ADVANCED SHEET METAL FORMING OF ALUMINUM ALLOYS

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ABSTRACT The review describes recent researches and developments made on various kinds of aluminum alloy sheets. Three subjects will be given independently but all contribute to advanced forming technology on the alloys simultaneously. The object of the paper is described as follows: (1) To demonstrate characteristic serrated flow behavior in Al-Mg alloys in wide range of strain ratio. (2) To show the good quality and the feasibility of pre-coated Al sheets developed recently. (3) To introduce revised superplastic blow forming techniques for superplastic Al alloys by using gas generant.

Keywords: *serration, FLD, pre-coated, SPF, hollow structure*

1. INTRODUCTION

Aluminum alloys are best known for low density and corrosion resistance. Electrical conductivity, ease of fabrication and appearance are also attractive features. Because of these, the world production of aluminum has been increasing since the first discovery of this material at the end of 18th century. Survival in the sheet metal working processes, however, is very closely linked to formability, which is also a complex property, and must now be related to failure definition relevant to sheet products. Generally speaking, shortcomings in sheet forming of Al or Al alloys in comparison with steel sheets showing better formability are described as follows. 1. Spring-back after stamping is not a negligible amount. This is due to small modulus of elasticity. 2. n value, common measure of ability of work hardening is small also. So less uniform deformability, particularly in stretch forming this leads to poor formability up to failure. 3. Al alloys may exhibit almost zero post-uniform elongation in uniaxial tensile test. Since there is a definite correlation between post-uniform elongation and strain rate sensitivity, this must mean very small or negative strain rate sensitivity in this metal. 4. r value, normal anisotropy being small is closely related to trivial deep drawability of Al alloys sheets. 5. Surface flaw or scratch due to soft material. Al-Mg alloys where Mg atom occupies Al lattice site substitutionally shows sometime stretcher strain markings on the surface.

For these factors it has been believed that the alloys can not be substituted easily for steel. There may be, of course another reason of its higher cost than steel. Serrated flow of the metals can be regarded as one of the factors that constitutes poor formability. Fig.1-1 [1] shows serrated flow in substitutional alloys: the serrations are regular and follow various reproducible ptterns. There may be differences in the appearance of the stress strain curves depending on the type of tensile machine used. The curves b to f refer to rigid machine with load measuring cell, but the curve a does to when the load is step-wise or continuously increased, as when using a stress-controlled tensile machine. This kind of serrated flow, serration or after its first investigators, Portevin-LeChaterier effect can be described as an interaction of alloying atoms with the stress fields of moving dislocations. Under certain working conditions, these atomistic effects cause a negative strain rate sensitivity of the flow stress. The strength characteristics decreases as the applied strain rate is increased, and this leads to highly localized deformation, i.e., to the appearance of luders bands[2]. The possibility for atoms to react with dislocations will depend on their diffusional behavior, and thus on strain rate and temperature.

So far almost all the discussions have been based on uniaxial deformation, but in the practical sheet metal working the discussion must be opened to very wide range of strain ratio. Unfortunately we have not obtained enough knowledge to explain how serration and stretcher strain marking are related each other, and how the appearance of serrated flow may degenerate the formability of Al alloy sheets when engineering stamping is assumed, i.e., when strain ratio changes uniaxial to equibiaxial tension

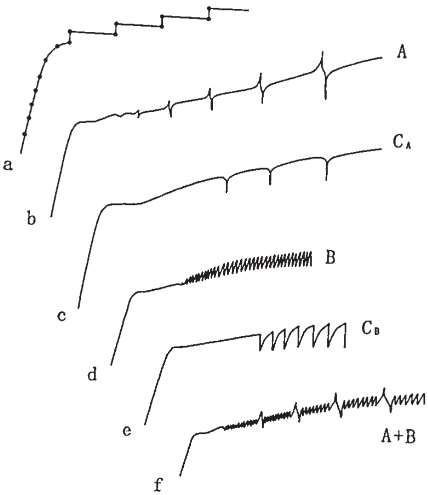

Fig.1-1 Schematic stress-strain curves of substitutional alloys showing various type of serrations [1].

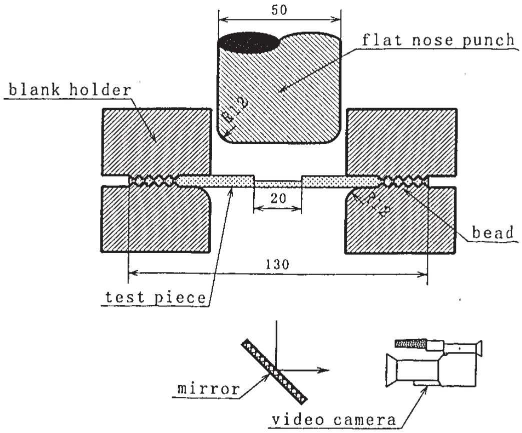

Fig.2-1 Die set and apparatus assembly for in in-plane and out-of plane deformation.

