Materials Characterization at High Speed by Dynamic Tensile Tests*

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Abstract

In this paper, the dynamic deformation behaviors of 2 aluminum alloys (AA6016, AA5182) and 2 steels (v 1158, FeP04) are investigated. Firstly, the test method, an improved Hopkinson pressure bar test, is introduced. Then, the test results are presented and analyzed. The strain rate range used in this study is between 290 s^{-1} and 1750 s^{-1}.The test results show that the yield stresses of all four tested materials increase along with the increase of strain rate, but the ductility does not. An interesting finding is that the tested Al alloys demonstrated larger elongation than those of steels. In conventional tensile tests, as it is well known, the tensile elongation of low carbon steels is usually much higher than the one of Al alloys. So, it can be predicted that the aluminum alloys could have better formability than the steels in high speed forming processes, though the underlying mechanism is not fully understood.

Key Words:

High speed, Material test, Aluminum alloy, Steel

1 Introduction

In recent years, the automotive industry has been facing three major challenges: 1) the increasingly strict legislations on environment protection; 2) higher safety standards; 3) more sophisticated customer demands and, therefore, more product segmentations. To meet these challenges, the automotive makers have been in continuous pursuit of new

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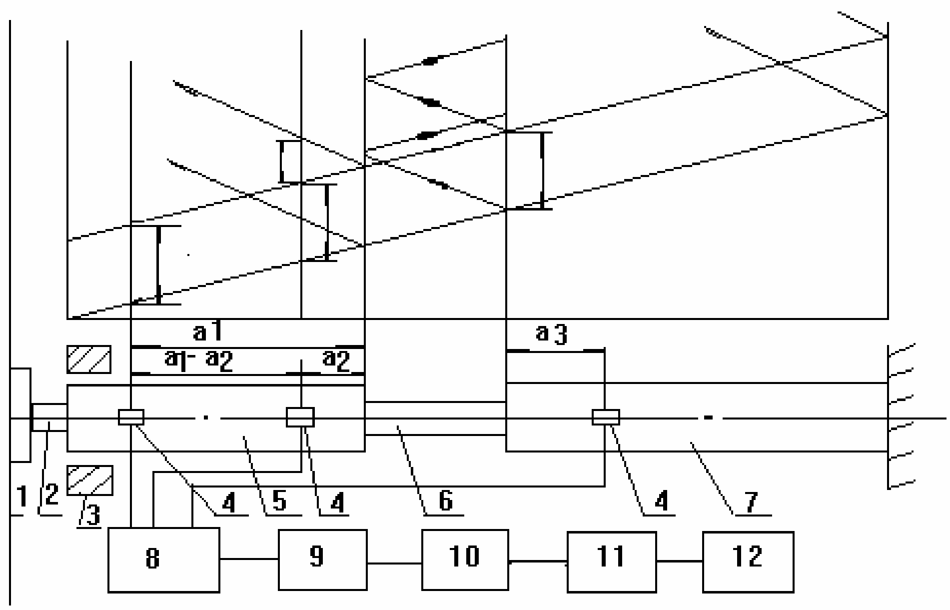
materials and new manufacturing technologies in order to be able to provide lighter and safer cars with lower costs by using lightweight materials like aluminum alloys and more flexible manufacturing processes. In this context, innovative processes such as electromagnetic forming (EMF) and electrohydraulic forming (EHF) received more attention and have become the subject of many research projects. EMF and EHF technologies are based on high-voltage discharge of capacitors: through the conductive coil or the electrodes in water the large pulsing energy discharged from the capacitor banks can generate high pressure and deform the workpiece in very high velocity. The advantages of these technologies include low investment in one sided dies [1], increased formability [2], reduced wrinkling and springback [3]. Strain rates in these forming processes are usually in the range of 10^2-10^3 s^{-1}, much higher than the strain rates in which the conventional tensile tests are carried out (10^{-4} to 10^{-2} s^{-1}). For the design and analysis of high speed forming processes the characteristics and deformation behaviors of workpiece materials must be known. However, today there exist only limited dynamic material test data. On the other hand, the need for vehicle crashworthiness design and optimization poses further demands for systematic materials testing under dynamic conditions. The combined needs make the investigation of material dynamic characteristics more imperative.

The actual high speed material testing techniques include dropweight machines [4, 5], split hopkinson pressure bars (SHPBs) [6, 7], Taylor impact [8], and shockloading by plate impact [9]. These testing methods have a common problem related to the disturbed wave by mechanical oscillation. In this paper, a new method based on “rotating disk indirect bar-bar tensile impact apparatus (RSHTB)” is presented. The novelty of the RSHTB method consists in the fact that a destructive short metal bar is used to solve the problem of the mechanical oscillation, using its fracture to filter the oscillation wave. As a result, the reliability of the acquired data is significantly improved.

