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# Effect of strain rate on behaviour of $Fe_3Al$ under tensile impact

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The effect of strain rate on the behaviour of $Fe_3Al$ has been investigated experimentally in the range 90–1300 $s^{-1}$ under tensile impact. The experimental results indicate that $Fe_3Al$ is strain-rate sensitive and its critical strain in maximum stress increases with increasing strain rate. According to the test results for $Fe_3Al$ in air and water, it is confirmed that environmental embrittlement induced the fracture of $Fe_3Al$ under tensile impact. With testing at faster strain rate, further hydrogen embrittlement is suppressed. This is consistent with the micrography of the fracture surface in $Fe_3Al$ specimens, which indicates that these iron aluminides are intrinsically quite ductile.

## 1. Introduction

In recent years, considerable effort has been devoted to the study of ordered intermetallics, a unique class of metallic materials that have long-range order crystal structures below a critical temperature in the solid state. Some of these ordered intermetallics, especially those based on aluminides, such as $Fe_3Al$, possess many attractive properties for structural use at elevated temperature in harsh environments [1–3]. In general, the aluminides contain sufficient amounts of aluminium to form, in oxidizing environments, oxide scales that are often compact and protective. These intermetallics have relatively low density, high melting point, good thermal conductivity, and superb high-temperature strength. As a result, these intermetallics are particularly suited for structural applications at elevated temperatures. However, the aluminides, like other ordered intermetallics, generally exhibit brittle fracture and low ductility at ambient temperatures [4, 5]. Poor fracture resistance and fabricability have restricted the use of these intermetallics as engineering materials in most cases. Because of concerted efforts, however, significant progress has been made in our understanding of the lack of ductility in these intermetallics, and both intrinsic and extrinsic factors governing their brittle fracture behaviour have been identified.

Recent studies have shown that $Fe_3Al$ aluminides are intrinsically ductile, and the poor ductility commonly observed in air tests is caused mainly by extrinsic effects [6–8]. Moisture-induced hydrogen embrittlement has been recognized as one of the major causes of low ductility. These attempts have led to the development of more ductile and stronger $Fe_3Al$ based alloys for structural applications. At present, several intermetallic $Fe_3Al$ alloys are in a relatively mature stage of development and are either ready or almost ready for industrial use. However, little effort has been devoted to the behaviour of this alloy at high strain rate under tensile impact. For a clear understanding of $Fe_3Al$ behaviour, more detailed information is required. This paper reports a comprehensive study of the behaviour of $Fe_3Al$ under tensile impact and emphasis is placed on understanding the environmental effect on fracture behaviour of $Fe_3Al$.

## 2. Experimental procedure

The $Fe_3Al$ alloy, (Fe–28Al in atomic per cent) was prepared by arc melting under argon using commercial pure iron and aluminium. The alloy buttons were remelted for four times to improve their homogeneity. The alloy bars with a size of 20 mm diameter × 100 mm were prepared by drop casting from a master alloy button. After homogenizing for 5 h at 1100 °C, these bars were hot rolled to about 1.2 mm sheets at 800–1000 °C. All specimens were kept at 850 °C for 30 min for annealing and then cooled in the furnace to 500 °C for 120 h. The Tensile specimens were cut from the sheets by electrical sparking. The specimen and its connection to the bars is shown in Fig. 1. Tensile impact tests were carried out at four different strain rates ranging from 90–1300 $s^{-1}$ on a self-designed bar–bar tensile impact apparatus with a rotating disc.

Fig. 2 is a schematic diagram of the apparatus and measuring principle. The specimen is glued to slots in the ends of the input bar (4) and the output bar (6) using high shear-strength adhesive agent. As the hammer (1) of the high-speed rotating disc impacts the block (2), the short metal bar (3), made of aluminium alloy, breaks and an approximately rectangular input stress impulse wave is transmitted through the input bar to the specimen (5). A partial impulse wave is reflected to the input bar and the survival wave is transferred to the output bar (6). Therefore, the input stress wave, $\varepsilon_i(t)$, and reflective stress, $\varepsilon_r(t)$, wave can be measured by strain gauges (7) on the input bar, and

