マグネシウムおよびアルミニウム合金の拡散接合
における接合強度の算定と評価

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1. INTRODUCTION

A huge number of studies of superplasticity have ever been done since its discovery. From view of both material science field and engineering application, characteristic behavior at elevated temperature has been examined to understand until now. At the present time, behavior in certain ceramic has even come to be involved in the concept of superplasticity as well. Of all superplastic technologies, however, a very limited number of the methods are only known to be commercially success. One of these is SuperPlastic Forming/Diffusion Bonding for manufacturing hollow components from Ti alloy in US aircrafts. At elevated temperature, very free gas blow forming and diffusion bonding are carried out at the same time, which can lead to an integrated complex geometry of the hollow structure without using other joining process. Material substitution from steel to lighter metals, on the other hand, seems to proceed steadily, especially in manufacturing any kind of vehicle's body structure. With respect to aluminum alloys, the higher cost, less strength and lower elastic modulus may be offset by lower density anyhow. Low strength in a material with low density can be made up for geometrical shape, dimension and internal structure. The aims of the study are: to present an integrated processing from lighter alloy sheets to structural component such as engine food without mechanical joining in assembly and to examine the possibility of diffusion bonding in several Al and Mg alloy sheets through Weibull statistical analysis.

2. RB/SPF:RollBonding/SuperPlasticForming

There are several chemical substances which are known as GAS GENERANT, being used in forming foam polymer or metal and as an explosive in an air bag of automobile. Each GAS GENERANT has its own thermal decomposition temperature, when reaching this temperature it spontaneously yields a certain amount of inert gases. During heating and keeping at some elevated temperature, dilatational work of gases can form a closed space surrounded by metal sheet. This can be useful for high temperature forming instead of external gas blowing [1]. A revised method how to form an integrated complex internal structure from metal sheets have been presented [2], which is composed of a series of process, metal surface treatment to be bonded, printing of designed pattern on the metal surfaces, pre-packing, hot roll bonding to make a clad sheet, and consequent heating of the clad. In printing, an ink, (composed of some chemical substances, STOP OFF to hinder metal from joining, and GAS GENERANT are mixed by using diluted solution (NH_3)) is served. This integrated processing was termed Roll Bonding/ SuperPlastic Forming, RB/SPF. Diffusion bonding can not be effective in Al alloys because of tenacious oxide thin film being always on the surface. RB/SPF, however, must be useful for such kind of material, since in rolling large deformation destroys the firm film layer and can lead to bonding with enough strength against shearing/peeling.

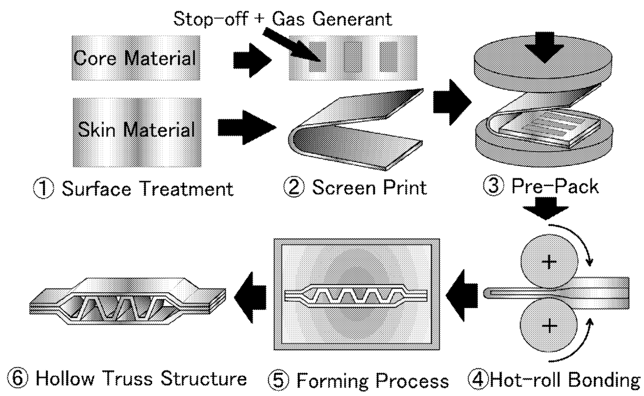

Fig.1 Processing to hollow component with internal complex cellular structure, demonstrating Roll Bonding /SuperPlastic Forming (RB/SPF). Superplasticity in core metal may not be necessarily needed. This is one of examples in Process Fusion.

No.	Kinds of Gas Generat	Concentration of Gas Generant to Stop-off	Un-join : Join	Forming Height
1	ADCA	80%	3:1	10.5mm
2	ADCA	80%	3:1	9.5mm
3	CELLTETRA	20%	3:1	8.5mm

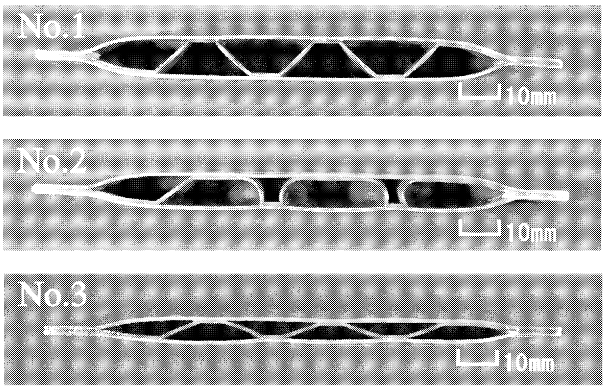

Fig.2 Cross sectional views of truss structures made by the method shown in Fig.1. Skin matrial:A1050, Core:SPZ (Zn78wt%-Al22wt%).