In this paper, the dynamic deformation behaviors of 2 aluminum alloys (AA6016, AA5182) and 2 steel (V1158, FeP04) materials are investigated by means of the RSHTB dynamic tensile test method.

2 Experimental procedure

The schematic drawing of a RSHTB device is shown in Figure 1. The novelty with the RSHTB device is the introduction of a mechanical filter. When the mass 1 is impacted by hammer 3 on the rotating disk the produced rectangular impulse tensile stress wave is transmitted to input metal stick 5 from the destructive short metal stick 2. The short metal stick 2 is deformed until fracture occurs. So, an incident wave is generated by impact between 2 and 5, other than between 3 and 1. In this way, the incident rectangular wave reached at the input metal stick 5 is mechanically filtered, hence it is clean and stable with a very little disturbed wave. This is very important for obtaining reliable test results. In addition, the height and width of the incident rectangular wave can be adjusted easily with this kind of device to obtain the strain rate range 10^1-$3.5x10^3 s^{-1}$. The test sample’s shape, dimension, and the clamping method are illustrated in Figure 2.



1-mass; 2-the destructive short metal stick; 3-hammer; 4-strain cage; 5-input stick; 6-sample; 7-output stick; 8-supper dynamic strain meter; 9-TCL wave shape recorder; 10-connect switch; 11-computer; 12-printer.

***Figure 1**: Apparatuses t for RSHTB*

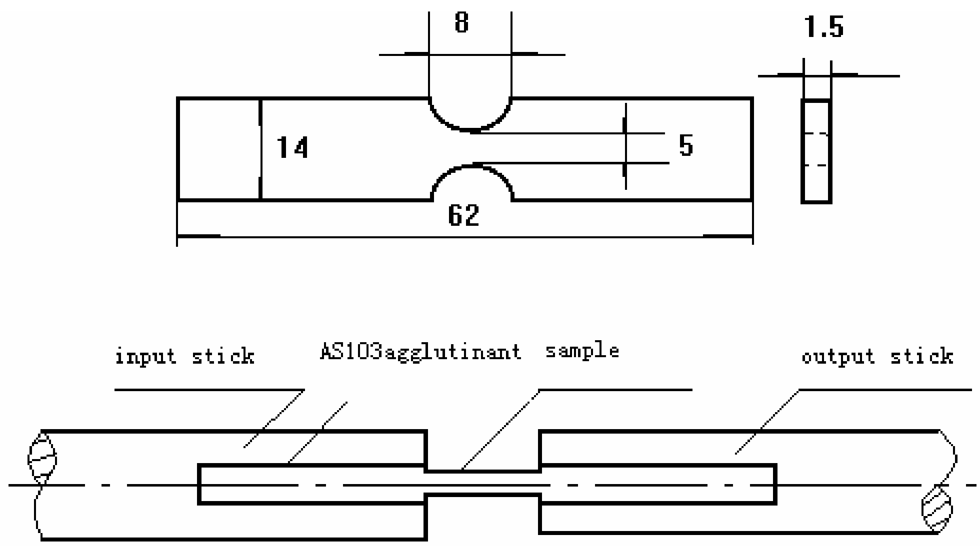


***Figure 2**: Dimension of test sample and its linking type*

From the theory of one-way stress wave the force and the displacement in the two end s of test sample are expressed as follows:

$$P_1(t) = E_1 A_1[\varepsilon_i(t) + \varepsilon_r(t)] \qquad (1)$$

$$P_2(t) = E_2 A_2 \varepsilon_t(t) \tag{2}$$

$$u_1(t) = C_{01}\int_0^t [\varepsilon_i(\tau) - \varepsilon_r(\tau)]\, d\tau \tag{3}$$

$$u_2(t) = C_{02}\int_0^t \varepsilon_t(\tau)\, d\tau \tag{4}$$

The E1, A1, C01 and E2, A2, C02 are the elasticity modulus, cross section area, and longitudinal wave speed of elasticity respectively for the end surfaces of both the input stick and output stick. The εi(t), εr(t), εt(t) are the strain signals of the incident wave, the reflective wave, and the transmission wave respectively.

