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Improvement in Metal Formability by Lowering Process Temperature Consciously

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Recently increasing amount of light metal sheet, especially based on Magnesium, is being involved into various structural constructions and functional components. Such a rising trend can be observed, for instance, at automotive, aerospace and electronic industry. On the other hand, there exist some processing difficulties, such as less stable deformation and poor forming limit, caused by crystalline structure. An analysis on plastic instability theory together with some constitutive equations involving strain, strain rate and temperature leads to simple conclusion, which suggests an increase of stable deformation range by falling off temperature intentionally during the process. By optimum settings of the deformation process, especially temperature and strain rate, uniform elongation can be successfully extended. Actually at elevated temperature in tensile test by using Magnesium alloy hollow tube, where flowing cool air inside pipe may effectively lower the temperature of the work during the test, a significant rise in stable deformation range could be observed. The result may be applied to any other metal, being independent of metal class in the analysis, thus generalized concept seems to be reached to extension in stable deformation range of metals with poor formability.

Keywords: *Stable Deformation, Magnesium Alloys, Plastic Instability Theory, Temperature Descent, Improvement of Formability*

1. Introduction

A biggest issue of some problems preventing the widespread use of Magnesium alloy is how to control its poor formability. Generally, improvement in formability was made by process with high process temperature. Here, the concept of temperature descent is provided and the usefulness of cooling down the process temperature is shown by the comparison to process with constant temperature. The object of this paper is to analyze the effect of temperature descent on improvement of stable formability and to demonstrate actually the utility. This paper contains both experimental results and theoretical analysis of the onset of diffuse necking.

Analysis on instability [1, 2]

Assuming that ductile sheet metals are homogeneous and isotropic under two-dimensional stress state, and it is proportionally loaded, Swift's criterion at the onset of a diffuse necking is given by:

$$\frac{d\bar{\sigma}}{d\bar{\varepsilon}} = \frac{\bar{\sigma}}{Z_0}. \tag{1}$$

where, $\bar{\sigma}$ is an equivalent stress $\bar{\varepsilon}$ is an equivalent strain and Z_0 is a critical subtangent at the onset of the diffuse necking.

$$Z_0 = \frac{4\left(1-\alpha+\alpha^2\right)^{3/2}}{\left(1+\alpha\right)\left(4\alpha^2-7\alpha+4\right)}. \tag{2}$$

$$\alpha = \frac{\sigma_2}{\sigma_1} \text{ (principal stress ratio) } = \frac{2\beta+1}{2+\beta} \qquad \left(\beta = \frac{\varepsilon_2}{\varepsilon_1}\right). \tag{3}$$

Let us assume that material constants in constitutive equations do not change within some arbitrarily specified range of strain, strain-rate and temperature.

Here, the following three constitutive equations for flow stress are quoted from references [3, 4].

$$\bar{\sigma} = K_1 \dot{\bar{\varepsilon}}^{m_1} \bar{\varepsilon}^{n_1} \exp\left(\frac{A_1}{T}\right) \qquad \text{(Multiplication type)} . \tag{4}$$

$$\bar{\sigma} = K_2 \left\{ \bar{\varepsilon}^{n_2} + m_2 \ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right) \right\} \exp\left(\frac{A_2}{T}\right) \qquad \left(m_2 = \frac{1}{K_2} \frac{\partial \sigma}{\partial \ln \dot{\bar{\varepsilon}}} \right) \quad \text{(Addition type)} . \tag{5}$$

$$\bar{\sigma} = K_3 Z^{m_3} \bar{\varepsilon}^{n_3} \qquad \left(Z = \dot{\bar{\varepsilon}} \exp\left(\frac{A_3}{T}\right), m_3 A_3 = A_1 \right) \quad \text{(Multiplication type)} . \tag{6}$$

where, $K_{1,2,3}$ = constant, $A_{1,2,3}$ = constant, $n_{1,2,3}$ = strain hardening exponent, $m_{1,2,3}$ = strain-rate hardening exponent, T = absolute temperature and Z = Zener-Hollomon parameter.