Fig.1 demonstrates the whole process of the method already presented [2]. In Fig.2, cross sectional views of samples made from the above method are shown. Internal details need to be a little improved but if they are trivial, these products are effective in actual use as they are. In this type of structure, along the longitudinal direction there is no change in geometrical shape and dimension. RB/SPF is also applicable to other type of structure, for example honeycomb, with a just little device on printing patterns.

3. PROCESS FUSION

In general terms, technological development in conventional processes of plastic working of metals, such as rolling, forging, extrusion, wire drawing and sheet metal stampings reaches to almost maximum, gets to saturation and we cannot expect any drastic improvement. In those days SPF/DB for manufacturing aircraft frame from Ti alloy was definitely innovative technology. This is also true for Gatoriging method for manufacturing turbine disk in aircraft's engine. Both processes are composed of several works. They are totally combined process. As these suggest, for the breakthrough to external space, several forming processes can be combined to one process that may yield a completely new product. Thus, the concept is termed as Process Fusion. It means that some methods dissolved to one body consecutively yield another new method.

Surface Treatment + Screen Printing + Pre-Packing (Diffusion Bonding) + Roll Bonding + Heating (Superplastic Forming) → **RB/SPF**

4. DIFFUSION BONDING

4.1 Magnesium alloy sheet

Sheet magnesium has been used to make a number of production components. These parts did not require exceptionally high forming strains and were formed using a warm stamping technique at approximately 200℃. However, the complex shapes and higher forming strains, required for automobile components, would likely necessitate a superplastic forming (SPF) or SPF-type process with magnesium to avoid splitting during forming. SPF magnesium research is very limited; however, very high ductility at rather low temperatures have been demonstrated in wrought magnesium [3].

In Pre-Pack in Fig.1 secure bonding at the interfaces can not be expected. This is simply a preparation for next step, hot-roll bonding. During roll bonding with large deformation, firm joining can be achieved. If Pre-Pack itself can yield high bonding strength, roll bonding will not be needed. Then, both geometrical and dimensional accuracy in the final product can be improved, since large plastic strain may distort the clad metal. If possible, it is preferred not to use rolling process at all.

For application of magnesium alloy sheet to this method without hot-roll bonding, bond strength was examined by means of a simple shear test. Enough strength at the interfaces against peeling or shearing action in spontaneous gas forming from thermal decomposition of GAS GENERANT may yield a truss of lighter Mg alloy sheet. The stress-strain curves of commercially available and typical Mg alloy sheet AZ31-O at each temperature are shown in Fig.3.

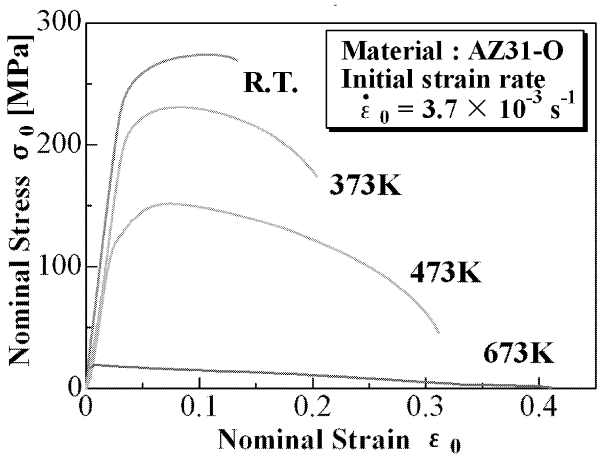

Fig.3 Stress-Strain curves at each temperature.

4.2 Simple Shear Test

Half-cut tensile specimens from AZ31 sheet were prepared and as shown in Fig.4 over lapped areas of each pair specimens were bonded, surface roughness after appropriate surface treatment, over lapped area, bonding temperature, pressure and time are process variables. After surface cleaning with supersonic vibration and several treatments, 4 pairs are set into each die cavities at the same time as shown in Fig.5. The assembled die set was then placed in between preheated two plates in vacuum chamber (Fig.6). Then in vacuum, heating and loading pressure on upper plate above the over lapped area in the each specimen were executed.