It is supposed that the stress and strain are uniform in the sample without cracks, thus in the uniaxial tension sample, the stress, strain, and strain rate are the following:

$$\sigma_S(t) = \frac{1}{2A_S}[p_1(t) + P_2(t)] = \frac{1}{2A_S}[E_1 A_1 \varepsilon_i(t) + E_2 A_2 \varepsilon_t(t)] \tag{5}$$

$$\varepsilon_s(t) = \frac{1}{l_s}[u_1(t) - u_2(t)] = \frac{1}{l_s}\left\{C_{01}\int_0^t [\varepsilon_i(\tau) - \varepsilon_r(\tau)]\, d\tau - C_{02}\int_0^t \varepsilon_t(\tau)\, d\tau\right\} \tag{6}$$

$$\varepsilon_s(t) = \frac{1}{l_s}[C_{01}(\varepsilon_i(t) - \varepsilon_r(t)) - C_{02}\varepsilon_t(t)] \tag{7}$$

where A_s and l_s are the cross-area and length of the gauge. When the diameters of input stick and output stick are same we have:

$$E_1 = E_2 = E, A_1 = A_2 = A, C_{01} = C_{02} = C_0$$

,thus

$$\varepsilon_i(t) + \varepsilon_r(t) = \varepsilon_t(t) \tag{8}$$

$$\sigma_s(t) = \frac{EA}{2A_s}[\varepsilon_i(t) + \varepsilon_r(t) + \varepsilon_t(t)] = \frac{EA}{A_s}\varepsilon_t(t) \tag{9}$$

$$\varepsilon_s(t) = \frac{C_0}{l_s}\int_0^t [\varepsilon_i(\tau) - \varepsilon_r(\tau) - \varepsilon_t(\tau) d\tau = \frac{2C_0}{l_s}\int_0^t [\varepsilon_i(\tau) - \varepsilon_t(\tau) d\tau \tag{10}$$

$$\varepsilon_s(t) = \frac{C_0}{l_s}[\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)] = \frac{2C_0}{l_s}[\varepsilon_i(t) - \varepsilon_t(t)] \tag{11}$$

From equation (8) to (11), the stress, stain, and strain rate of the test sample can be obtained at anytime so long as strain signals of input stick and output stick are measured precisely. With the dynamic tensile test device and the test specimen described above the largest reachable strain rate is about 2.2x103s^{-1}.

3 Results and discussions

The engineering stress – engineering strain curves of AA6016 and AA5182 are shown in Figure 3 and Figure 4 respectively. And in Figure 5 and Figure 6 the curves of engineering stress vs. engineering strain for two steels V1158 and Fep04 are shown. It can be clearly seen that for all four materials the yield stress increases with strain rate, but the ductility showed a complex picture. The increase of yield stress of steels is much more evident than that of Al alloys, the ductility of Al-alloy is even higher than that of the steel. A comparison between all 4 materials under similar strain rate conditions is shown in Figure 7.

