steels

Seok Hong Min, Jung Ho Moon, Woo Young Jung, and Tae Kwon Ha

**Abstract**—The hot deformation behavior of high strength low alloy (HSLA) steels with different chemical compositions under hot working conditions in the temperature range of 900 to 1100°C and strain rate range from 0.1 to 10 s<sup>-1</sup> has been studied by performing a series of hot compression tests. The dynamic materials model has been employed for developing the processing maps, which show variation of the efficiency of power dissipation with temperature and strain rate. Also the Kumar's model has been used for developing the instability map, which shows variation of the instability for plastic deformation with temperature and strain rate. The efficiency of power dissipation increased with decreasing strain rate and increasing temperature in the steel with higher Cr and Ti content. High efficiency of power dissipation over 20 % was obtained at a finite strain level of 0.1 under the conditions of strain rate lower than 1 s<sup>-1</sup> and temperature higher than 1050 °C. Plastic instability was expected in the regime of temperatures lower than 1000°C and strain rate lower than 0.3 s<sup>-1</sup>. Steel with lower Cr and Ti contents showed high efficiency of power dissipation at higher strain rate and lower temperature conditions.

**Keywords**—High strength low alloys steels, hot workability, Dynamic materials model, Processing maps.

## I. INTRODUCTION

STEEL has been regarded as the most important metallic material for many industries, although stainless steels and some nonferrous alloys are used for some specialized applications. High strength low alloy (HSLA) steels are by far the most widely utilized metallic materials [1]. Steels with low carbon content but containing Nb, V, and Ti are called microalloyed or high strength low alloy (HSLA) steels. These steels are economically more feasible in the form of pipe than plate, where thickness are typically greater, and their good weldability and high yield strength have made them attractive alternatives to more conventional steels [2]. The fabrication of HSLA steels mainly consists of melting, casting, hot working, and heat treatment processes. In the hot working process, high speed rolling is usually employed, in which the steels deform under very high strain rate. In fact, the optimum process conditions for rolling are critical to provide the final product with required quality.

The previous studies have focused primarily on the microstructural evolution under relatively low strain rate deformation conditions [3-5] and studies on the high strain rate deformation behavior of HSLA steels are now lacking. In this regard, it is necessary to systematically investigate the hot

workability of HSLA steels, especially the effect of chemical contents such as Cr, Mo, Nb and Ti, which are well known as carbide former [6-8]. In the present study, high temperature and high strain rate compression tests were conducted on the HSLA steel and hot workability of the steels with different chemical compositions was investigated by constructing the stress maps, material processing maps employing the dynamic materials model (DMM) proposed by Prasad et al. [9], and instability maps based on the Kumar's model [10].

## II. EXPERIMENTAL PROCEDURES

TABLE I  
CHEMICAL COMPOSITIONS OF HSLA STEELS USED IN THIS STUDY. (WT.%)

No.	Cr	Nb	Ni	Si	Ti	Mn	C	Mo
A	0.18	0.05	0.2	0.2	0.04	1.0	0.05	0.1
B	-	0.06	0.3	0.2	0.01	1.0	0.07	0.3

The ingots of high strength low alloy steel with different chemical compositions were cast by vacuum induction melting (VIM) into the ingots with dimensions of 140 mm × 140 mm × 400 mm. The chemical compositions of the ingots are listed in Table I. The ingots were solution heat treated at 1200°C for 1.5 hr followed by furnace cooling. As shown in Fig. 1, microstructure observation revealed primarily ferrite, fine pearlite and some martensite in both steels.

The high temperature compression tests were conducted up to 50 % reduction in a vacuum of 0.1 torr at temperatures of 900, 950, 1000, 1050 and 1100 °C with various strain rates between 0.1 s<sup>-1</sup> and 10 s<sup>-1</sup> on both steels. Cylindrical compressive specimens with a diameter of 10 mm and a height of 12 mm were prepared by electro-discharge machining. Specimens were heated up at a heating rate of 5°C/min and soaked for 300 sec at test temperatures before the tests were started. The true stress-true strain curves were obtained from the load-displacement data.