2. ENGINEERING ASPECTS OF SERRATED YIELDING IN Al-Mg ALLOY SHEETS

Test were performed by pressing a flat nose or semi-spherical rigid punch into sheet specimens which was gripped by the locking beads (Fig.2-1). Width dimension of each sheet is varied so that the different strain ratios could be reached according to the ratio of the dimensions.

During deformation load evolution by load cell and surface straining by video camera were measured simultaneously. For avoiding the failure at the punch radius and getting the localized neck at the center of the specimen, center circle area was chemically etched to reduce the thickness by 26 to 28%. Punch speed was held constant and the range of the speed was 0.2 to 200mm/min.

2.1 Test Results

Fig.2-2 shows the relationships between the intensity of serration, defined by $S_2 = \Delta P/P_{max}$ where ΔP is load amplitude, P_{max} maximum load during pressing. There is a prominent feature on this relation. If the strain ratio is positive, namely stretching dominates, the intensity of of serration is almost zero and no serrated metal flow can not be observed. The larger the strain ratio towards unity which means equibiaxial stretching, the less the intensity of serration regardless of lubrication. In the drawing domain with negative strain ratio 0 to -0.5, the intensity of serration becomes higher and higher as the absolute value of negative strain ratio increases. In Fig.2-3, test results for semi-spherical punch are shown. Since out-of-plane deformaton whose results are shown in Fig.2-3 involves bending process naturally, the interpretation the contents should be more complex than in Fig.2-2. But the similar explanation in the relationship between the serration intensity and strain ratio as in Fig.2-2 may be deduced.

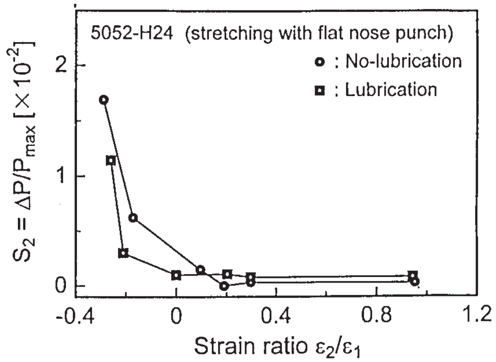

Fig.2-2 The intensity of serration vs strain ratio (CHS=2mm/min).

The reason why so could be found from Hill's necking theory. We can not find any direction of zero extension in in-plane to fulfill the condition of plane strain if stretching is considered solely. There is no possibility to occur localized slip in in-plane stretching region. It follows that this can lead to the above result. The lack of smoothness of cold-deformed or deep-drawn sheet surface is but one, and possibly a minor aspects of serrated flow. More serious is the loss of ductility or formability of the material while it is worked under critical conditions.

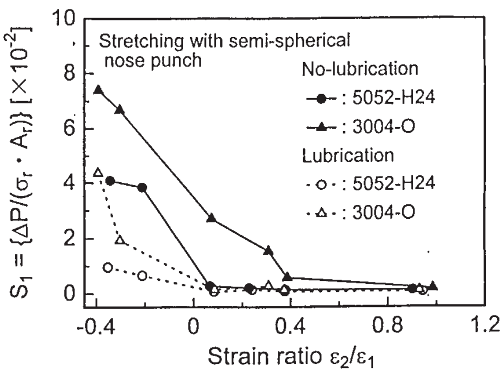

Fig.2-3 The intensity of serration vs strain ratio (CHS=2mm/min).

3. PRE-COATED ALUMINUM ALLOY SHEETS

Surface treatment and coating technology have made great progress to meet various social needs. In the fields of pre-coated metal in particular, a lot of the sheets have been developed and their output has been remarkably increased with brisk demand in the automobile, architecture and home electrical industries. Pre-coated metal is finished in surface treatment and coating before forming and has many advantages such as saving energy, natural resources, preservation of earth environment, effective use of work shop and lowering cost in production. The number of engineers who must know the sheet formability of pre-coated aluminum showing some advantages and problems in advance becomes higher and higher because of these benefits by using actually. With respect to the pre-coated aluminum sheets, there may be a classification according to the aim of use and surface properties. Three coat compositions in commercially available at the present time and typical pre-coated metals are demonstrated schematically in Fig.3-1.

