Quasi-static-dynamic formability of AA5052-O sheet under uniaxial and plane-strain tension

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Abstract: An experimental study on the quasi-static-dynamic formability specified in electromagnetically assisted sheet metal stamping (EMAS) was presented. A series of uniaxial and plane-strain tensile experiments were carried out on AA5052-O sheet by using a combined quasi-static stretching and pulsed electromagnetic forming (EMF) method. Failure strains representing formability beyond conventional quasi-static forming limits are observed under both uniaxial tensile and plane-strain states. The total forming limits of the as-received aluminum alloy undergoing both low and high quasi-static pre-straining are almost similar in quasi-static-dynamic deformation. Ultimate total formability seems to depend largely on the high-velocity loading conditions. Thus, it appears that for quasi-static-dynamic deformation, the quasi-static pre-straining of material is not of primary importance to the additionally useful formability. These observations will enable to develop forming operations that take advantage of this improvement in formability, and will also enable the use of a quasi-static preform fairly close to the quasi-static forming limits without weakening its total formability for design of an EMAS process in shaping large aluminum shell parts like auto body panels.
Key words: electromagnetically assisted sheet metal stamping (EMAS); aluminum alloy sheet; electromagnetic forming (EMF); quasi-static-dynamic deformation

1 Introduction

In the recent years, continuing pressure to reduce vehicle weight and emissions in automotive industry has caused many manufacturers to substitute Al alloys for steels in applications[1]. Unfortunately, insufficient formability of aluminum at room temperature can be a major issue in traditional press forming of complex parts like automotive body panels. Efforts to obtain improved formability have led to renewed interest in high velocity forming processes, among which electromagnetic forming (EMF) is widely used[2].

Electromagnetically assisted sheet metal stamping (EMAS)[3−5] is one of the most attractive techniques developed that integrates EMF into traditional sheet stamping in the fabrication of aluminum alloy automotive body panels. Excellent improvement in formability of Al alloys has been experimentally demonstrated by using this method[3−5]. However, the experimental data available are generally limited in establishing the efficacy of this concept and the validation of this technique, but there is hardly systemic

discussion on the issues concerning the viability of the EMAS process from the fundamental material mechanics and plasticity aspects.

In essence, material response under a combined quasi-static-dynamic loading condition is the basic issue involved in an EMAS deformation process. As mentioned, a question that naturally follows is whether we can regard this enhanced formability of a combined quasi-static-dynamic deformation from a more basic material behavior way. The plastic deformation of metals has been extensively investigated, not only under high strain-rate loading conditions, but also when the loading is essentially quasi-static in nature. However, with path dependency of plastic deformations, it would not be expected that the combined effect of static and dynamic deformations of a sheet material is symmetric or independent of application sequence. Early works[6−7] have provided the information of material response under a dynamic-static deformation sequence. For example, FYEE and RAJENDRAN[7] demonstrated the quasi-static terminal behavior (fracture) of Al alloys and copper. But little attempt is found concerning the reverse sequence of deformation[3]. In addition, although the

hyperplasticity effect[8] of high rate deformation is fairly well documented, its fundamental mechanism is still under challenge[9]; and whether these high-velocity results are due to the influence of inertia or the strain history is not clear. Especially, the high velocity sheet metal forming cited in the literature is almost entire for fully dynamic deformations starting from flat blanks or uniform tubes with initial cold work state. The quasi-static-dynamic case, on the other hand, will be confounded by the various levels and distributions of pre-strain introduced into the sheet material during the initial quasi-static forming stage of the process. The non-uniform deformation and early plastic instability in tension after pre-straining[10−11] have made the quasi-static- dynamic terminal behavior a more dispute one.

With all the issues mentioned above in mind, the purpose of this study is to assess an enhanced forming capability with the EMAS process. Hereby, the forming limits of an as-received aluminum alloy (AA5052-O) sheet are evaluated under a basic quasi-static-dynamic loading condition. The plane-strain deformation, which in quasi-static case often leads to the minimum fracture limit strain and thus is typically considered an important situation representing material formability, in conjunction with the uniaxial case, is experimentally investigated to provide reasonable insight about the material behavior during EMAS process. The effects of quasi-static pre-straining through the acquisition of basic material formability data are also assessed and discussed.