Equivalent strain $\bar{\varepsilon}_u$ at the occurrence of diffuse necking can be found by each combination Eq. (1) and Eq. (4), Eq. (1) and Eq. (5), Eq. (1) and Eq. (6). In the case of the combination of Eq. (1) and Eq. (4) :

$$\bar{\varepsilon}_u = Z_0 \frac{d \ln \bar{\sigma}}{d \ln \bar{\varepsilon}} = Z_0 \left(n_1 + \bar{\gamma} m_1 + A_1 \delta \right). \tag{7}$$

where

$$\bar{\gamma} = \frac{d \ln \dot{\bar{\varepsilon}}}{d \ln \bar{\varepsilon}} . \tag{8}$$

$$\delta = \frac{d(1/T)}{d \ln \bar{\varepsilon}} . \tag{9}$$

In the case of the combination of Eq. (1) and Eq. (5), $\bar{\varepsilon}_u$ is derived from a solution of the following algebraic equation.

$$\bar{\varepsilon}_u^{\,n_2} - Z_0 \left(n_2 + A_2 \delta \right) \bar{\varepsilon}_u^{\,n_2 - 1} + m_2 \gamma \bar{\varepsilon}_u - Z_0 \left(1 + A_2 \delta \right) m_2 \gamma = 0 . \tag{10}$$

where

$$\gamma = \frac{d \ln \dot{\bar{\varepsilon}}}{d \bar{\varepsilon}} \quad , \quad \bar{\gamma} = \gamma \bar{\varepsilon} . \tag{11}$$

In the case of the combination of Eq. (1) and Eq. (6) :

$$\bar{\varepsilon}_u = Z_0 \left(n_3 + \bar{\zeta} m_3 \right) = Z_0 \left\{ n_3 + m_3 \left(\bar{\gamma} + A_3 \delta \right) \right\}. \tag{12}$$

where

$$\bar{\zeta} = \frac{d \ln Z}{d \ln \bar{\varepsilon}} = \zeta \bar{\varepsilon} \quad , \quad \zeta = \frac{d \ln Z}{d \bar{\varepsilon}} . \tag{13}$$

Inspection of Eq. (7), Eq. (10) and Eq. (12) indicates that $\bar{\varepsilon}_u$ are decided by material constant n, m, A and processing parameters γ, $\bar{\gamma}$, δ. If material constants do not vary during the deformation, the fluctuation of $\bar{\varepsilon}_u$ depends on only processing parameters. When n > 0, m > 0 and A > 0, $\bar{\varepsilon}_u$ increase by rise of γ, $\bar{\gamma}$ and δ because of Eq.(7), Eq.(12) and nature of root of Eq.(10). In other words, an increase of the deformation speed and a decrease of the temperature during the deformation are linked to the increase of $\bar{\varepsilon}_u$.

In this study, attention was paid to temperature descent and it may be demonstrated that the process with temperature descent lead to larger increase of $\bar{\varepsilon}_u$ than it in the process of constant and uniform temperature. Experimental results which are obtained by a uniaxial tensile test are compared and examined by using Multiplication type (Eq. (4)) and Addition type (Eq. (5)) constitutive equations. If uniaxial tensile test are used, it is necessary to note that the critical subtangent Z_0 is unity because principal stress rate α is taken zero. In this case, strain at ultimate tensile stress can be thought of as a criterion of uniform strain. In uniaxial tensile test, an axial strain is given as following by Eq. (7):

$$\varepsilon_1 = n_1 + \bar{\gamma} m_1 + A_1 \delta . \tag{14}$$

where

$$\bar{\gamma} = \frac{d \ln \dot{\varepsilon}_1}{d \ln \varepsilon_1}, \quad \delta = \frac{d(1/T)}{d \ln \varepsilon_1}. \tag{15}$$

and given as following by Eq. (10) :

$$\varepsilon_1^{n_2} - (n_2 + A_2 \delta)\varepsilon_1^{n_2 - 1} + m_2 \gamma \varepsilon_1 - (1 + A_2 \delta) m_2 \gamma = 0 . \tag{16}$$

where

$$\gamma = \frac{d \ln \dot{\varepsilon}}{d\varepsilon}, \quad \bar{\gamma} = \gamma\varepsilon . \tag{17}$$

2. Tensile Test

When test had been carried out with typical uniaxial tensile testing samples, a method of cooling were natural cooling by opening a furnace's door after reaching the desired temperature of specimens [5]. However, sufficient increases of uniform strain were not shown because temperature descent rate were too slow. Fig. 1 shows temperature change of a sample by natural cooling. Then, we conducted a test using air flow cooling caused by a fan. Cooling rate is faster than natural cooling but enough effect of temperature descent were not obtained because of temperature dispersion in specimens. From the above mentioned, the design of specimens and the method of test need to consider the following constraints ; (a) the temperature of specimens are lowered effectively during the test, (b) the temperature dispersion in the specimen are controlled in the acceptable range. To address these problems, hollow tubes and air blow cooling were used.