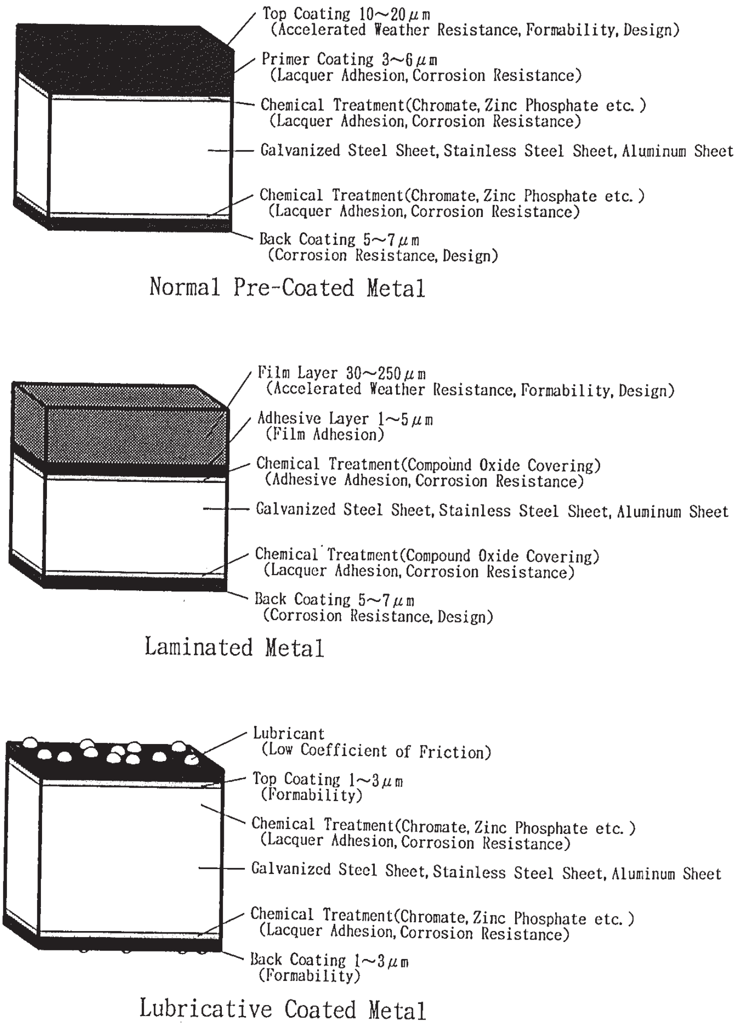

Fig.3-1 Typical compositions of coat in pre-coated metal sheets.

3.1 Improved formability by using pre-coating sheet

Experimental analysis was made on FLD (Forming Limit Diagram) of Al-Mg alloy sheets with naked and pre-coated surfaces. Used die set assembly was the same as one explained and shown previously in Fig.2-1. One of the test results for A5052-H34 is shown in Fig.3-2. Scattered solid and hollow points correspond to measured strain combinations in strain plane at the onset of necking in the thickness direction. In Fig.3-2 theoretical curves are also exhibited. It seems that among these predictions, instability strains of S-R theory[3] indicate the reasonable agreement with experimentally measured strains. In comparison of naked with coated surface a little but significant difference can be understood easily. The reason why the differences came out may be deduced from the improvement of lubrication and suppression of serrated flow by coating.

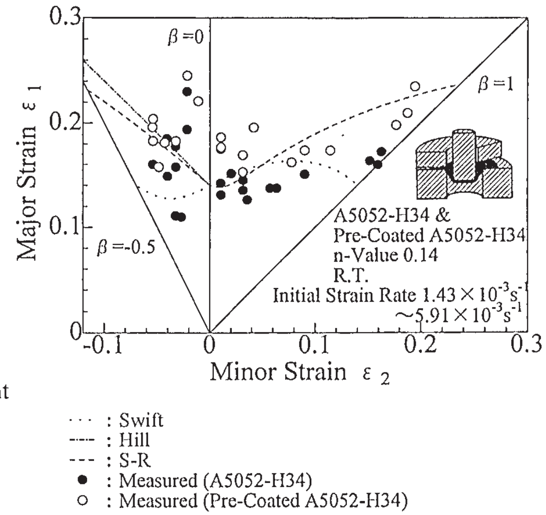

Fig.3-2 Improvement of FLD by using pre-coated surfaces.