## III. RESULTS AND DISCUSSION

Fig. 2 shows some selected results obtained from compression tests at temperatures of 900 and 1100°C under the various strain rates. Flow curves obtained at high strain rate condition (above 0.3 s<sup>-1</sup>) exhibited remarkable oscillations together with fine serrations, which was presumably associated with microstructure evolution. Interestingly, surface roughening was found to occur even at 1100°C when the strain rate was higher than 0.3 s<sup>-1</sup>, which suggested that a large amount of plastic strain (50% in this case) could cause inevitable failure in the mechanical working. It is easily noted from the figure that the flow stress monotonically increases with decreasing temperature and with increasing strain rate, regardless of chemical compositions.

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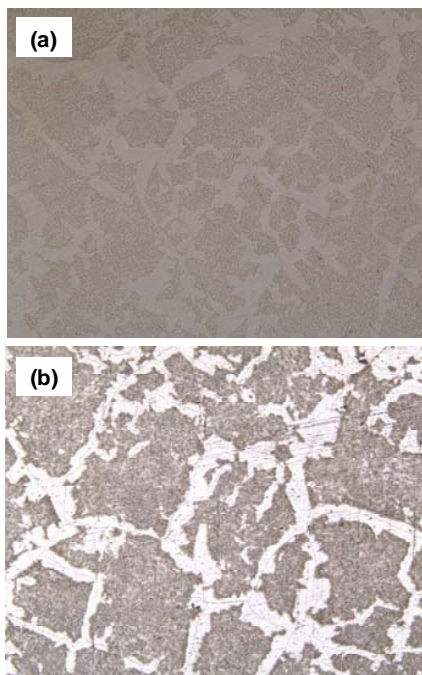


Fig. 1 As-cast microstructure of the ingots of (a) A and (b) B used in this study observed after solution heat treated at 1200°C for 1.5 hr followed by furnace cooling

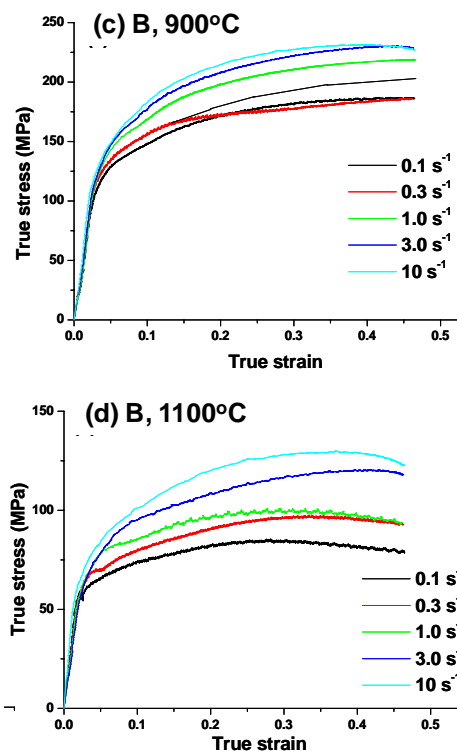
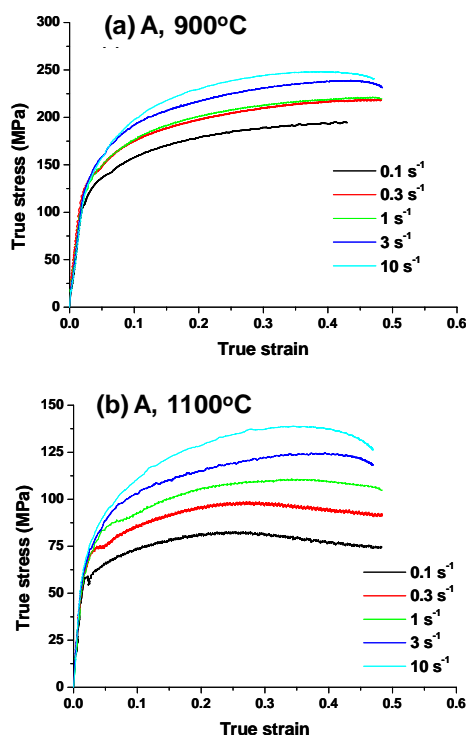