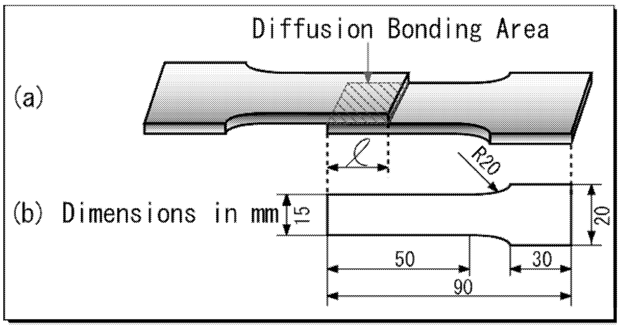

Fig.4 Geometrical configurations in bonding and dimensions of specimen.

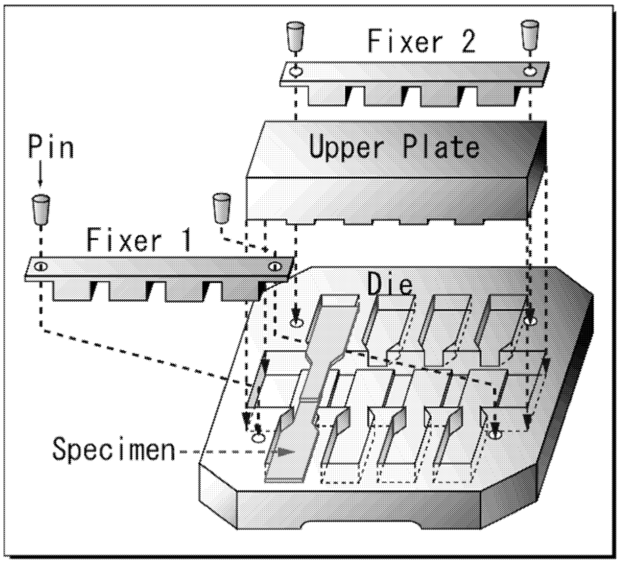

Fig.5 Bonding die set and assembling the specimens.

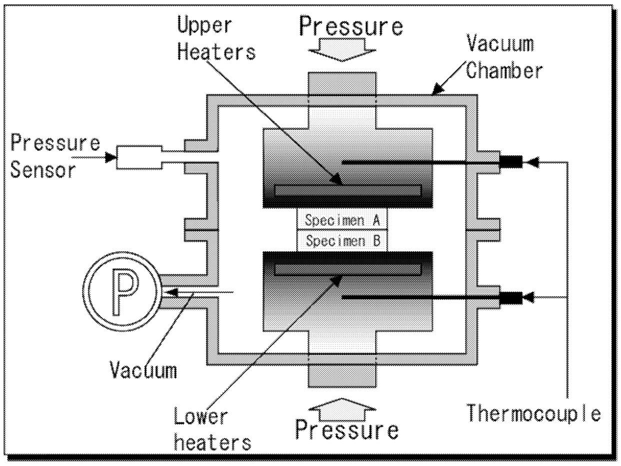

Fig.6 Bonding process was done in a vacuum chamber.

4.3 Weibull Probability Analyses

Probability Density Function(PDF;f(x)) in Two Parameter Weibull Distribution is given by Eq.(1).

$$(1) \qquad f(x) = \left[\frac{b}{\theta}\left(\frac{x}{\theta}\right)^{b-1}\right]\left\{\exp\left[-\left(\frac{x}{\theta}\right)^{b}\right]\right\}$$

x = Variable (Applied maximum shear stress)
b = Weibull slope or shape parameter
θ = Characteristic strength or scale parameter

The measured bond fracture strengths were then analyzed in terms of Weibull probability function so that the effect of changes in each process variables could be ascertained. The probability of failure F was estimated from Median rank method.

(2) $$F = \frac{j - 0.3}{n + 0.4}$$

where n is the total number of test results for a given set of bonding conditions and j is the position of a single test result in a series of results ranked in ascending value of the measured failure stress.

5. EVALUATION OF BOND INTEGRITY

5.1 On Surface Finish

Fig.7 indicates lap shear fracture strength at 673(K) against surface roughness, each value corresponding to various surface finishes before bonding test. Bonding condition was kept constant except surface finish. In this case the results show clearly that the smoother surface the higher strength is achieved. The following results are all mirror treatments.