2 Experimental

2.1 Material

The material used in this investigation is commercially available AA5052-O sheet with 1 mm in thickness. This material was chosen for its use as an important candidate for car body applications.

2.2 Methods

2.2.1 Descriptions of quasi-static-dynamic forming and experimental set-up

The combined quasi-static-dynamic process was conducted by two separate phases in sequence, quasi-static and dynamic. First, the samples were all quasi-statically strained to specific levels in a standard tensile test machine (Fig.1(a)). The actual pre-straining levels of each labeled sample were measured and recorded. The samples were then clamped in a coil fixture (Fig.1(b)) connected to an EMF system, and subjected to an electromagnetic pulse to fracture. Thereby, the quasi-static-dynamic deformation was achieved and the hybrid formability of material could be assessed. Besides, the quasi-static and dynamic test procedures applied to the sheet samples were designed to restrict the sample deformation to stretching, and accordingly the plane-strain tensile[12−13] and uniaxial tensile methods could be adopted to achieve these two kinds of strain states. For the typical bulging effect of EMF, the simplification similar to that of GOLOVASHCHENKO[14] was applied to reasonably gaining a dynamic uniaxial tensile phenomenon by using the apparatus schematically shown in Fig.1(b). The two-step assumption of the combined quasi-static-dynamic deformation process may be feasible for the deviations are not deemed to affect the applicability of the trail experiences to the development of actual EMAS deformation.

The quasi-static tests were conducted using the Instron−5569 electrical tensile testing machine. And EMF procedures were performed using a 30 kJ EMF system manufactured by Harbin Institute of Technology, China. This system has the following main characteristics: capacitance 720 μF (including six capacitors of 120 μF
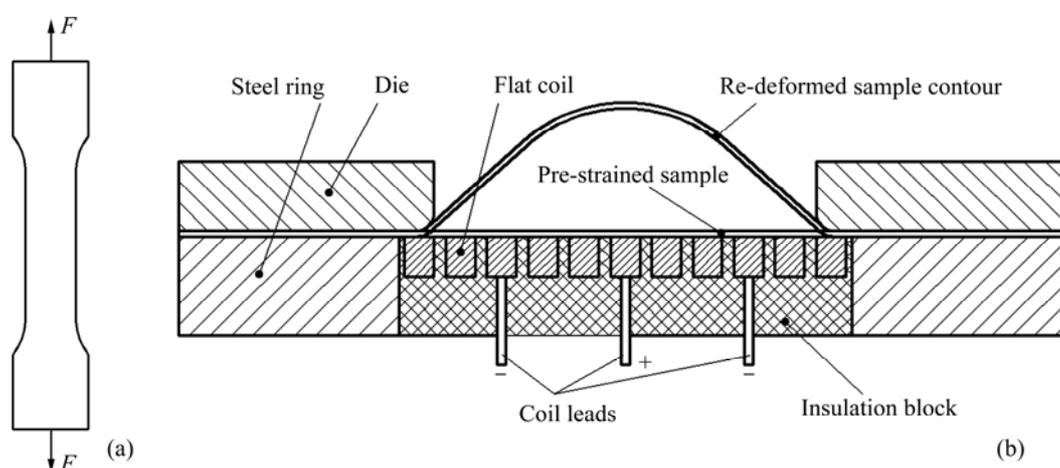

Fig.1 Schematic of combined quasi-static-dynamic forming process (sample shape just for illustration): (a) Quasi-static; (b) Dynamic

each), discharge voltage 3.0−9.0 kV, and the maximum energy storage 30 kJ at about 9.0 kV charge. Fig.1(b) schematically shows the EMF testing procedures. A flat coil is mounted inside the insulation block, which is press-fit into a steel ring, serving the following dual purposes: as a bandage for the coil preventing its expansion, and as a flat lowering binder for the flat sample tested. A die with an open-rectangle window with 100 mm× 80 mm in dimensions and an entry radius of 10 mm, typical for formability testing fixtures, also serves as an upper binder. The coil leads are connected to the EMF system.