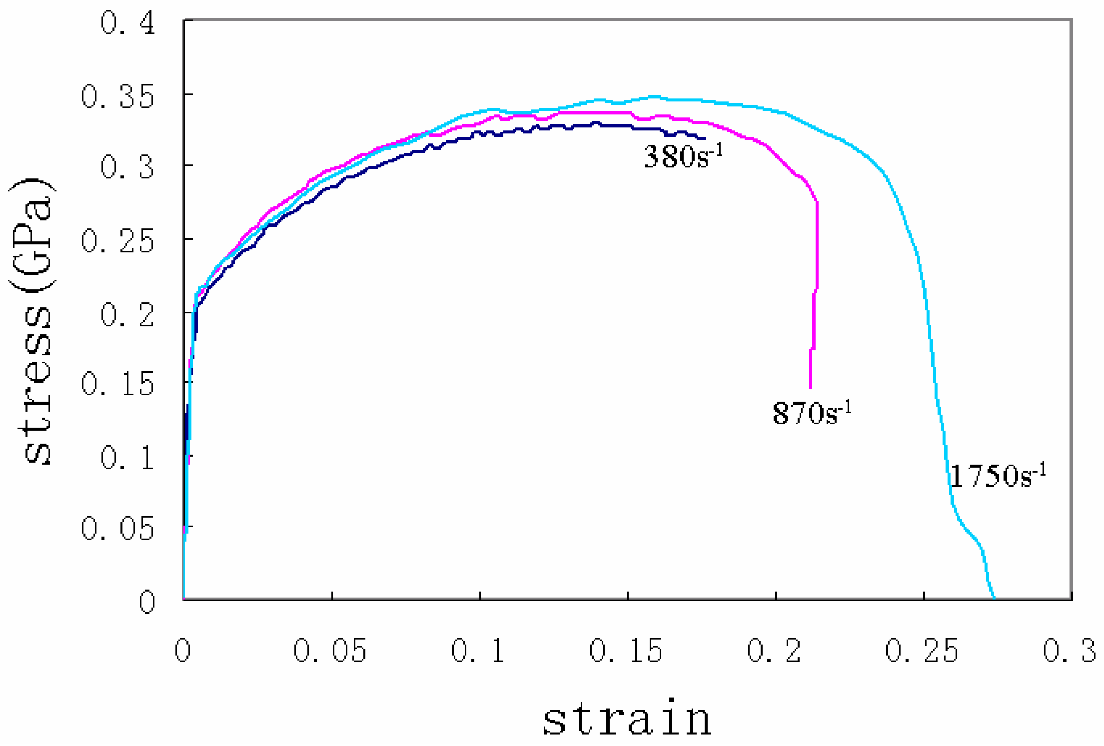


Figure 3: *Engineering stress vs. engineering strain of AA6016 alloy*

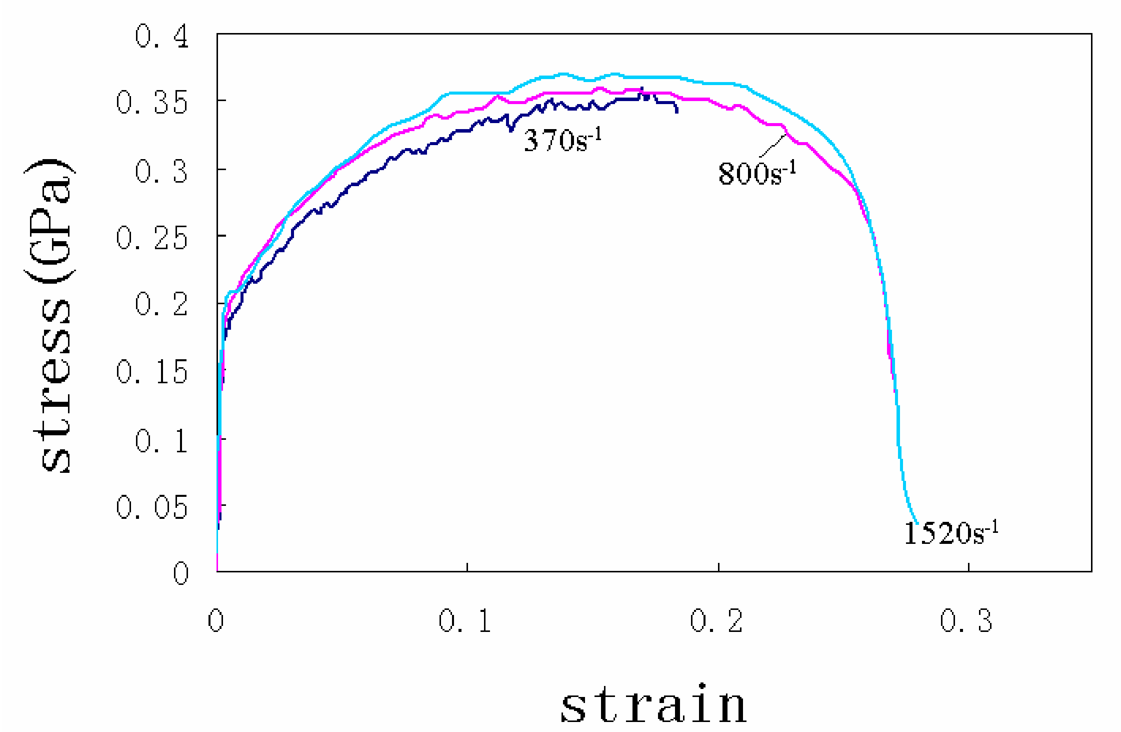


***Figure 4**: Engineering stress vs. engineering strain of AA5182 alloy*

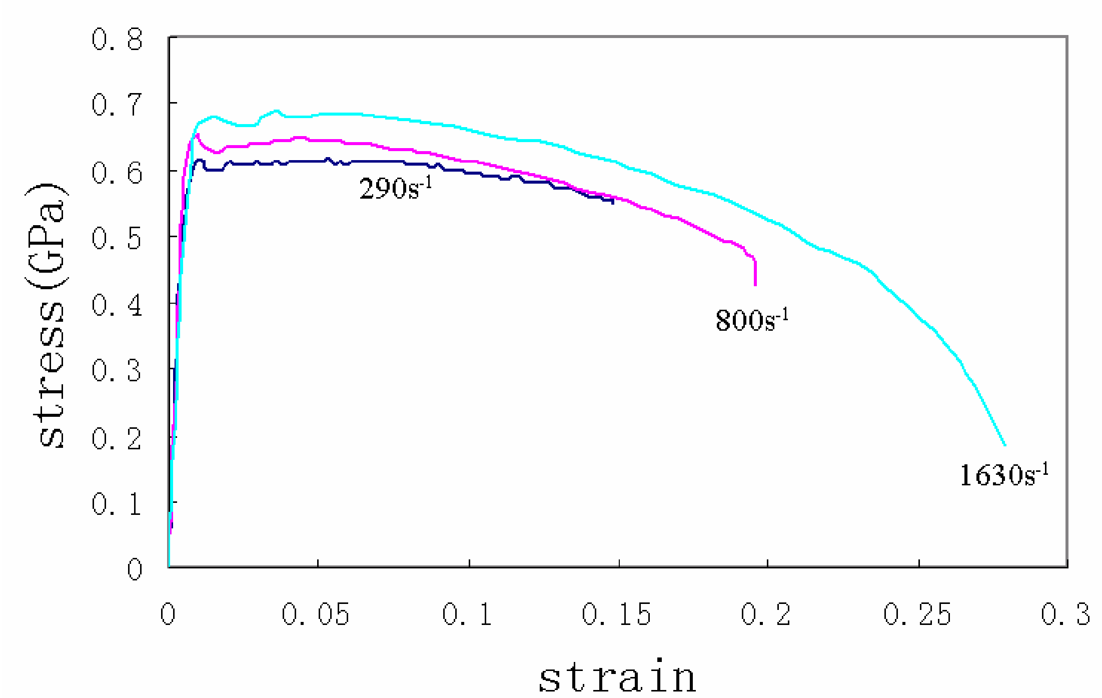


***Figure 5:** Engineering stress vs. engineering strain plot of V1158 steel*

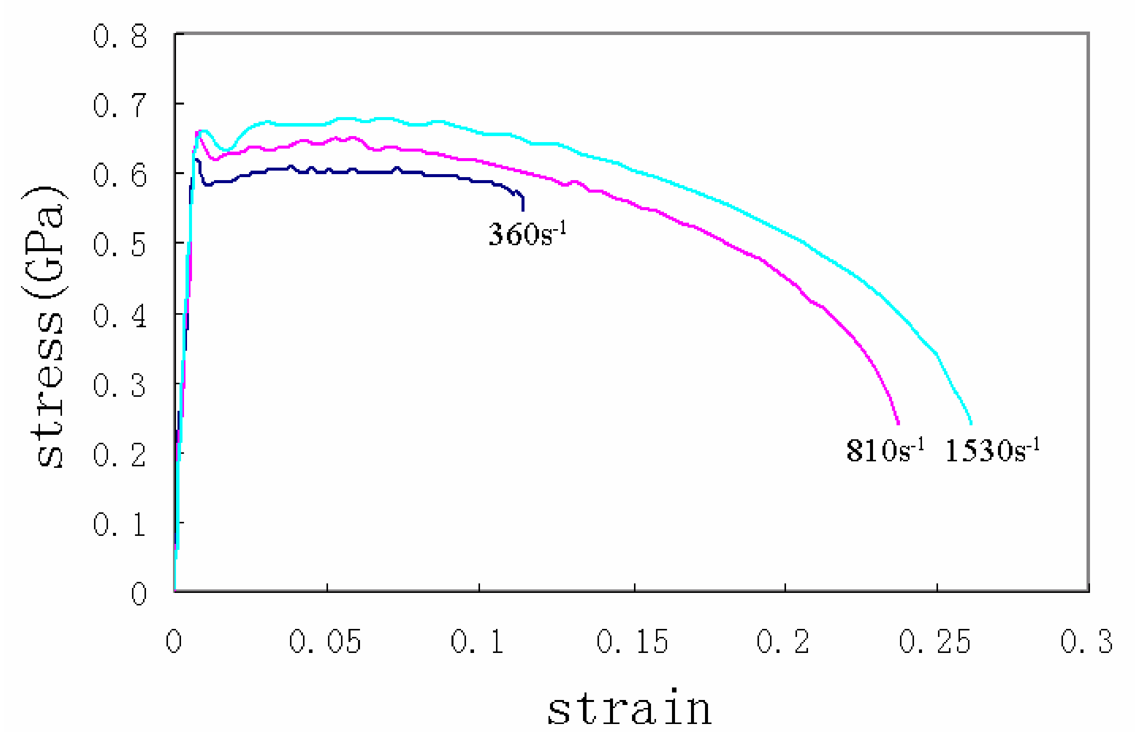


Figure 6: *Engineering stress vs. engineering strain plot for FeP04 steel*

In conventional quasi static tests, as it is well known, the ductility of low carbon steels is much better than that of aluminum alloys. For example, the total elongation of FeP04 steel sheet can be as high as 45% in conventional quasi static tensile tests (see Figure 8).