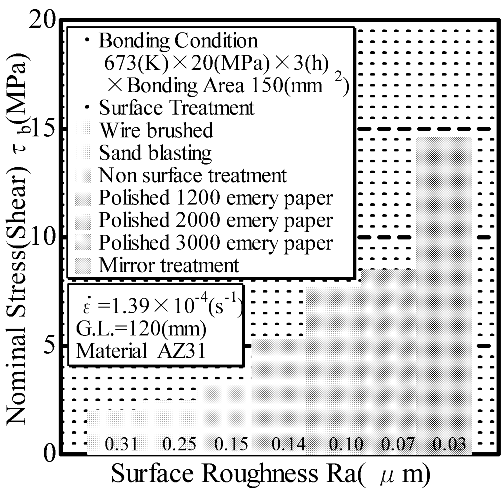

Fig.7 Lap shear fracture strength against surface roughness.

5.2 Over Lapped Area

Dependence of lap shear strength on bonded over lapped area is due to combined application of shearing and peeling simultaneously (Fig.8).

5.3 Bonding Temperature

From Fig.9, the optimum bonding temperature is not the highest and can be drawn as 450℃.

5.4 Bonding Pressure

Higher surface pressure in bonding will lead to stronger fracture strength but also to larger thickness reduction (Fig.10)

5.5 Bonding Time

Longer time in bond indicates better result too, but it should not go beyond the bounds (Fig.11).

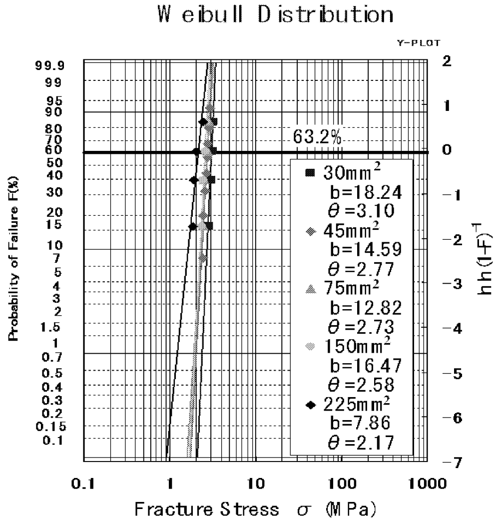

Fig.8 Lap shear fracture strength vs bond area. (400℃ x 3h, 20MPa)

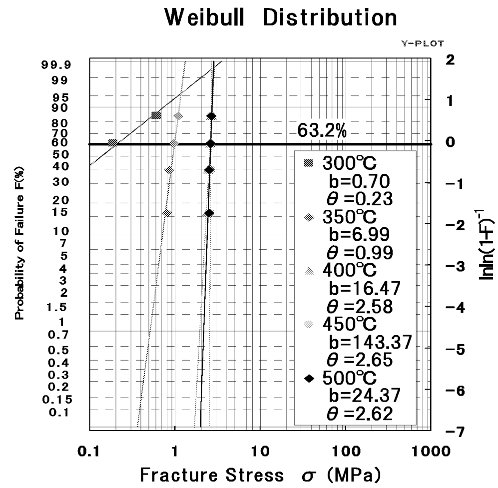

Fig.9 Lap shear fracture strength vs temperature. (x 3h, 20MPa, 150mm^2)

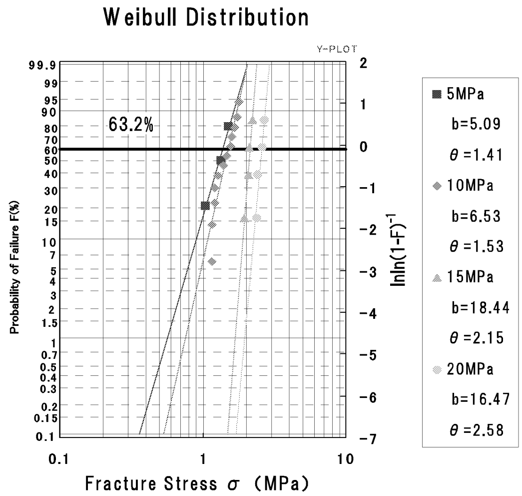

Fig.10 Lap shear fracture strength vs pressure. (400℃ x 3h, 150mm^2)