A special coil with rectangular flat spiral was used here for the reason that this kind of coil together with the die with rectangular open window provided an opportunity to deform samples with wide variety of width, especially narrow samples, for the drawing side of the forming limit diagram (FLD). Such a coil (Fig.2) with outer dimensions of 160 mm× 80 mm and a 4 mm-wide turn was fabricated from a solid piece of copper plate of 20 mm thick in order to improve its durability. Other information on this kind of coil can also be found in Refs.[14−15].

Fig.2 Photograph of rectangular flat coil

2.2.2 Uniaxial tensile experiments

Uniaxial tensile experiments were performed in both quasi-static case and hybrid loading case where specimens were quasi-statically pre-strained and then dynamically loaded. All the uniaxial specimens were cut parallel to the rolling direction, according to ISO 6892—1998 (gauge length and width of 50 mm and 12.5 mm, respectively), as shown in Fig.3(a).

2.2.3 Plane-strain experiments

Plane-strain tensile method[12−13] was used to evaluate the plane-strain material response in both loading cases mentioned above. A proportional variation of the WAGONER and WANG[12] plane-strain tensile specimen (Fig.3(b)) was used for investigation. The quasi-static experiments were first performed to evaluate the quasi-static forming limits of material for comparison; at the same time, the limit grip displacements were recorded as the upper bound for determination of quasi-static pre-straining in the hybrid loading case.

2.2.4 Formability measurement

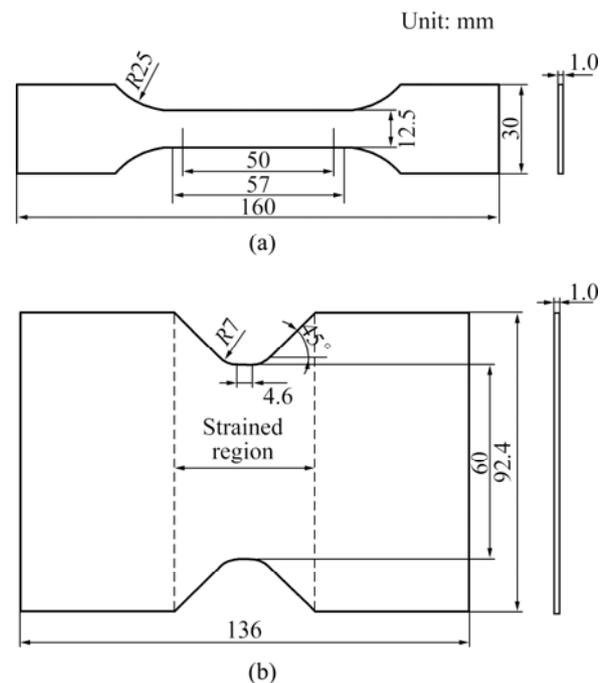The formability descriptions of all the processes

Fig.3 Configurations of specimens used in this study: (a) Uniaxial tensile specimen; (b) Plane-strain tensile specimen

including an EMF phenomenon are based on a forming limit diagram concept that is widely used in the analysis of conventional sheet metal forming processes. For each combination of strain state and pre-straining level in hybrid-forming, multiple samples were electro-magnetically loaded with incrementally increasing discharge energies until an energy level sufficient to initial fracture of the sheet was reached. The limit strain pairs near the fracture zone were then reported from grid analysis of the failure samples using the CamSys, Inc. software ASAME (Automated Strain Analysis & Measurement Environment) Lite Version 4.1.

3 Results and analysis

3.1 Experimental validation of hybrid quasi-static-dynamic deformation

The hybrid quasi-static-dynamic deformation process has been described by the superposition of two separate deformation processes as mentioned above. To validate the hybrid characteristics, in principle, strain paths of quasi-static forming and EMF should keep the same or very close to each other.