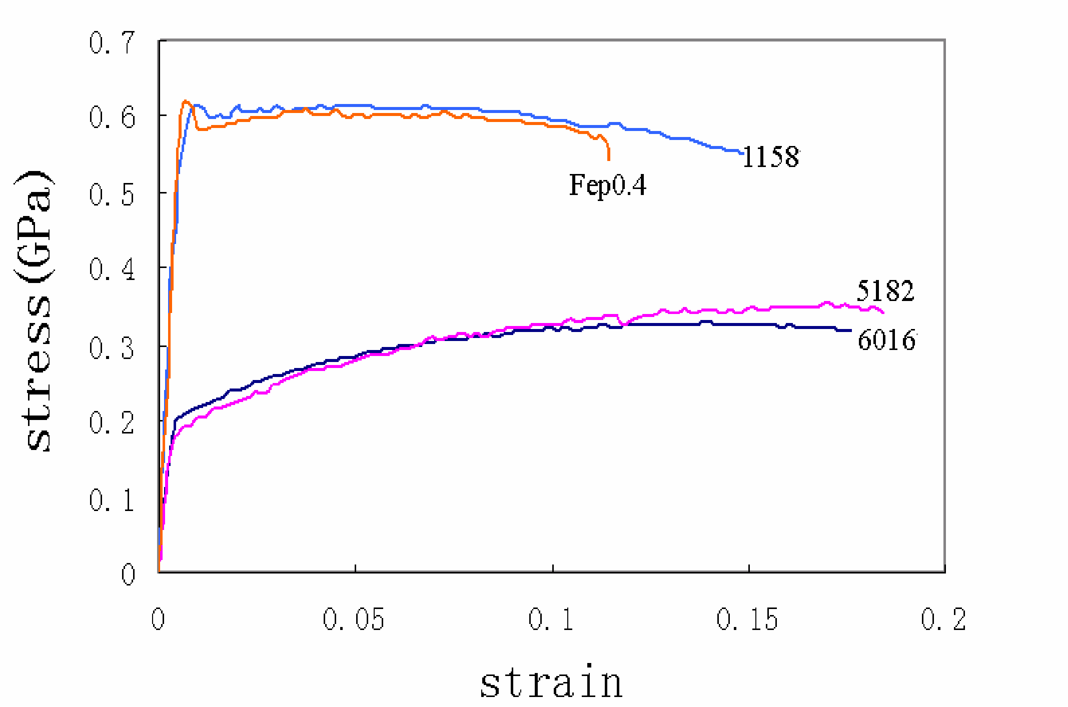


Figure 7: *Engineering stress vs. engineering strain plot for all 4 materials under different deformation strain rates: 6016(380 S^{-1}),5182(370 S^{-1}),1158(290 S^{-1})andFep0.4(390 S^{-1})*

For 5000 and 6000 series aluminum alloys the total tensile elongations are usually less than 25%. However, it is interesting to note that the dynamic test results showed the contrary trend. The aluminum alloys demonstrated a higher total elongation than that in quasi static test, although the gain is not large. On the other hand, the steel materials reached a much lower total elongation than that obtained in conventional tests, unexpectedly lower than that of aluminum alloys tested in this investigation. This observation is contrary to the results of some previous studies, which stated that the fracture strain of bcc-steels often was enhanced by 20 to 50% at strain rates about $10^3 s^{-1}$ [10] and attributed the possible reasons to twinning and adiabatic heating [11]. The increase in ductility of aluminum alloys is in agreement with the results obtained in other studies [12].