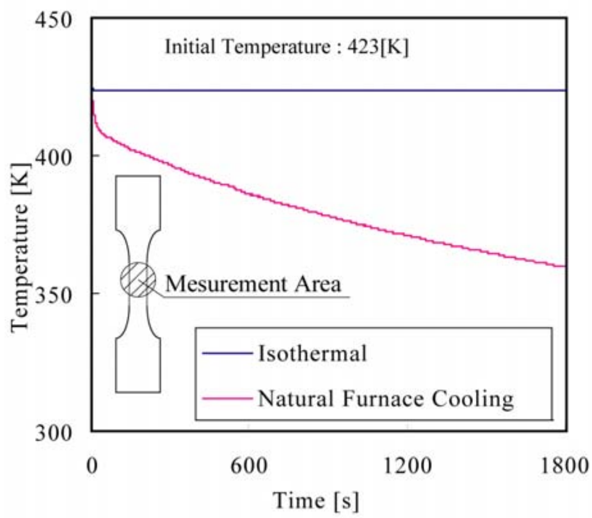

Fig. 1 Temperature profile during the natural cooling of the furnace.

2.1 Specimen geometry and testing conditions

Supplied hollow tubes are Magnesium alloy AZ31. Tensile tests were carried out with the specimens shown in Fig. 2. The surface of measurement area of specimens was marked lines at 2.5mm intervals.

Tensile testing machine used for this experiment was Instron-type universal testing machine. Its Cross Head Speed (C.H.S) is possible to change as follows: 2, 5, 10, 20, 50, 100 and 200 [mm/min]. Testing temperatures had been set up from 373K and then rose by 100K up to 673K.

During the experiment a video movie camera was attached to the computer and whole sequence was taken. Later the computation of an actual deformation was possible by means of comparison of the deformed and the original dimension within the interval in any desired time. Thus the moment of onset of the unstable deformation can be detected.

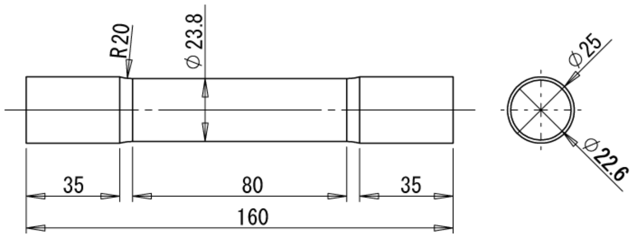

Fig.2 Geometries of tube specimen.

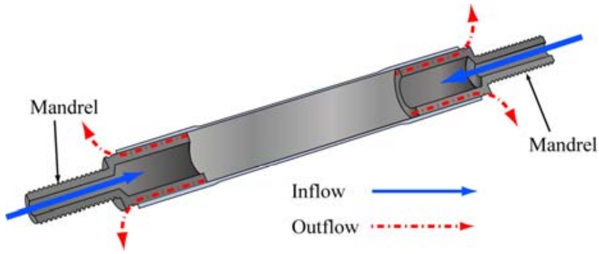

Fig.3 Air flow in the tube.

2.2 Testing modes

Two types of testing modes were taken.

(A) Isothermal Test

The specimen was placed into furnace and heated to the required temperature during test.

(B) Air Blowing Cooling Test

The specimen was placed into furnace and heated to the required temperature before test. When test started, we cut the power supply of furnace and blew cool air inside pipe. Flow of air into a specimen is illustrated in Fig. 3.

3. Results

3.1 Experimental results

Fig. 4 shows variations of temperature in the specimen during the test. Measurement of temperature was used a thermocouple and measurement point were 3 points (A, B and C in Fig. 4).This indicates temperature were sharp drop at the same time that test was stared and deviations in the specimen were controlled in the acceptable range. Based on the data from Fig. 4, δ values at each C.H.S. can be calculated by the above discussed definition of Eq. (15). Fig. 5 shows temperature versus nominal strain at each C.H.S.

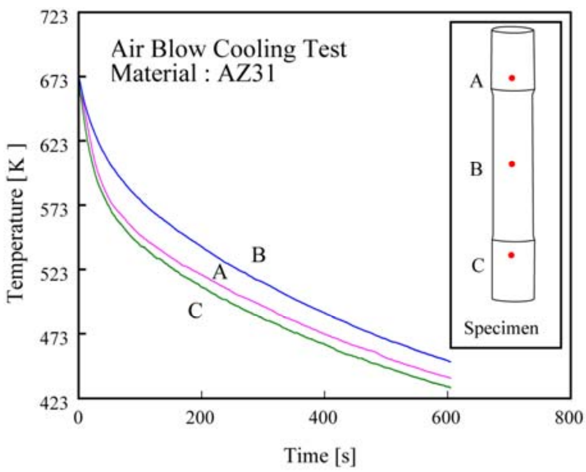

Fig. 4 Temperature descent at each part in air blow cooling test.