Measurements of strain features on the deformed plane-strain specimens were made along two sections (*A-A* and *B-B*) of the strained region, as shown in Figs.4 and 5. It is clear that the strain distributions under both loading conditions fully validate the assumption[12−13]
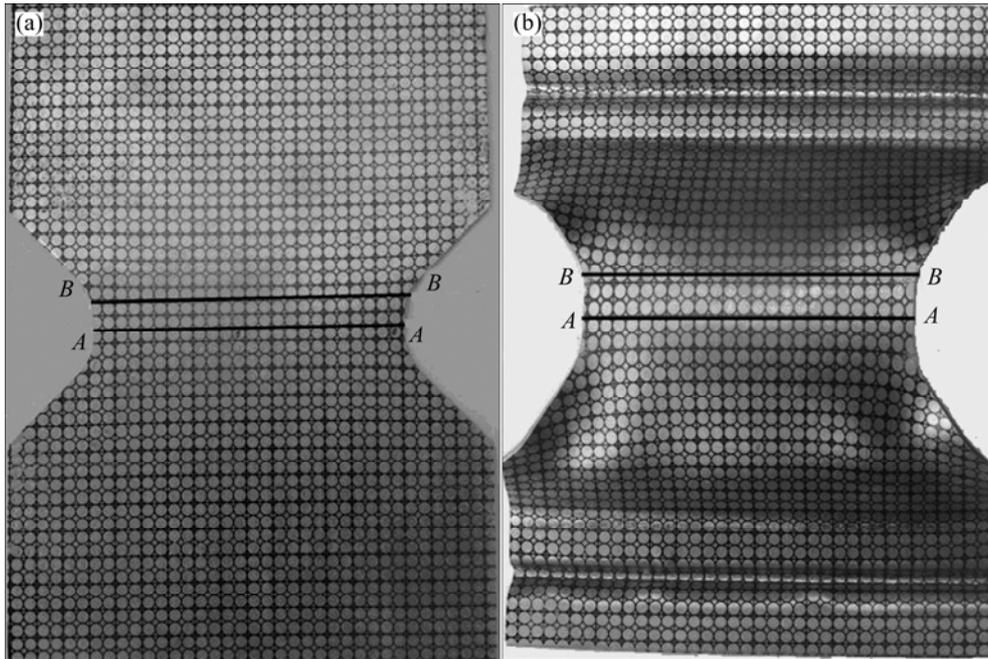
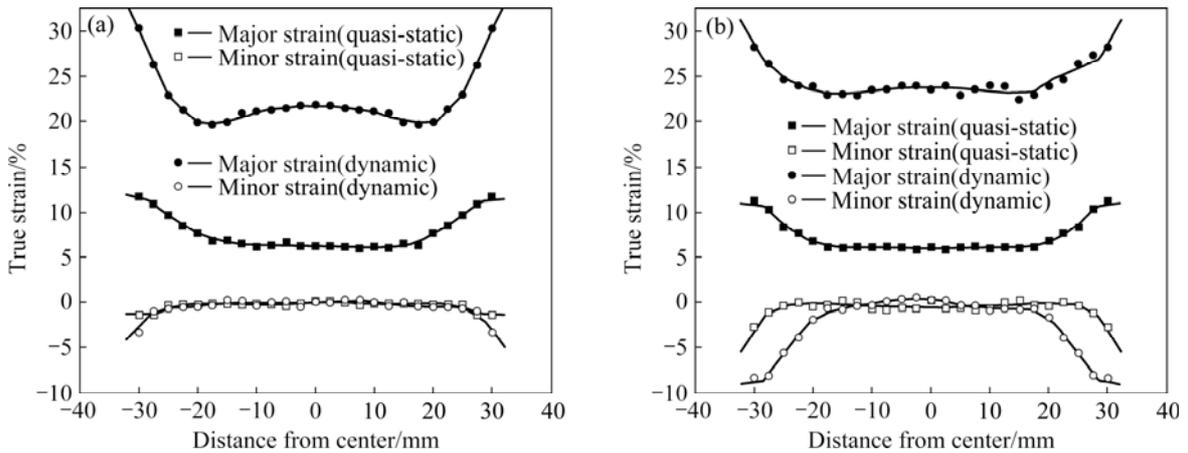**Fig.4** Plane-strain tensioned specimens: (a) Quasi-static; (b) Dynamic

Fig.5 Strain distributions on plane-strain tensioned samples: (a) Along section *A-A*; (b) Along section *B-B*

that a region of relatively homogeneously distributed plane strain exists in the center of the specimens.