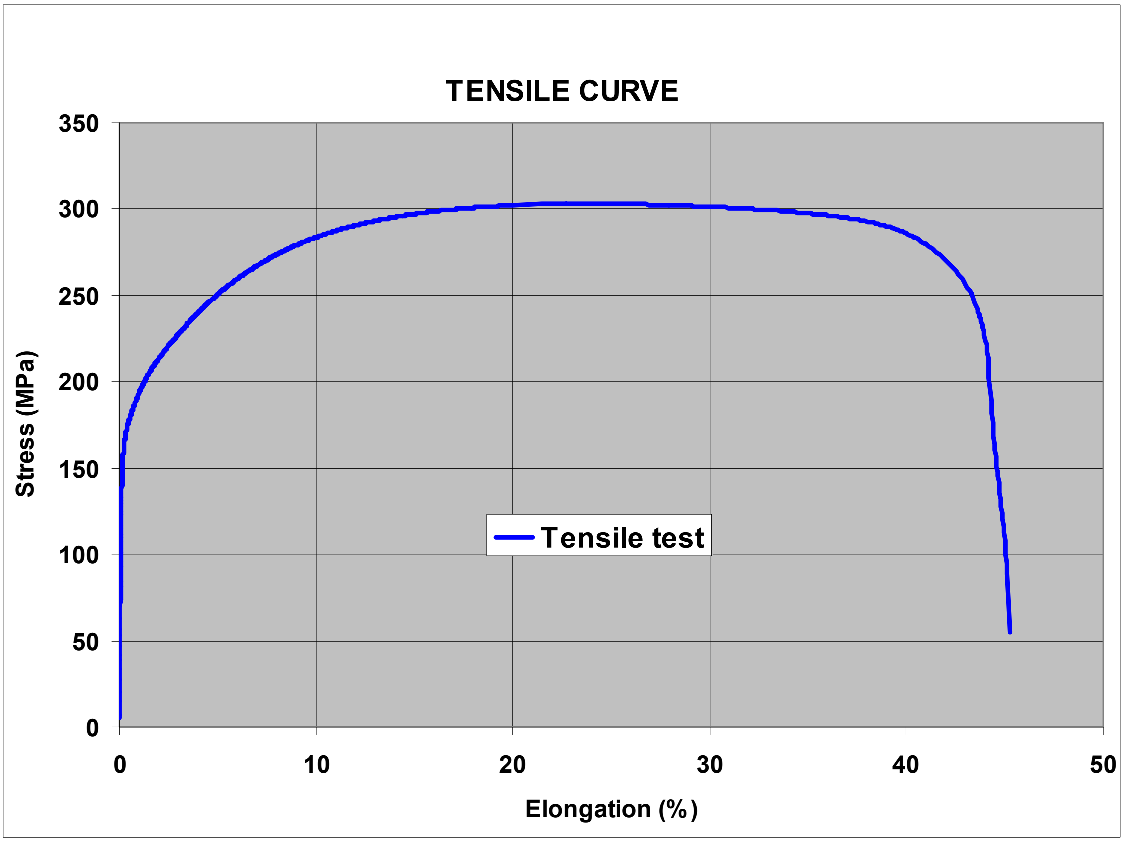


Figure 8: *Engineering stress vs. engineering strain curve of FeP04 obtained with conventional quasi static tensile tests*

In order to understand the experimental phenomena observed in this study, an analysis on the constitutional stress – strain relationship will be helpful. The strain hardening exponent and strain rate sensitivity are important parameters for the explanation of material flow behavior. Since the data presented above are in engineering stress and engineering strain, true stress and true strain data are needed to get the strain hardening exponent *n* and the strain rate sensitivity value *m*. True stress and true strain are calculated according to the following equations:

$$\sigma = s \cdot (1+e) \tag{12}$$

$$\varepsilon = \log_e(1+e) \tag{13}$$

where

e is the engineering strain
ε is the true strain
S is the engineering stress
σ is the true stress

The *n* and *m* values are then calculated according to the slope method. The *n* values are obtained from log-log plot of true stress and true strain, the selected strain range is between 0.05 and 0.10. For each material the strain hardening exponent at each strain rate is calculated and the results are included in Table 1. Similarly, for each material the *m* value is obtained from log-log plot of true stress and strain rate, the true stress values corresponding to true strain o.15 were taken. The results are given in Table 2.

Materials	n-values (at true strain 0.05 – 0.10) in different strain rates		
AA6016	0.118 (380s^{-1})	0.203 (870s^{-1})	0.195 (1750s^{-1})
AA5182	0.225 (370s^{-1})	0.197 (800s^{-1})	0.235 (1520s^{-1})
V1158	0.0014 (290s^{-1})	0.0015 (800s^{-1})	0.0026 (1630s^{-1})
FeP04	0.0021 (360s^{-1})	0.0032 (810s^{-1})	0.0048 (1530s^{-1})

Table 1*: Strain hardening exponent (corresponding to strain range 0.05 – 0.10)*

Material	AA5182	AA6016	V1158	FeP04
m-value	0.0350	0.0377	0.0624	0.0717

Table 2*: Strain rate sensitivity value m (calculated at true strain 0.15)*

In metal forming, particularly in stretching and bending deformations, the strain hardening exponent is an indicator of the formability of the material. A higher level of this exponent is desirable since it results in a better distribution of the strain. In conventional tensile tests at room temperature the *n* values for FeP04 range between 0.23 and 0.25. From table 1 it can be seen that while for the Al alloys the strain hardening exponents are still close to 0.20, those for steels, however, approach to zero. Without strain hardening the steels continuously lose the ability to sustain a stable deformation and, as a result, the total elongations are quite low. As to strain rate sensitivity, for engineering metals at room temperature the *m* values are in the range of -0.005 to 0.015. The *m* value is the measure of a material to resist necking and is particularly important for superplastic deformation at high temperatures, but considered less important in quasi static deformation at room temperature. From Table 2 it can be noted that the two steel materials possess much higher *m* values than the two aluminum alloys. That is why in the steels a significant increase in yielding strength is observed.

