Fundamental Study on Impact Toughness of Magnesium Alloy at Cryogenic Temperature

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Abstract- Research on mechanical properties of the magnesium alloys at low temperature is few. In this study, we investigated deformation and fracture behavior of the magnesium alloy at cryogenic temperature. As received extrusion-pressed AZ61 magnesium material was used. Impact tests were carried out at temperatures of range from 83K (-190℃) to 293K (20℃) with loading speed of approximately 1.0 m/s for miniature size U-notch specimen. Impact load-deflection responses of the alloy tested at 293 K and 83 K were evaluated. Failure begin of both specimens was achieved at maximum load, P_{max} and toughness at 83 K was degradable compere with that at 293 K. From observation results of crack path behavior, formation energy of fracture surface of specimen tested at 293 K was higher than that tested at 83 K.

Keywords –Magnesium Alloy, Impact Toughness, Low Temperature, Fracture Behavior

I. Introduction

Light-weight materials offer a high potential for weight reduction to improve fuel consumption and emissions in transportation and logistics industries. The automobile industry made a voluntary commitment to reduce fuel consumption by 25 % in comparison with 1990 levels by the year 2005 [1]. Therefore, there is a growing trend to substitute these nonferrous materials for conventional steel and cast irons especially in automobile field. However, compared to steel materials, the mechanical property of nonferrous materials, such as aluminium, titanium and magnesium base alloys under impact loading is much less investigated. Generally, the number of research on dynamic deformation and failure of magnesium alloys is not many. The knowledge of dynamic deformation response of the light-weight structures is essential in improving and developing product resistance to shock loading, for crashworthiness, safety, and reliability. In the past, structures have been designed on the basis of strength at quasi-static strain rate and at ambient temperature, whereas impact and cryogenic strength properties were dealt with.

In this paper, the purpose of this investigation is to evaluate fundamentally impact toughness and fracture morphology on extruded AZ61 magnesium alloy tested at cryogenic temperature.

II. Experimental Procedure

A. Material –

The material used in this study was an extruded AZ61 magnesium alloy of 29.4mm diameter, received from OSAKA FUJI CORP. (Amagasaki, JAPAN). The chemical compositions and extrusion condition are presented in Table 1 and Table 2. After homogenization treatment of the alloy billet, the extrusion is performed at a billet temperature of 523 to 623 K, and an extrusion rate of 2000mm/min. Extrusion rate is 13. Artificial ageing treatment is not applied to this alloy. Table 3 shows tensile properties and Vickers hardness of this alloy.

Table-1 Chemical composition of the extruded AZ61 magnesium alloy used in this study

Al	Zn	Mn	Fe	Si	Cu	Ni	Mg
6.67	**0.84**	**0.28**	**0.003**	**0.043**	**0.003**	**<0.001**	**Bal.**

Table-2 Extruded condition of the AZ61 magnesium alloy used in this study

Extrusion ratio	**13**
Extrusion Temperature (K)	**523-623**
Extrusion speed (mm/min)	**2000**
Environmental condition	**Pressure atmosphere**

Table-3 Tensile property and Vickers hardness of extruded AZ61 magnesium alloy used in this study

Yield stress (MPa)	**188**
Tensile strength (MPa)	**240**
Elongation (%)	**16**
Vickers hardness (HV)	**60**

B. Impact test at cryogenic temperature –

Impact tests were carried out at temperatures of 83K (-190℃) and 293K (20℃) using small type impact testing machine of lab' own work as shown in Figure 1 [2]. To achieve cryogenic temperature, cryostat in Figure 2 made of foamed styrene was disposed on an anvil of impact testing machine. To determine impacting temperature, a cooling curve was measured for dummy sample of the extruded alloy attaching a thermocouple. Firstly, the alloy specimen and dummy sample in liquid nitrogen until it reached equilibrium, moving to the testing setup, and then pouring liquid nitrogen into the cryostat.

Figure 1 shows the impact testing equipment aided with a personal computer containing "EXCEL software". In this system [2], impact load is measured by one load cell (9321B, Kisler Group.) with capacity of 10 kN, and displacement is measured by laser displacement sensor (KEYENCE CORP., LK-030) in pursuit on loading axis to movement. Load and deflection data were conducted and stored in digital storage oscilloscope (YOKOGAWA WE-7000) to the personal computer by a USB (Ver.2.0) interface. The yield load, P_y, peak load, P_{max} and absorbing energy, E_t were calculated from the load-displacement curve.

Figure 3 shows miniature size U-notch specimen that was cut in a constant hardness region in extruded alloy. Fifth Specimens for impact test at different temperature were prepared. Initial loading speed of impact test is approximately 1.0 m/s.