Fig.6 further demonstrates the strain distribution in the gauge center of deformed specimens on the traditional FLD window. As can be seen, similar strain state (uniaxial tensile and plane strain) can be obtained in both quasi-static forming and EMF processes by controlling the shape of tested samples except that there is small deflection on strain axis (specified by $\varepsilon_2/\varepsilon_1$), which is probably due to the induced non-uniform distribution of eddy currents in specimens, and is within the accuracy of the ASAME measurement. Without regard to these small deviations, it is available to combine the two separate phases of deformation into a whole in this work.

3.2 Quasi-static results

Quasi-static experiments were conducted to assess the quasi-static forming limits of the as-received aluminum alloy sheet and to accordingly produce a series
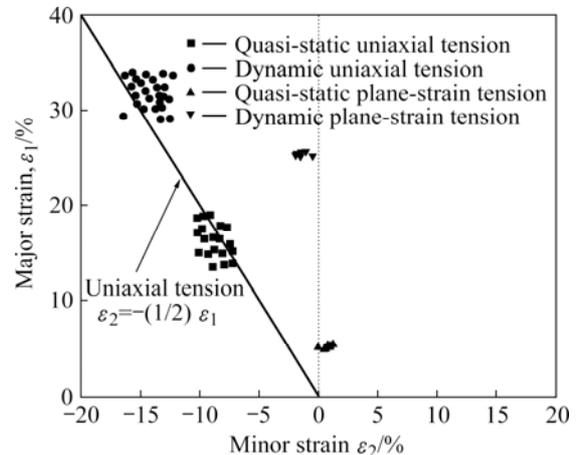

Fig.6 Strain distributions in gauge center of specimens

of quasi-statically pre-strained samples for further dynamic forming. For all the quasi-static tensile procedures, the crosshead speed used was 2 mm/min, which gave an average overall strain rate of $6.7 \times 10^{-4} \, \text{s}^{-1}$. Table 1 lists the tensile properties of AA5052-O sheet.

The in-plane principal strains were reported by grid analysis, and replicate tests were conducted to measure the quasi-static limit strains near the fracture zone on the samples. A convention was typically used for generating the forming limit curves on FLD. An average failure strain (major strain) level of 27% for uniaxial case and 18% for plane-strain case is observed in this work. A detailed demonstration of limit strains is shown to compare with the hybrid-forming results. The extensometer was used for continuous displacement measurement. Under each strain state, four groups of quasi-statically pre-strained samples were obtained by using displacement control in stretching, as shown in Table 2. The true strain pairs of each pre-strained sample were measured using ASAME technique for plane-strain

Table 1 Tensile properties of AA5052-O sheet

Yield strength/MPa	Ultimate tensile strength/MPa	
90	199	
Strain hardening exponent, n	Uniform elongation/%	Total elongation/%
0.25	22.2	25.6

Table 2 Quasi-static pre-straining parameters used in this study

Strain state	Sample group number	Pre-straining level/%	Replicates
Plane-strain	0	0	4
	1	2−3.4	
	2	4.9−5.3	
	3	7.3−8.0	
	4	9.0−9.3	
Uniaxial tensile	0	0	4
	1	5	
	2	10	
	3	15	
	4	20	

case, and the simple total engineering pre-strain was used for the uniaxial tensile case. Here, the initial cold work sheets without pre-straining were also included.

3.3 Quasi-static-dynamic formability

As indicated, the quasi-statically pre-strained aluminum sheet samples were launched with increasing velocities (energies) by adjusting the discharging voltages, and the samples in which tearing had just initiated were selected for further strain analysis. Up to four replicates for each case have been tested. Fig.7 illustrates the typical fracture fragments in uniaxial tensile and plane-strain specimens. The failure strain pairs from grid analysis were plotted on the traditional FLD window, as shown in Fig.8, and comparison of quasi-static results was also included in the plots. The results from these tests clearly show that for both uniaxial and plane-strain deformation, regardless of the extent of quasi-static pre-straining, the failure strains reported in the hybrid quasi-static-dynamic loading condition exceed those in tested quasi-static condition, which convey the extent of improvement in formability quite clearly. A further comparison of plane-strain forming limits is the most critical examination of data, since failures most commonly take place near plane strain conditions. Fracture strains were taken from the hybrid forming samples to pick locations where the major strains near fracture were closest to zero. A nearly two-fold increase in plane-strain forming limit can be observed with respect to the quasi-static case.