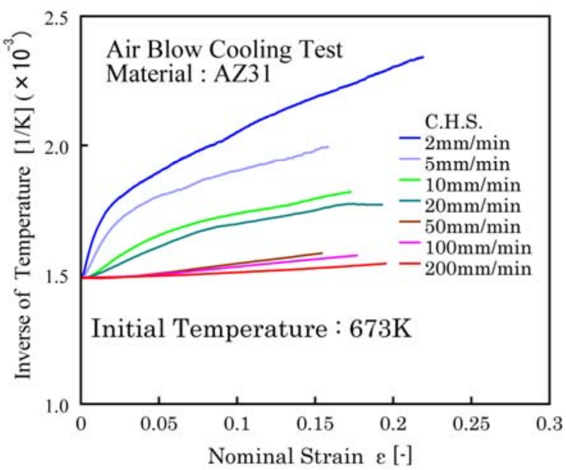

Fig. 5 Inverse of temperature vs. nominal strain at each C.H.S. Gradient of each curve may be specified as the value of Eq. (15).

Outcome of uniaxial tensile tests are seen in Fig. 6. This figure is plotted for constant temperature of 673K, but results of other temperature conditions become similar mutual relative dependence.

The most significant material's behavior is illustrated in Fig. 6. Uniform strain at ultimate tensile stress (U.T.S.) shown by rhombuses in Fig. 5 and Fig. 6 obviously increase in air blow test. There appears to be sufficient evidence that temperature descent have a strong influence on uniform strain. In 2 mm/min, a uniform stain increased by temperature descent became six times as large as the one of constant temperature because the deformation speed was slow, and it was able to effectively receive influence of temperature descent. Moreover, average of an increase of uniform strain was 2.9 times as large as the one of constant temperature.

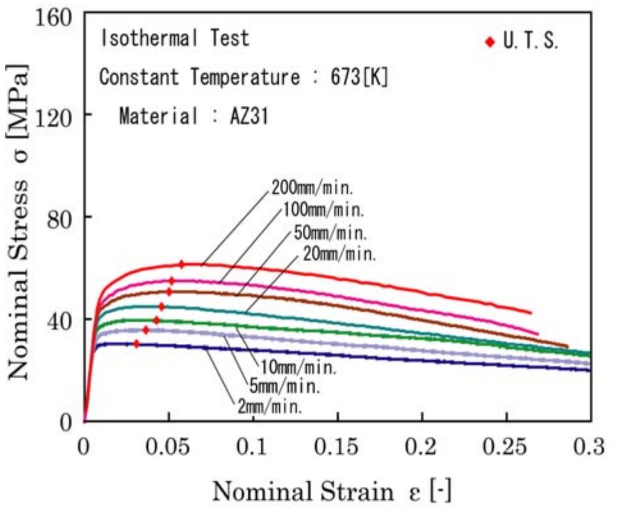

Fig.6 Summarization of uniaxial tensile test at the elevated constant testing temperature 673K. The variable parameter is Cross Head Speed (C.H.S.) and its particulars values are stated in the figure.

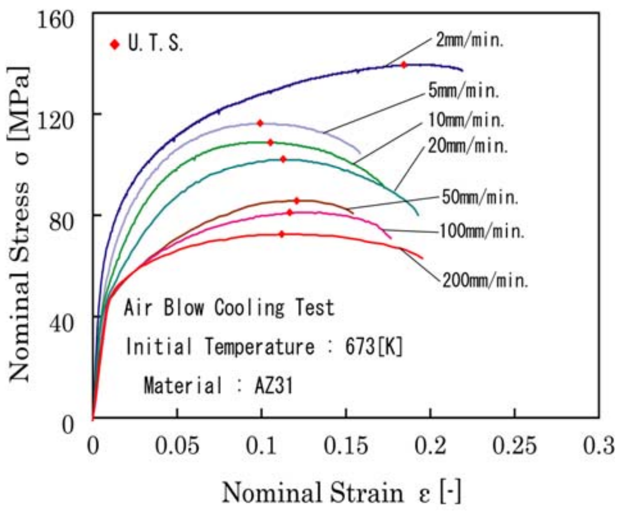

Fig.7 Comparison of tensile testing results that were obtained at gradually decreasing temperature. The initial testing temperature is 673K .