The above mentioned analysis can explain why the steels investigated in the present study demonstrated lower ductility at high speed deformation, but the reason why the aluminum alloys showed better ductility is not understood. For the purpose of EMF and EHF, the results described above reveal that aluminum alloys are ideal materials for high speed forming processes because of their lower strain rate sensitivity and high ductility properties under dynamic conditions, in addition to the advantage of good conductivity which is useful for EMF processes. On the other hand, the high strain rate sensitivity of steels in high speed deformation is a great advantage for automotive applications since this can contribute to the improvement of crashworthiness.

4 Conclusions

The rotating disk indirect bar-bar tensile impact apparatus is proved to be one of the best methods for high speed dynamic material tensile tests. According to the test results, under dynamic conditions the aluminum alloys showed better ductility than in conventional quasi static tests and at the same time there is a noticeable increase in yield strength. The two steel materials investigated in this paper demonstrated quite high strain rate sensitivity in high speed tensile deformation with a significant increase in yield strength in comparison to quasi static conditions. The ductility of the two steels is found to be lower than that obtained in conventional quasi static tensile tests due to close-to-zero strain hardening exponents. These mechanical properties mean that aluminum alloys are very suitable for high speed forming applications, while the high strain rate sensitivity of steels can bring about big advantages in automotive applications in terms of crashworthiness.

References

[1] *Wilson, F. W.:* High Velocity Forming of Metals. ed. American Society of Tool and Manufacturing Engineers. Prentice-Hall,Inc,Englewood Cliffs, N.J. 1964

[2] *Golovashchenko, S.; Mamutov, V.; Dmitriev, V.; Sherman, A.*: Formability of sheet metal with pulsed electromagnetic and electrohydraulic technologies. Prooceedings of TMS symposium “Aluminum-2003,”San-Diego, 2003, p.99-110.

[3] *Golovashchenko S.*: Numerical and experimental results on pulsed tubes calibration, Proceedings of a 1999 TMS Symposium “Sheet Metal Forming Technology”, San-Diego,1999, p.117-127.

[4] *Radford, D. D.; Walley, S.M.; Church, P.; Field, J.E.*: Dynamic upsetting and failure of metal cylinders: Experiments and analysis. J. Phys. IV France 110(2003)263-268.

[5] *Swallowe, G. M.; Lee, S.F.*: A study of the mechanical properties of PMMA and PS at strain rates of 10-4 to 103 s-1 over the temperature range 293-363K. J. Phys. IV France 110(2003) 33-38.

[6] *Albertini, C.; Cadoni, E.; Labibes, K.:* Study of the mechanical properties of plain concrete under dynamic loading. Exper. Mech. 39 (1999) 137-141.

[7] *Gorham, D.A.*: Measurement of stress-strain properties of strong metals at very high strain rates. Inst. Phys. Conf. Ser. 47 (1980) 16-24.

[8] *Couque, H.; Walley, S.; Lichtenberger, A.; Chartagnac, P.; Dormeval, R.; Petit, J.*: Test recommendation: Dynamic compression testing using the Talor test, publ. DYMAT, Arcueil, France (2001)

[9] See the website www.dymat.org.

[10] *Hartmann, K.-H.; Kunze, H.-D.; Meyer, L.W.*: Metallurgical Effects of Impact Materials. In: Shock Waves and High Strain Rate Phenomena in metals. Hrsg.M.A. Meyers and L.E.Murr, Plenum Press, New York 1981, S. 325-337.

[11] *Reinders, B.-O.; Kunze, H.-D.*: Influence of Mechanical Twinning on the Deformation Behavior of Armco Iron. In: Shock Waves and High-Strain-Rate Phenomena in Materials Eds. M.A. Meyers, L.E.Murr, K.P. Staudhammer, M. Dekker, 1990, S. 127-136.

[12] *Xin, L.; Zhongren, W.; Jintao, H.:* A Comparison of Mesomechanism of Dynamic Deformation between Copper and Aluminum. Journal of Materials Processing Technology 70 (1997)228-230.

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