Besides, the introduction of quasi-static loading conditions, either as pre-straining levels or as strain states, does not appreciably change the above observation. As expected, the experimental data provide reasonable evidence for the enhanced formability in EMAS from a more basic material response view. The fact of a much wider necking surface in quasi-static sample, as shown in Fig.9, also seems to conform this kind of enhanced formability in hybrid-forming process.

3.4 Effect of quasi-static pre-straining

Analyzed from the deformation process of hybrid forming, the enhanced formability observed should reasonably be attributed to the well-documented hyperplasticity effect[8] of the high velocity forming
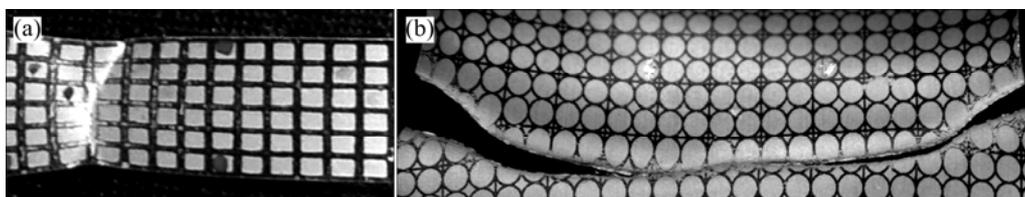

Fig.7 Typical fracture fragments on deformed samples during quasi-static-dynamic deformation: (a) Uniaxial tensile; (b) Plane-strain
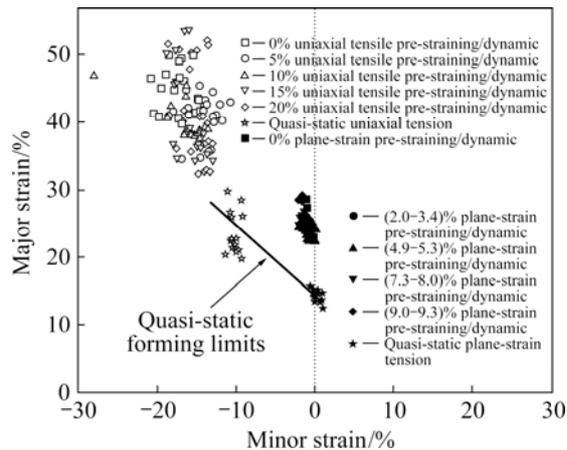
Fig.8 Experimental comparison of hybrid-forming and quasi-static forming limits for AA5052-O

phase. However, much different from a fully dynamic process, the hyperplasticity effect will be confounded by the various levels and distributions of pre-strain introduced into the sheet material during the initial quasi-static forming stage of the process. In most cases, the pre-strain will introduce work hardening and non-uniform deformation[10−11] into the material. An idea that adequate hybrid formability of a fully work-hardened sheet is not expected to be similar to that of an initial or a lightly worked condition then comes out. To specify this, it is of principle importance to elucidate the relationship between introduced quasi-static pre-straining and ultimate formability of material, as shown in Fig.10. It is interesting to note that although there are large differences in quasi-static pre-straining levels, such is not the case with the hybrid quasi-static-dynamic formability of the samples under both uniaxial tensile deformation and plane-strain deformation. The fully pre-strained sample (with a pre-straining level close to quasi-static forming limit) seems to perform in a manner as the initial sample without pre-straining (which will induce a fully dynamic deformation), and both exhibit similar ultimate formability. The results clearly show that the useful formability (additionally useful plasticity over quasi-static forming limits) of the fully quasi-statically work-hardened sheets can be dramatically improved by this mode of forming, but it is far less effective in increasing the ductility of sheets that still have good quasi-static formability.