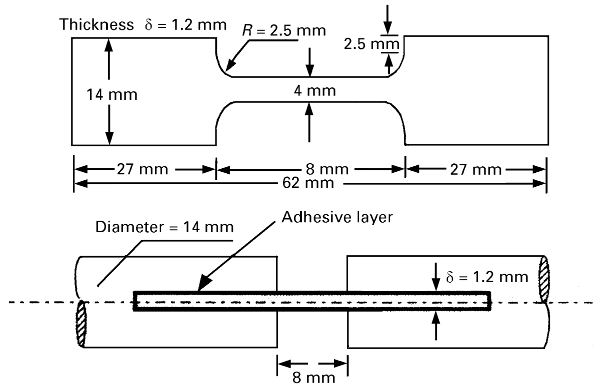


*Figure 1* $Fe_3Al$ specimen and its connection to the bars.

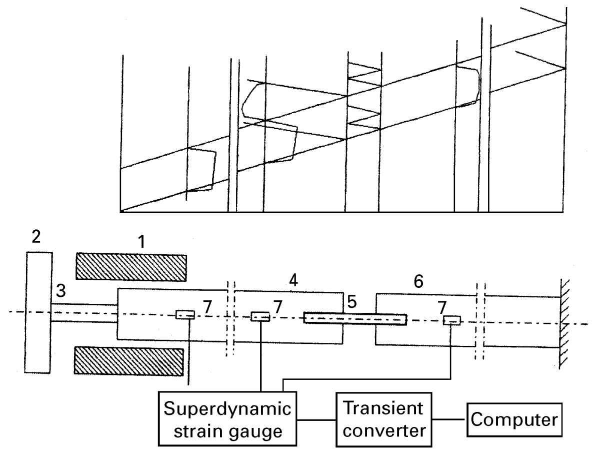


*Figure 2* Sketch of the self-designed tensile impact apparatus and the measuring principle.

the transmission wave, $\varepsilon_t(t)$, can also be measured by strain gauges on the output bar. These wave signals are recorded on a transient converter through a superdynamic strain gauge. The equations of stress $\sigma_s(t)$, strain $\varepsilon_s(t)$ and strain rate, $\dot{\varepsilon}_s$, of the specimens are as follows [9]

$$\sigma_s(t) = \frac{EA}{A_s}\varepsilon_t(t) \tag{1}$$

$$\varepsilon_s(t) = \frac{2C_0}{L_0}\int_0^t [\varepsilon_i(\tau) - \varepsilon_t(\tau)]\,d\tau \tag{2}$$

$$\dot{\varepsilon}_s(t) = \frac{2C_0}{L_0}[\varepsilon_i(t) - \varepsilon_t(t)] \tag{3}$$

where $E$, $A$ and $C_0$ are the modulus, cross-section and elastic wave speed of input bar and output bar, respectively, and $L_0$ and $A_s$ are the length and cross-section of the testing part of the specimen. Experimental results for different strain rates can be obtained by adjusting the impact speed and diameter or length of the short metal bar.

## 3. Results and discussion

Fig. 3 shows the strain–stress responses of $Fe_3Al$ in the strain-rate range 90–1300 $s^{-1}$ under tensile impact in air. It is obvious that $Fe_3Al$ is strain-rate sensitive and exhibits high-velocity ductility under tensile impact. This means the higher the strain rate, the larger the critical strain in maximum stress of $Fe_3Al$. Fig. 4 shows stress–strain curves of $Fe_3Al$ specimens in air and water under a strain rate of 300 $s^{-1}$. The critical strain drops to around 27.45% in water, which is comparable to the values of $Fe_3Al$ in air at the same strain rate. Table I lists the effect of tensile impact on properties of $Fe_3Al$ under different strain rates.