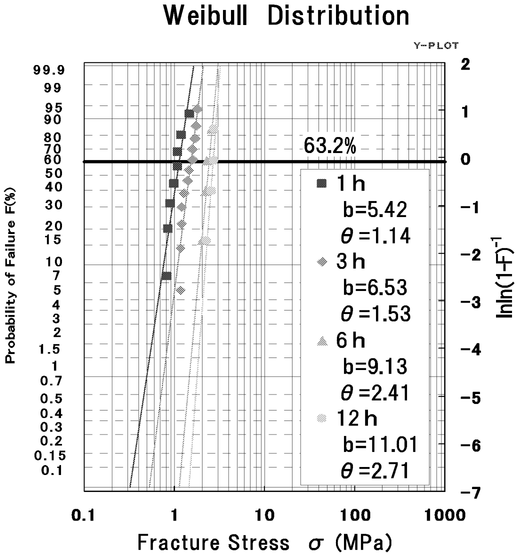

Fig.11 Lap shear fracture strength vs time.
(400℃×10MPa, 150mm²)

5.6 Fracture Shear Strength after Annealing

Lap shear fracture strengths must be estimated essentially from a ratio to parent's strength. Since after various annealing they change correspondingly, they are needed to be measured after each heat treatment. There may be three ways of estimation on that. In terms of tension test results, shear strength τ_p can be determined, if Tresca's yielding condition holds,

$$\tau_p = \frac{UTS}{2} \tag{3}$$

where UTS is ultimate tensile strength.
Secondly, if von Mises can be applied to metal flow,

$$\tau_p = \frac{UTS}{\sqrt{3}} \tag{4}$$

And as third value, at stamping in terms of direct blanking or punching, we can get another experimental shear strength τ_p.

In Fig.12, lap shear fracture strengths after various heat treatments are plotted against annealing temperatures. It should be noticed that the values themselves and decreasing relation with increasing temperature are almost the same for both Tresca's and experimental ones.

In heating step in RB/SPF (Fig.1), bonded area is to be subjected to both shearing and peeling action at the elevated temperature. Without hot-roll bonding, if AZ31 sheets were supplied to this hot forming, bond and material strength must be evaluated in advance for having a finished product at the temperature.

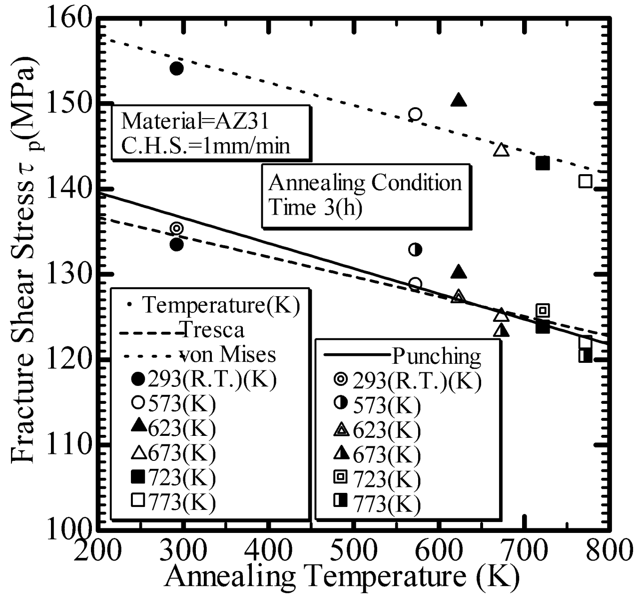

Fig.12 Fracture shear stresses after each annealing decreases gradually with annealing temperature.

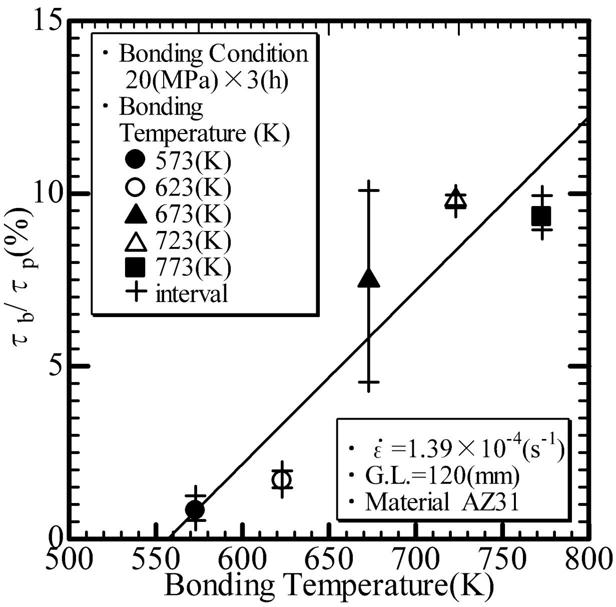

Fig.13 Ratio of averaged fracture shear stress τ_b after each annealing to parent's strength τ_p in terms of Eq.(4) or experimental value against bonding temperature.