The little effect of quasi-static pre-straining on ultimate hybrid formability in this work seems to challenge the inertial drag model of neck suppression, which is typically regarded as the first-order factor responsible for enhanced ductility observed in high velocity deformation[8, 16]. According to the model of inertial stabilization, inertial effects at high strain rate
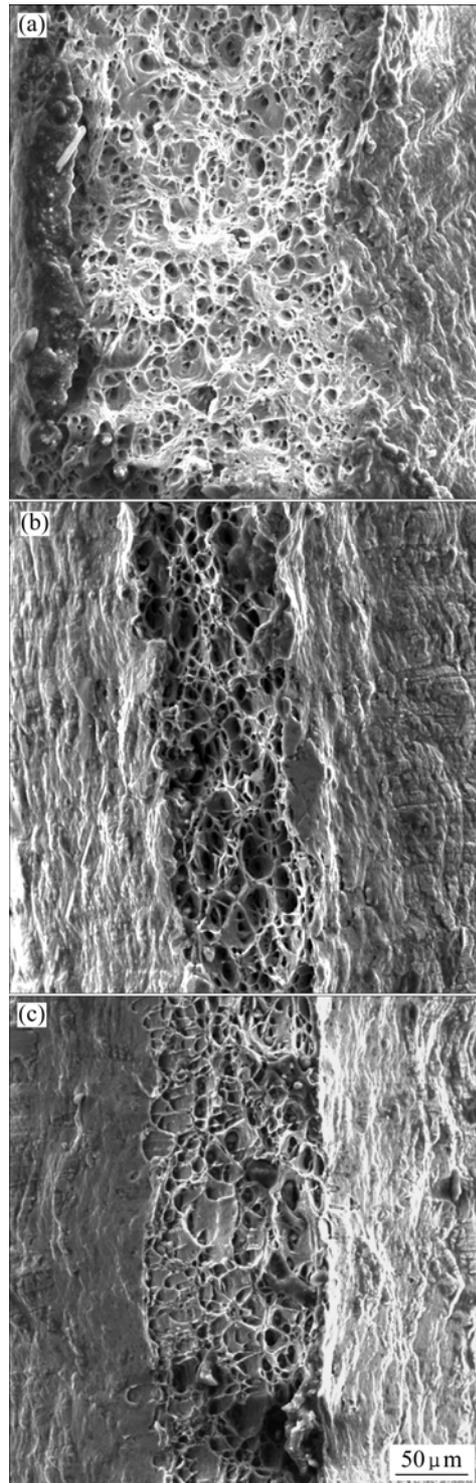

Fig.9 SEM fractographs of fractured uniaxial tensile specimens: (a) Quasi-static; (b) Dynamic forming (i.e. hybrid forming with 0% pre-straining); (c) Hybrid quasi-static- dynamic forming with 20% pre-straining

deformation will only extend plastic behavior of sheet materials whose dominant failure mode is necking. Materials exhibiting little or no necking before fracture at low velocities are not expected to show a significant increase in ductility at high velocities unless there is a
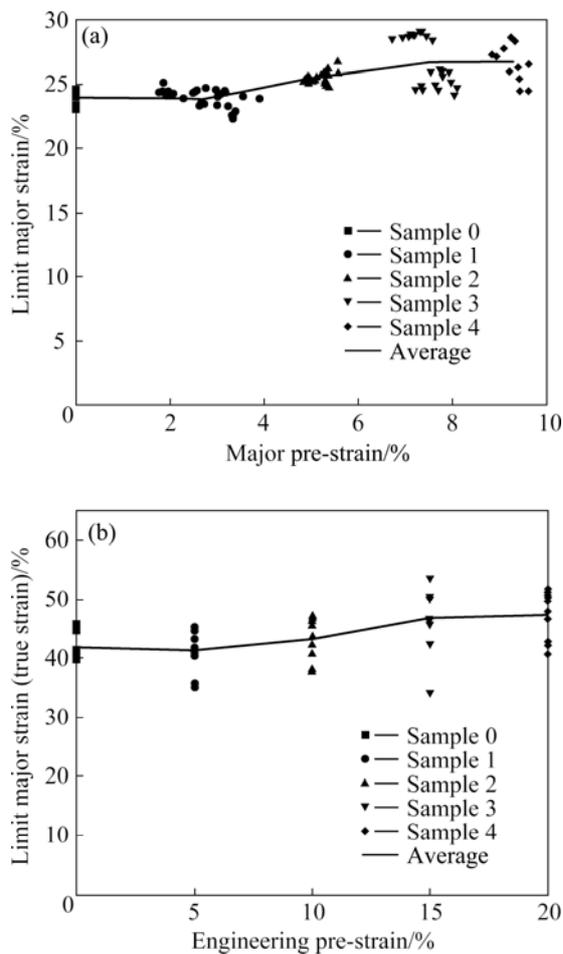
Fig.10 Relationship between quasi-static pre-straining and hybrid limit strain: (a) Plane-strain deformation; (b) Uniaxial tensile deformation