The test results indicate that moisture in air is a major cause of fracture in $Fe_3Al$ specimens. It is thought to act by oxidizing reactive elements in

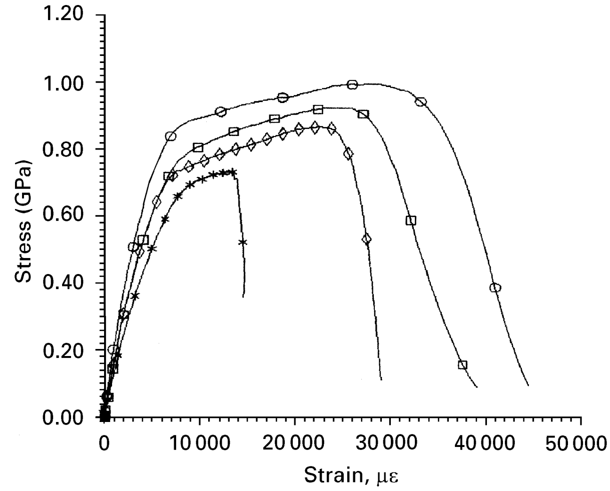


*Figure 3* Stress–strain curve of $Fe_3Al$ under tensile impact. Strain rates: (∗) 90 $s^{-1}$, (◇) 300 $s^{-1}$, (□) 700 $s^{-1}$, (○) 1300 $s^{-1}$.

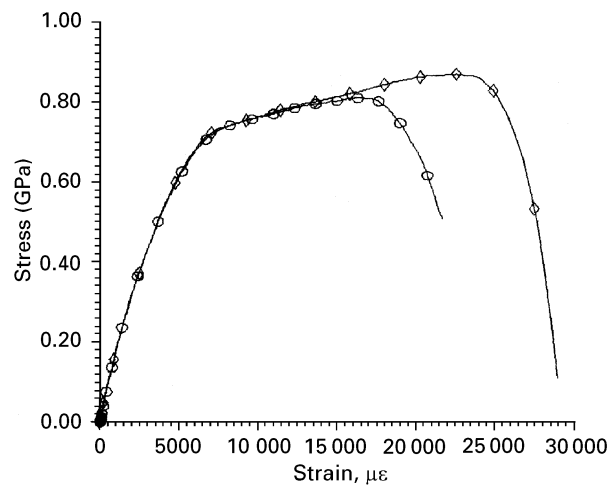


*Figure 4* Stress–strain curve of $Fe_3Al$ at (◇) air and (○) water environments, at a strain rate of 300 $s^{-1}$.

TABLE I The effect of tensile impact on properties of $Fe_3Al$ under different strain rates

| Strain rate ($s^{-1}$) | Test environment | Critical strain (%) | Ultimate tensile strength (GPa) |
|---|---|---|---|
| 90 | Air | 1.289 | 0.7363 |
| 300 | Air | 2.248 | 0.8726 |
| 300 | Water | 1.631 | 0.8126 |
| 700 | Air | 2.412 | 0.9302 |
| 1300 | Air | 2.774 | 1.0010 |

the $Fe_3Al$ specimen (the aluminium present in $Fe_3Al$), thereby generating atomic hydrogen ($2Al + 3H_2O \rightarrow Al_2O_3 + 6H$), which then enters the metal and causes crack-tip embrittlement. This reaction in $Fe_3Al$ at a high strain rate is much slower than that at a low one; therefore, the amount of generated atomic hydrogen in the metal at high strain rate is less. With tensile testing at a faster strain rate, further hydrogen embrittlement is suppressed. Thus $Fe_3Al$ shows high-velocity ductility under tensile impact. The test results of $Fe_3Al$ in air and water further verify that the extrinsic factor, moisture-induced hydrogen embrittlement, has an intense effect on the fracture of $Fe_3Al$. The results also indicate that molecular hydrogen is not as harmful as $H_2O$, probably because it is not readily dissociated into atomic hydrogen by the iron aluminide surfaces. When moisture-induced environmental embrittlement is suppressed, $Fe_3Al$ exhibits substantial ductility, which implies that these iron aluminides are intrinsically quite ductile.