Fig. 2 True stress-true strain curves obtained at temperatures of 900°C (a, c) and 1100°C (b, d) under the various strain rates



Based on the data, the stress maps were constructed as shown in Fig. 3 at the strain level of 0.1. As the strain rate increases and the temperature decreases, stress increases monotonically. These results are employed to construct the power dissipation maps illustrated in Fig. 4. The contours in the maps represent constant efficiency of power dissipation ( $\eta$ ), which is directly related to the relative rate of entropy production in the system caused by a change in the microstructure. The map consists of three-dimensional variation of the efficiency of power dissipation ( $\eta$ ) as a function of temperature and strain rate. The dimensionless parameter  $\eta$  is obtained by comparing the dissipative characteristics of the workpiece with that of a liner-dissipator and is expressed as  $2m/(m+1)$ , where  $m$  is the strain rate sensitivity parameter of flow stress. Detailed method of developing the map was given in the other literatures on the basis of dynamic materials model [6]. It is generally reported that the value of  $\eta$  should be reached up to 30~40% for successful hot working process such as forging [11].

As shown in Fig. 4, at relatively low temperature (below 1000°C) and high strain rate (above 3.0 s<sup>-1</sup>) regime, the dissipation efficiency is very low less than 10 %. On the contrary, high temperature region near 1100°C, regardless of strain rates, exhibited relatively high efficiency of power dissipation higher than 20 %. In the case of steel A, there appeared a peak with efficiency higher than 20 % near the temperature of 1050°C and the strain rate of 1 s<sup>-1</sup>. Hot working of the HSLA steel can be operated near the domain with highest power dissipation efficiency. On the other hand, in the case of

steel B, higher efficiency of power dissipation of about 30% has been obtained in the domain at the temperature of 1000°C and at the strain rate of 5 s<sup>-1</sup>. It is very interesting to note that minor change of chemical compositions can cause a significant change in the hot workability of HSLA steel. In fact, it is well known that an addition of small amount of carbo-nitride former such as Nb, Ti, Mo, etc. dramatically affect the dynamic recrystallization behavior of HSLA steels [12-14]. In the light of thermomechanically controlled process design, the steel B is more favorable due to the higher strain rate and the lower temperature.

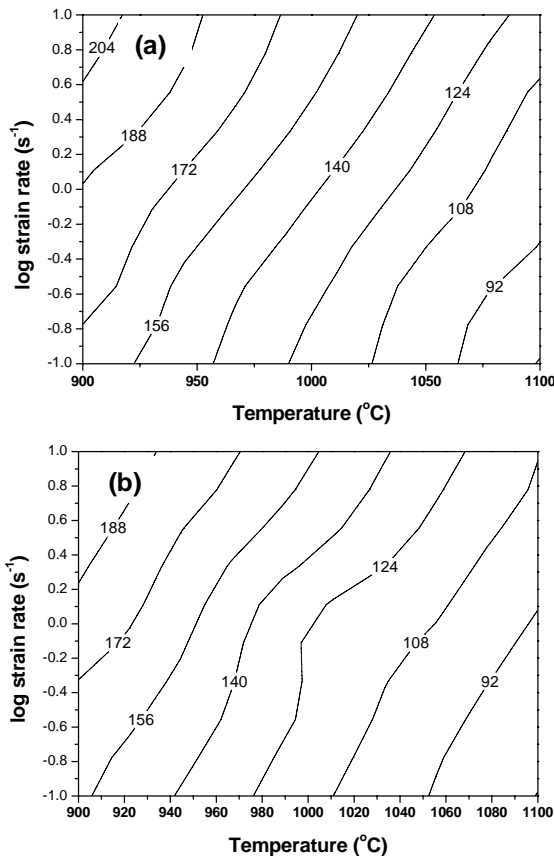


Fig. 3 Stress maps at the strain level of 0.1 obtained from compression tests on the steels (a) A and (b) B

Kumar [10] has shown that the condition for the plastic flow to become unstable as follow;

$$\xi = \frac{\partial \ln \left( \frac{m}{m+1} \right)}{\partial \ln \dot{\epsilon}} + m < 0 \quad (1)$$

The left hand side of equation (1) is denoted by  $\xi$  which, when negative, indicates microstructural instability in the material. The variation of  $\xi$  at strains of 0.1 and 0.3 as a function of strain rate and temperature are evaluated and

represented as instability maps in Fig. 5. Flow instability can be expected in the regimes designated by the negative value of  $\xi$ . It is apparent that the recommended regimes for hot working, i. e. 1050°C and 1 s<sup>-1</sup> for steel A, and 1000°C and 5 s<sup>-1</sup> for B, are in the safe condition.