3.2 Comparison of Experimental and calculated results

Based on the data from experimental results, material property values can be calculated. Those values are shown in Table 1. A and m value of Multiplication type are higher than those of Addition type. This means that Multiplication type is more sensitive to the change of strain rate and temperature during deformation than Addition type. However, each A value is high, so this implies that temperature descent have a strong effect on an increase of uniform strain in the case of both constitutive equations.

Measurement values of uniform strain are shown in Fig. 8 and calculated values against Multiplication type and Addition type are shown in Fig. 9.

In comparison of data of air blow cooling test in Fig. 8 and Fig. 9, calculated values do not show good agreement with experimental results. The following are thought as a cause for this difference.

As can be seen from Fig. 4, temperature descent rate became a gradual change with the passage of time, so δ value changed during test, too. But we treated δ value as constant. Since change of temperature descent was large until reaching U.T.S. at low C.H.S., difference is large. At high C.H.S. , change of rate of temperature descent was small, difference was small.

Another cause of difference is decision of each material constant. Each material constant was changed by measurement range (strain, strain-rate and temperature). When approximate results for A1100-O were calculated using different measurement range of strain, following results were gained. (A) Multiplication type suits approximation of a wide range. But it is necessary to expand the measurement range over U.T.S. (B) Addition type suits approximation of a narrow range, good approximation was gained by narrowing measurement range. However, these opinions do not fall under the definition of concept of "constant".

Table 1 Material property values in each constitutive equation.

	n_1	m_1	A_1	K_1
Multiplication Type	0.032	0.101	1233	16.86
	n_2	m_2	A_2	K_2
Addition Type	0.037	0.093	1047	8.96
Measurement Range ε : 0.05~0.09, $\dot{\varepsilon}$: 0.0524~0.1265[s^{-1}], T : 373~673[K], $\dot{\varepsilon}_0$: 0.00001[s^{-1}]				

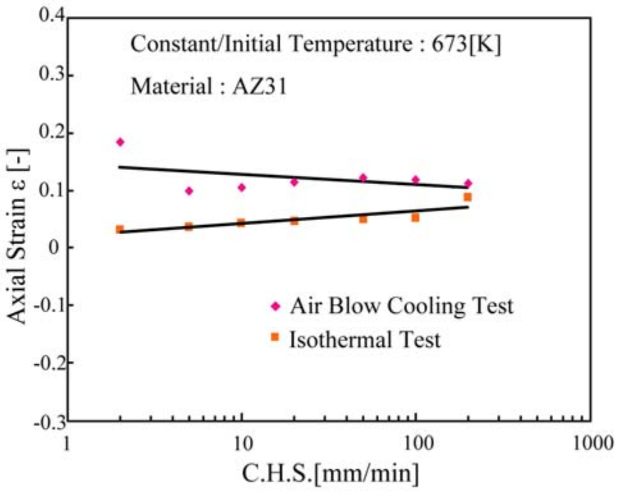

Fig. 8 Experimental results of ε_u .

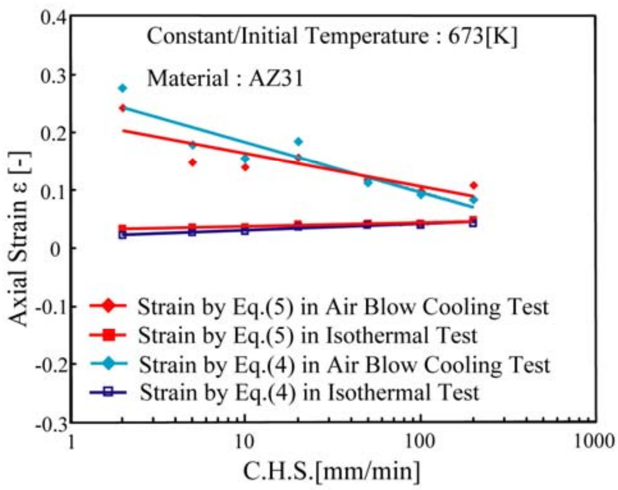

Fig. 9 Calculated values of ε_u .

4. Conclusion

Authors examined that there is relationship between increase of uniform strain and decrease of temperature during forming process. Temperature descent during forming process causes a significant rise of the uniform strain. This forming method is not limited to Magnesium alloys, which can be recognized as a general improvement method of formability.

Although only uniaxial tensile test was treated this time, this improvement method of formability can be applied to the general press process.

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