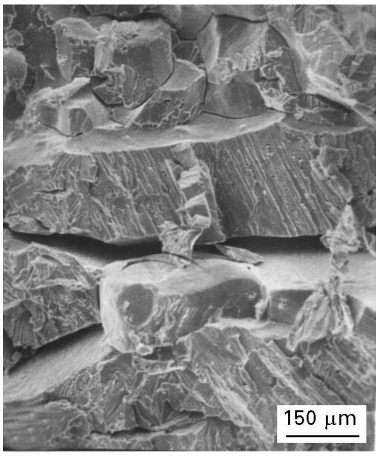


*Figure 6* Fracture surface of a specimen at a strain rate of $300\ s^{-1}$.

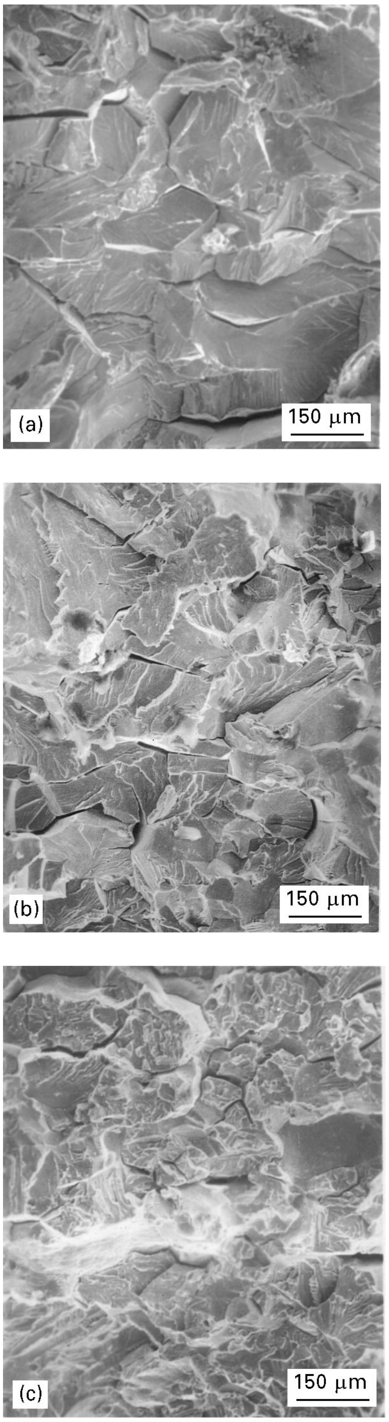


*Figure 5* Fracture surface of a specimen at different strain rates: (a) $90\ s^{-1}$, (b) $300\ s^{-1}$, (c) $1300\ s^{-1}$.

Fig. 5a–c show the typical fracture surfaces of $Fe_3Al$ after fracture at strain rates of 90, 300, and $1300\ s^{-1}$. It is clear that fracture is caused predominantly by transgranular fracture under tensile impact, even after extensive plastic deformation at a strain rate of $1300\ s^{-1}$. With increasing strain rate, the transgranular surface becomes smaller and smaller, and more and more ductile tearing is apparent. Fig. 6 shows transgranular fracture of a specimen tested at strain rate of $300\ s^{-1}$, which contained a larger secondary crack. The fracture surfaces of $Fe_3Al$ specimen at other strain rates also contained secondary cracks, as seen in Fig. 5a–c. The secondary crack is a common phenom enon in hydrogen embrittlement of intermetallics [10, 11]. It should be noted that the transgranular fracture is not totally brittle, but involved some plasticity.

## 4. Conclusions

The results of tensile impact tests showed that the fracture mode of $Fe_3Al$ differed with the test strain rates. The results are as follows:

1. $Fe_3Al$ is strain-rate sensitive and exhibits high-velocity ductility. The higher the loading speed, the larger is the critical strain at maximum stress.

2. The results showed that $Fe_3Al$ is intrinsically quite ductile, and the poor ductility usually observed in air tests is the result of an extrinsic factor, namely water vapour. The higher the loading speed, the greater is the suppression of environmental embrittlement. The mechanism of high-velocity ductility is induced by hydrogen embrittlement which is suppressed at high strain rates.

3. The fracture surface of $Fe_3Al$ specimens is changed with the loading speed. With increasing strain rate, the transgranular surface becomes smaller and smaller, and more and more ductile tearing is

apparent. This is consistent with the tensile impact results of $Fe_3Al$.

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