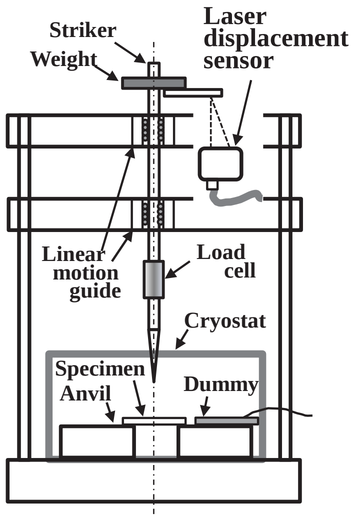

Figure 1. Schematic illustration of the small impact machine used in this study

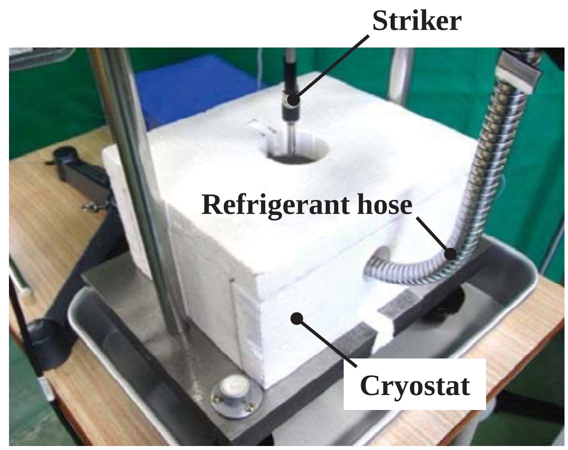

Figure 2. Photograph of the cryostat for the small impact machine used in this study

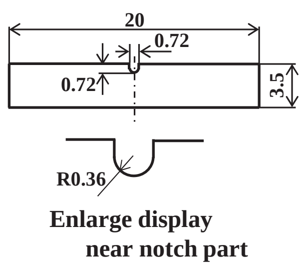

Figure3. Schematic illustration of the impact testing specimen for extruded AZ61 magnesium alloy

B. In-situ observation during tensile test –

Fracture morphology in the top of broken specimen after impact test at different temperatures was observed by digital microscope (KEYENCE, VHX-2000) and SEM (TM3030, Hitachi High-Technologies Corp.).

III. Results and Discussion

A. Inpact property at cryogenic temperature –

Typical impact load-deflection curve of the specimen at room temperature and cryogenic temperature of 83 K are shown in Figure 4, from which their respective yield load, P_y, peak load, P_{max} and absorbing energy, E_t were measured. There average values are listed in Table 4. Yield load at cryogenic temperature is approximately 32 % higher than that at room temperature, and peak loads at each testing temperatures are almost same. However, cryogenic impact toughness showed degradation of approximately 55 % compared to room temperature toughness. According to Wang et al [3], in Mg-rare earth alloys, yield strength increased while ductility decreased as the testing temperature decreased.

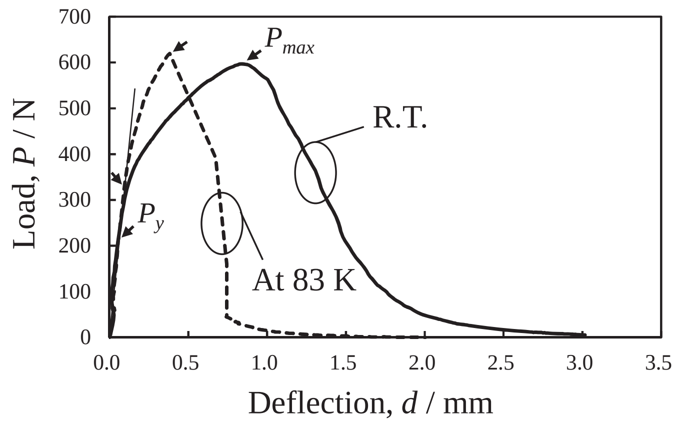

Figure 4. Typical load-displacement curves obtained from the extruded AZ61 magnesium alloy after impact test at room temperature and cryogenic temperature

Table-4 Impact properties of the extruded AZ61 magnesium alloy at room and cryogenic temperature

	R.T.	83 K
Yield load, P_y (N)	**226**	**330**
Peak load, P_{max} (N)	**596**	**616**
Absorbing energy, E_t (J)	**0.75**	**0.34**

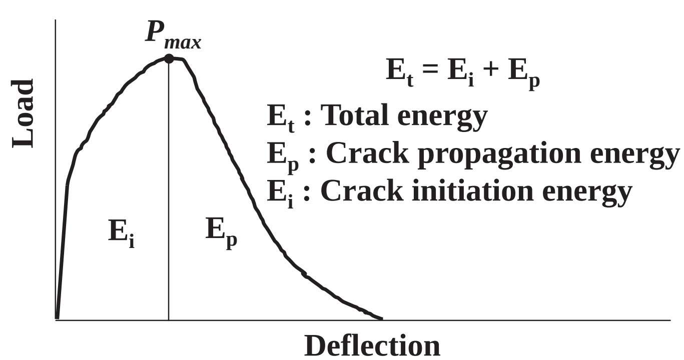

Figure 5. Schematic diagram for the toughness evaluation by instrumental impact test