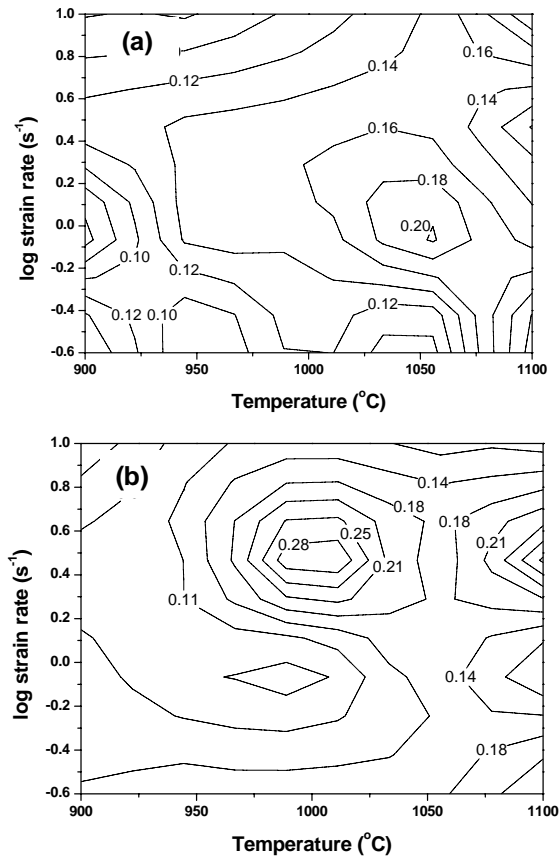


Fig. 4 Power dissipation efficiency maps evaluated at the strain level of 0.1 for (a) A and (b) B steels

Fig. 6 shows the microstructures taken from the specimens of steels A and B, compressed by 10% reduction under various conditions. It is very interesting to note from Fig. 6(b) that very fine and equiaxed microstructure, which is believed to form by dynamic recrystallization, has been obtained after hot compression test conducted under the condition of 1050°C and 1 s<sup>-1</sup>, clearly in the domain of high power dissipation efficiency in Fig. 4 and safe domain in Fig. 5, while an irregular microstructure was revealed after hot compression under the unstable condition and very low power dissipation efficiency as shown in Fig. 6(a). Almost the same results were obtained for steel B as illustrated in Fig. 6(c) and (d). Fig. 6(d) was observed on the specimen compressed at temperature of 1000°C and at the strain rate of 5 s<sup>-1</sup> and shows a uniformly fine and equiaxed grain structure, while Fig. 6(c) was obtained at temperature of 1000°C and at the strain rate of 1 s<sup>-1</sup> and show very irregular microstructure.