The ratio τ_b/τ_p in Fig.13 reaches almost 10 % at 750K, which was the highest attainable value obtained by our present experiment. Unfortunately, in simulating the RB/SPF process in Mg alloy sheet, AZ31 without hot-roll bonding, whether this maximum value is sufficient can not be decided and remains unidentified.

6. DB IN SIMILAR/DISSIMILAR METAL

Not only in similar metal, AZ31, but also in dissimilar metals, Al alloys, as a base material AZ31 being treated, solid state diffusion bonding test was carried out in just the same way described above. Supplied Al alloys are A3004, A5052 and superplastic A5083 at 520℃. Total results on fracture probability in terms of Weibull distribution are summarized in Fig.14. Of all the combinations, scale parameter θ in A5083 vs A5083 is 3.09, which is the highest and shape parameter *b* in this joining is 26.29, highest again. A5083 is also best compatible with AZ31 as shown in Fig.14. Superplasticity and accommodation for grain boundary slip at elevated temperature may be very effective in metal diffusion bonding.

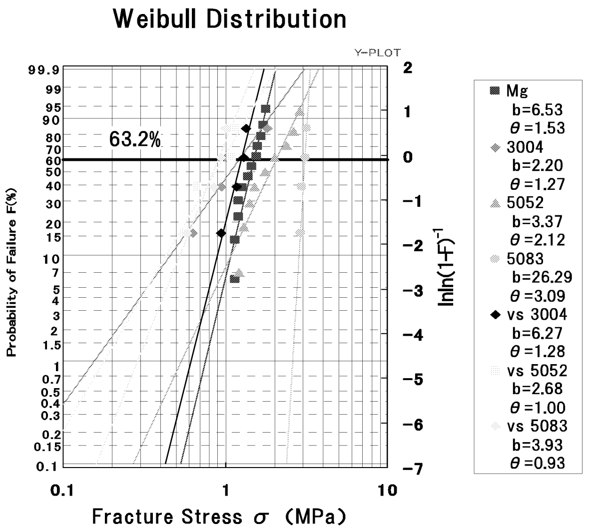

Fig.14 The relationships between probability of failure in simple lap shear test and lap shear fracture strength. (400℃ x 3h, 10MPa, 150mm^2)

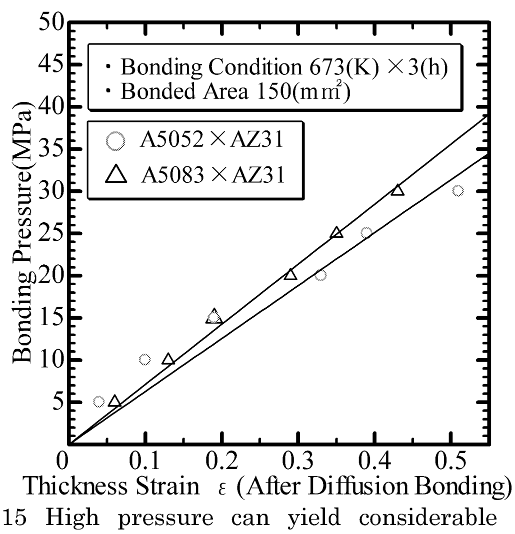

Fig.15 High pressure can yield considerable large thickness reduction in bonded area.

Diffusion bonding as the words suggests, means no appreciable plastic deformation. Since any macroscopic distortion of the component is not produced by diffusion bonding processes, they are attractive. When much higher or sufficient strength at the interfaces are expected, much bigger load on the joint to be bonded will be applied for even a little rise in strength. As in Fig.14, however, almost linear relationships between pressure and thickness reduction indicates that higher load can really produce any appreciable increase of bond strength but as it goes up, thickness reduction becomes significant, and there will be no diffusion bonding any more. In this case, use of diffusion bonding as a pre-pack with consecutive roll-bonding will be much better but in turn some distortion will be involved.

7. CONCLUSIONS

The process RB/SPF in terms of GAS GENERANT can produce hollow structural members with internal cellular rooms from lighter metal sheets. Solid state bondings in AZ31 and several aluminum alloys were done tentatively. The bond strength produced to date lacked sufficient anti-peeling strength and complete trust to warrant the initiation of the RB/SPF from these lighter metals.

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