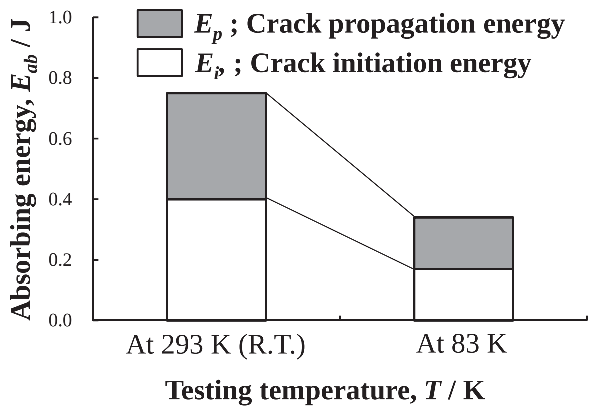

Figure 6. Change of the impact absorbing energy of the extruded AZ61 magnesium alloy at room and cryogenic temperature

Yield load and absorbing energy by impact test can be related to yield strength and ductility by tensile test [4]. These results were shown to be in relative agreement with reference [3].

On the other hand, total absorbing energy, E_t is expressed as follows;

$$E_t = E_i + E_p \qquad (1)$$

where, E_i and E_p are crack initiation energy and crack propagation energy, respectively in shown in Figure 5 [5]. Figure 6 shows change of the impact absorbing energy at room and 83 K for the extruded AZ61 magnesium alloy. The E_i at room temperature and cryogenic temperature accounted for about 53 % and 50 % of the E_t at each temperatures, respectively.

B. Fracture morphology at cryogenic temperature –

Figure 7 shows photographs of the crack propagation path of the lateral specimen surface after impact test at room temperature, (a) and at cryogenic temperature, (b). In Figure 7 (a) crack path was not straight and made a wide detour with ductility large shear lip. In Figure 7 (b), however, crack extension behavior keep in a straight, it has a marked tendency toward brittle fracture. On the other hand, the lateral expansion occurs on the compression side of the impact testing specimen. It is known that the lateral expansion means total ductility in Charpy impact test [6]. Figure 8 shows the definition of lateral expansion of fracture surface width in this study. As result, lateral expansion at cryogenic temperature (that is, average 0.118 mm) showed degradation of approximately 46 % compared to that at room temperature (average 0.254 mm). It is interesting to note that these results were shown to be in relative agreement with the degradation of cryogenic toughness in Figure 6. Figure 9 shows appearance of fracture surface after impact test at room temperature, (a) and cryogenic temperature, (b). Unevenness on the entire surface in Figure 9 (a) at room temperature indicates ductile fracture, which is also accompanied by a lateral contraction at the root of the notch and lateral expand deformation at the bottom of specimen. Generally, when the crack extends towards the free surface in the lateral direction, shear lips develop on both sides. However, the surface in Figure 9 (b) at cryogenic temperature is flat and indicative of cleavage fracture. Figure 10 shows crack initiation region near notch root, and magnification view of the symbol *a* and *b* in Figure 9, respectively. The fracture surface shown in Figure 10 can be divided into two parts that failed by different mechanisms. Initially, the fracture initiates at the center of tensile surface that is a plane strain shear fracture, which is identified as a ductile shear zone in Figure 10. The fracture surface surface of this shear zone between the notch root and dashed line is relatively smooth and approximately 45 degree angle with the surface. Ductile shear zone area at room temperature is larger than that at cryogenic temperature. Larger shear zone ahead of the notch-tip can be explained increasing of absorbing energy during impact fracture process. These observation results were in good agreement with the impact absorbing energy in Figure 6 obtained from impact tests. Moreover, the plastic zone size of crack-tip increases as a result of decreasing yield load at room temperature as shown in Table 4, leading to a blunt crack front to improve intrinsic toughening. On the other hand, the some secondary cracks marked by arrows in each figure are confirmed at both surfaces. Greater effort should be made in studying secondary crack and its role on absorbing energy. Finally, as results from observation of fracture morphologies, formation energy of fracture surface of the specimen tested at room temperature was higher than that tested at 83 K. The energy for fracture surface strongly relates impact toughness of ductility material.