phenomenon other than inertial force in working. The direct effect of this prediction is the present work is that the fully hard aluminum alloy is not expected to perform as that in lightly worked condition. However, as mentioned, the deduction seems to conflict with the experimental formability data and the marked necking phenomena observed in hybrid forming (Fig.9). Several analyses[17] suggest that enhanced dynamic formability should also account for increased strain-rate sensitivity occurring in Al alloys at high EMF strain rates. However, the results from these experiments do not provide enough resolution to shed much light on this issue. Further investigations on the combined deformation mechanism for the inter-relationship between quasi-static deformation and high speed dynamic deformation need to be performed in future.

4 Discussion

A series of experimental tests were conducted to provide a new insight into the deformation basis of

EMAS technique and have been shown to support the fundamental premise for the utility of the EMAS process. The test parameters and data as described are sufficient to ensure the control and repeatability of overall performance tests but are not sufficient to attempt a formulation of any basic constitutive relation. The test data are presented in a manner that is deemed conducive to providing insight about the material behavior during an EMAS process.

As expected, the "hyperplasticity" effect well-documented in a fully dynamic process (especially EMF of sheet without pre-straining) has also been shown in a hybrid quasi-static-dynamic deformation process, of which the formability is confounded by quasi-static pre-strain introduced by non-uniform deformation and work-hardening. The experimental results indicate that the two component processes, quasi-static tensile and high velocity bulging, have a synergistic effect on total limit plastic strain. The plastic strains produced by the combined process are slightly larger than those produced by either component process. The near plane-strain condition, in conjunction with the uniaxial tensile case, reasonably allows that the experimental results are applicable to actual applications using EMAS performing.

In particular, the forming limits of as-received aluminum alloy with both very low and high levels of quasi-static pre-straining are almost similar (Figs.8 and 10) in hybrid quasi-static-dynamic forming. Hybrid formability seems to depend largely on high velocity loading conditions. Thus, it appears that in hybrid-forming process, the quasi-static process parameter of pre-straining level is not of primary importance to the ultimate formability of the material. Based on these observations, one may be able to develop forming operations that take advantage of dramatic improvement in formability. It is suggested from this work that greater overall formability may be achieved by pushing the preform fairly close to the quasi-static material limits in an EMAS process. This is very important to apply the predicted advantage of EMAS concept to large parts where the ability to draw-in most of the part geometry can be coupled with the capability of achieving extended plasticity at high deformation rates over more localized areas of the part. Current work provides reasonably experimental basis for the EMAS process.

5 Conclusions

1) Experiments from both uniaxial tensile and plane-strain states show that the combined quasi-static-dynamic deformation can, as expected, improve the formability of the as-received AA5052-O sheet. Specially, a nearly two-fold increase in limit strain

of plane strain deformation is indicated with respect to the quasi-static case. This is confirmed by preliminary experiments of the combined quasi-static tension and electromagnetic forming results.

2) For quasi-static-dynamic deformation, where the quasi-static pre-strain follows a total formability pattern very similar to the fully dynamic case, pre-straining plays a very limited role in the ultimate fracture process, and total ultimate formability seems to depend largely on the high velocity loading conditions. The introduction of pre-straining will not weaken the total formability of sheet in a quasi-static-dynamic deformation process.

3) Without regard to the detailed mechanisms of the enhanced formability, this work has provided reasonably experimental evidence to shed much light on the deformation basis of electromagnetically assisted sheet metal stamping (EMAS).

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