4. APPLICATION OF SUPERPLASTIC SHEET FORMING TO Al ALLOYS

High Strength Al alloys which exhibit superplasticity at elevated temperature are expected to be found widespread use in various fields of modern technology. Superplastic forming and if possible, concurrent diffusion bonding will help in increasing design flexibility. However, superplastic inert gas blow forming for Al alloy sheets where surrounding atmosphere and working condition are considerably poorer than in commercial cold stamping, should be more refined for wider application of these alloys. An use of dilatational work of inert gas with increasing temperature was inspired instead of artificial gas blowing. Heating then holding the temperature constant with applying clamping force to avoid gas leakage will only be needed and this can make the whole apparatus simpler and cost effective. The combined application of superplastic gas blow forming and diffusion bonding (SPF/DB) to Ti alloy sheets has been a well established process in manufacturing various parts of the airplane structure. Some super-plastic Al alloys can be blown or vacuum formed at elevated temperature actually. Diffusion bonding of Al alloys, however, may not be suitable to this alloys because there always exists a thin but tenacious Al oxide layer on the surface. In making of a kind of clad metals, roll bond processing can take a significant part. High strength against shear loading or peeling at the interface will be obtained when thickness reduction during rolling is taken high enough. This is

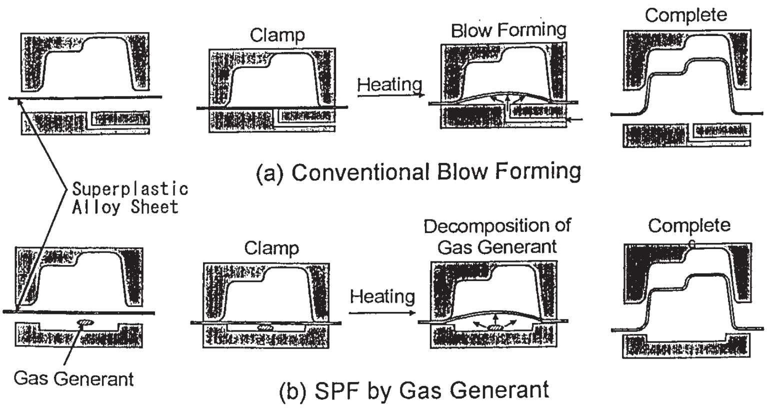

Fig.4-1. Conventional superplastic gas blow sheet forming vs SPF by gas generant.

also true for clad metals whose one component at least is pure Al or Al alloys[4]. Roll bonding for Al alloy sheets can make up for poor bondability in these alloys.

In this chapter, gas blowing tests to geometrically simple dies at elevated temperature by using chemical substances tentatively selected as the inert gas pressure source were described. Superplastic metal behavior and pressure changes during forming were measured simultaneously. In Fig.4-1 the process flow of the SuperPlastic Forming by using Gas Generant is schematically shown in contrast with conventional blow forming. A simple hollow structural component such as honeycomb which can have a high specific strength as a membrane parts was also made through roll bonding then heating (RB/SPF; Roll Bonding/SuperPlastic Forming). This may be very useful and practically processing for making this kind of hollow structural sheet. By applying suitably screen print for STOP OFF and after pack bonding gas or air blowing, simple truss structure can be made as shown

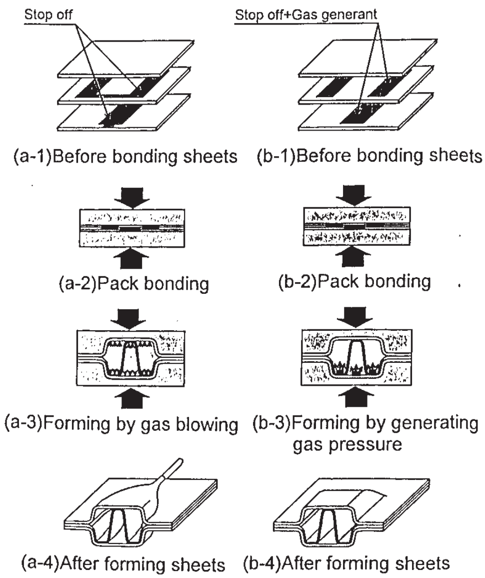

Fig.4-2. How to make truss structure by artificial gas blowing or RB/SPF by gas generant.

in left half of Fig.4-2. Not by using only STOP OFF but STOP OFF involving gas generant instead we can make the structure easily as shown in right half of Fig.4-2.

4.1 Gas generants

10 types of gas generating sources have been already selected for experimental uses. In this chapter, the results for three types of which were exhibited. These are azodicarbonamide (as ADCA) being used in automobile's air bag, hydrazodicarbonate (as HDCA) and basiczinccarbonate. Table.4.1 shows the typical chemical properties of these gas generants.

Table.4-1 Typical chemical properties of gas generants.