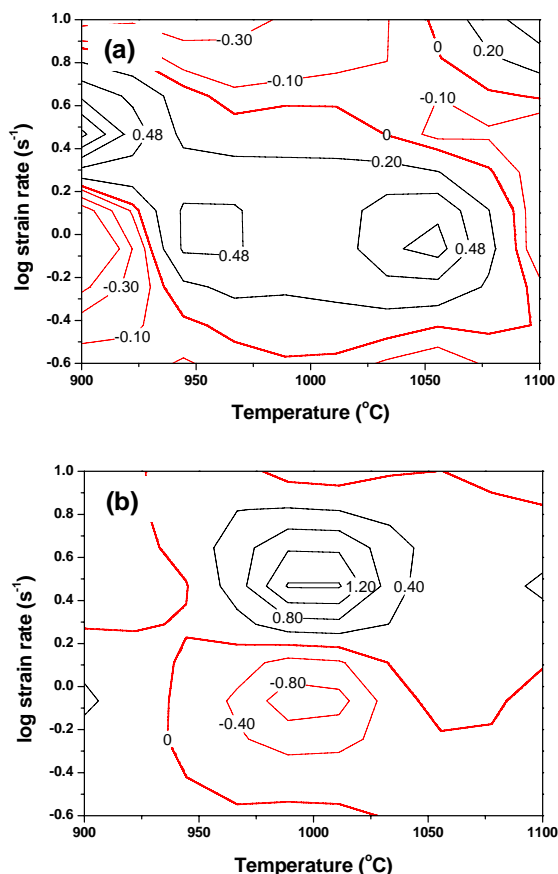


Fig. 5 Instability maps obtained at strains of (a) 0.1 and (b) 0.3

#### IV. CONCLUSION

By conducting a series of hot compression tests on the high strength low alloy (HSLA) steels and analyzing the results with dynamic materials model in the present study. Power dissipation efficiency map and instability map were developed at strain level of 0.1 within the strain rate ranging from 0.1 to 10  $\text{s}^{-1}$  and the temperatures from 900 to 1100°C. Optimum hot working conditions for the HSLA steels were obtained as the temperature near 1050°C and the strain rates of 1  $\text{s}^{-1}$  for steel A and as the temperature near 1000°C and the strain rates of 5  $\text{s}^{-1}$  for steel B. It is revealed in this study that a chemical compositional change can significantly affect the hot formability of HSLA steels.

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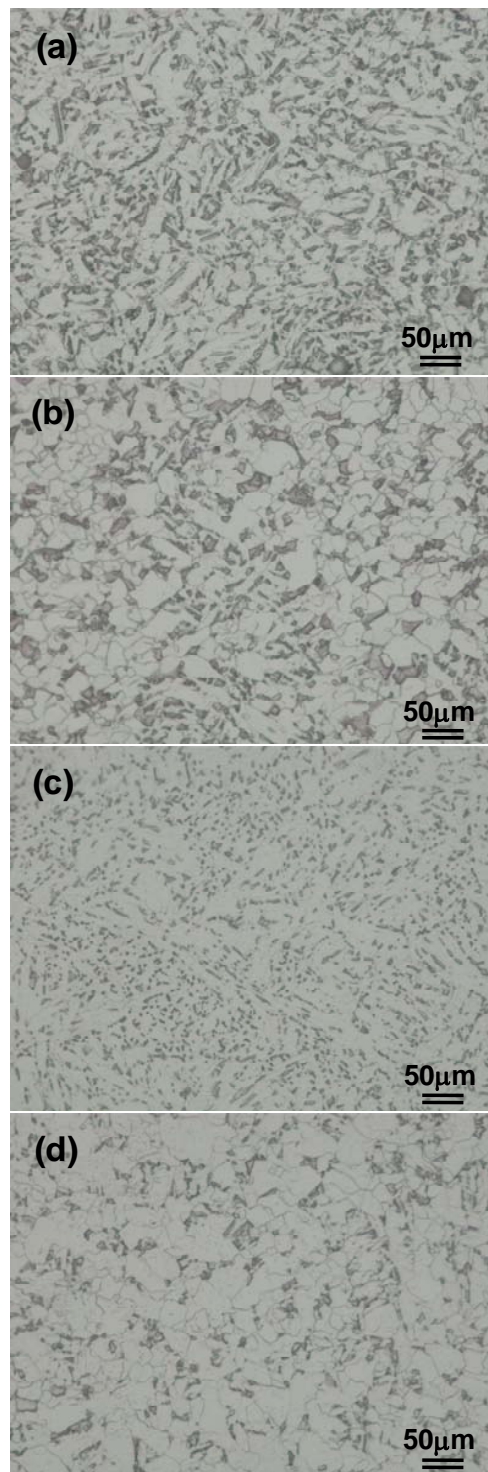


Fig. 6 Optical microstructures observed after hot compression tests. Steel A compressed under the strain rate of 1  $\text{s}^{-1}$  at temperatures of (a) 900°C and (b) 1050°C. Steel B compressed under strain rates of (c) 1  $\text{s}^{-1}$  and (d) 5  $\text{s}^{-1}$ , and at the temperature of 1000°C

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