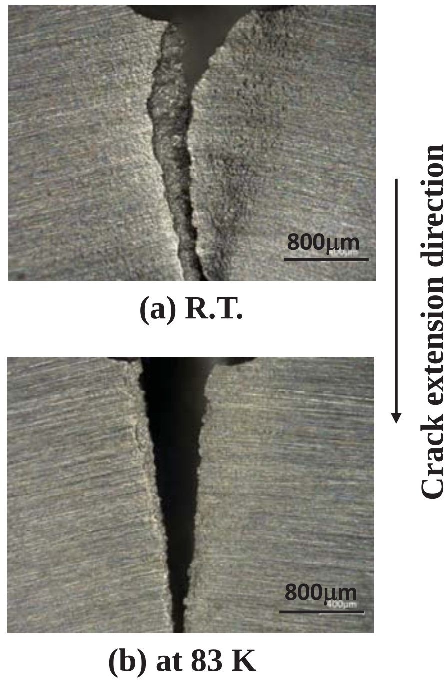

Figure 7. Schematic showing impact crack propagation path of the extruded AZ61 magnesium alloy tested at room temperature, (a) and 83 K ,(b)

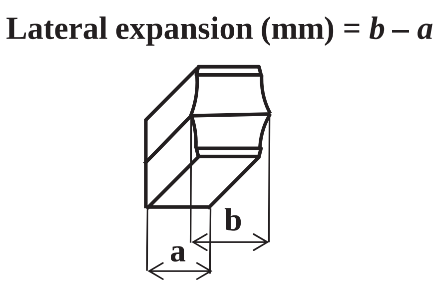

Figure 8. Schematic showing measurement definition of the lateral expansion after impact test

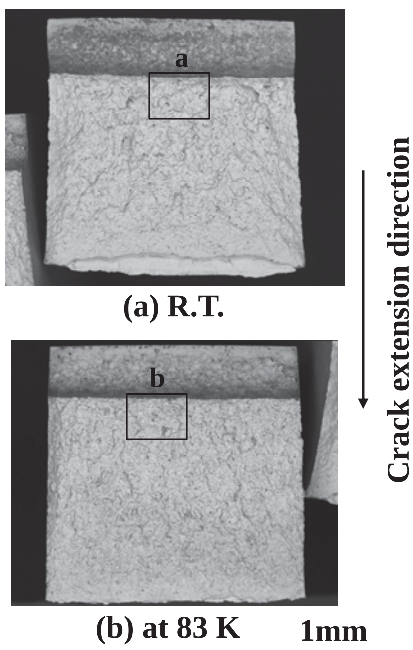

Figure 9. Schematic showing typical fracture appearance of the extruded AZ61 magnesium alloy tested at room temperature, (a) and 83 K ,(b)

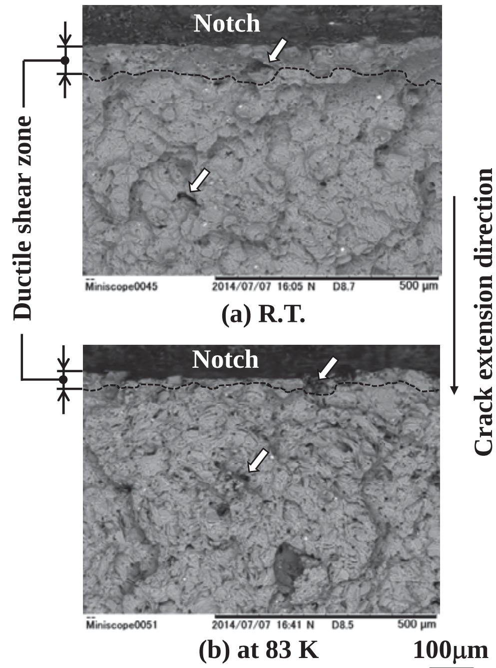

Figure 10. Schematic showing impact crack initiation region near notch root of the extruded AZ61 magnesium alloy tested at room temperature, (a) and at 83 K, (b). Arrow indicates secondary cracks perpendicular to the fracture surface

IV.CONCLUSION

In this study, impact test at cryogenic temperature was conducted for the extruded AZ61 magnesium alloy, which impact toughness and fracture morphology was investigated and evaluated fundamentally.

The results of this work can be summarized as follows.

(1) In extruded AZ61 magnesium alloy, yield load, P_y at cryogenic temperature is approximately 32 % higher than that at room temperature, and peak loads, P_{max} at each testing temperatures are almost same. However, cryogenic impact toughness, E_t showed degradation of approximately 55 % compared to room temperature toughness.

(2) The crack initiation energy, E_i at room and cryogenic temperature accounted for about 53 % and 50 % of absorbing energy, E_t at each temperatures, respectively.

(3) Crack path behaviour at room temperature made a wide detour with ductility by large shear deformation zone. On the other hand, crack extension at cryogenic temperature showed a marked tendency toward brittle fracture.

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