Gas Generant	ADCA	HDCA	Basic Zinc Carbonate
Chemical Formula	$C_2H_4O_2N_4$	$H_2NCONHNHCONH_2$	$2ZnCO_3$- $3Zn(OH)_2 \cdot H_2O$
Molecular Weight (g)	116	118	567
Decomposition Temp. (℃)	195-202	235-240	230-260
Generated Gases	N_2, CO, CO_2, NH_3	N_2, CO, CO_2, NH_3	CO_2, H_2O
Gas Generating Rate (cc/g) *	220-245	130-160	125

* at 500 °C, 1atm

4.2 Supplied sheet materials

Superplastic A5083 (Al-4.5%Mg-0.7%Mn-0.1%Cr) was used as a base material, which has the excellent service properties such as weldability and corrosion resistance. An eutectoid alloy of Al and Zn with slight addition of Cu (SPZ1; Al-78%Zn-0.15%Cu) and pure Al A3003 were also used because of relatively low superplastic temperature and the high bond strength at the interface of clad metal whose components are these alloys.

4.3 Practical forming test

An experimental system for SPF by gas generants was newly designed and manufactured, which is composed of a hydraulic material testing machine, a vacuum chamber installed in the testing

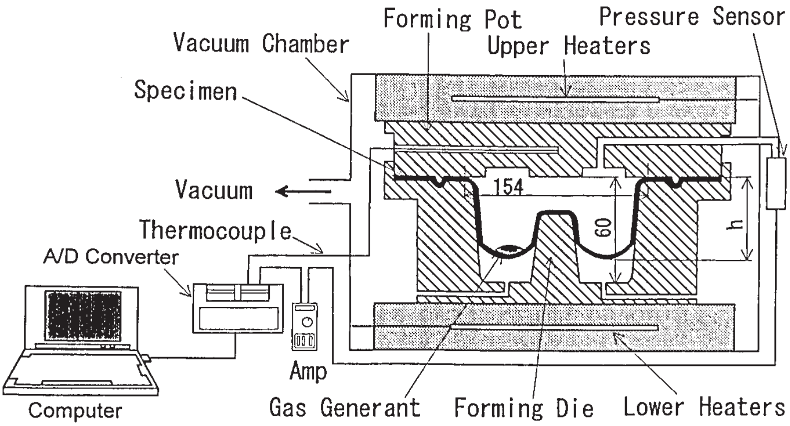

Fig.4-3. Whole system of experiment showing assembled die set and pressure, temperature sensing devices.

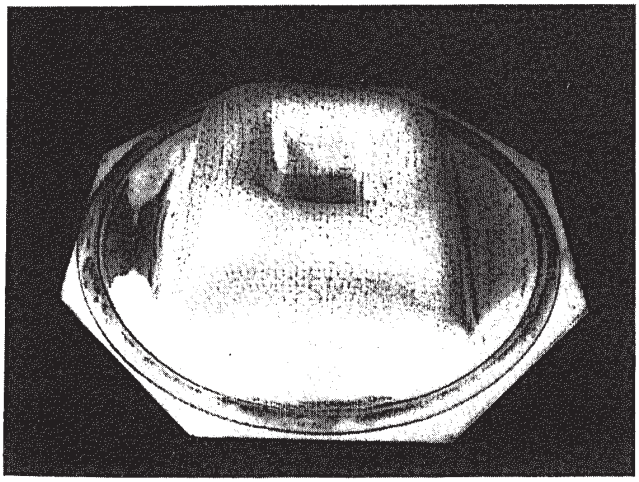

Fig.4-4. Superplastically formed Al alloy, A5083 by ADCA 0.4g, initial thickness 1.5mm.

machine, pressure and temperature sensing devices, controlling systems and die set assemblies. Load ability is 100 ton, test temperature up to 1000 ℃ and manually blowing of inert gas into the chamber or assembled dies is also possible. Fig.4-3 demonstrates the whole system of experiments schematically, showing assembled die set and pressure, temperature sensing and measuring devices. Die equipped in the center of the chamber for superplastic blow forming has a square opening and a square protuberance whose height is variable in the central area. Gas generant of powder can be just put on the surface of metal sheet after preheating up to about 150 ℃. Then slight clamping force is loaded for avoiding gas leakage and countering internal pressure. The force was always maintained constant during forming. Fig.4-4 shows a super-plastically formed by gas generant ADCA 0.4g prototype, aluminum alloy A5083. Considerable design flexibility, as this example shows, may be expected, which never be obtained in one path cold stamping.

In the die cavity, pressure changed after gas generation as shown in Fig.4-5. When temperature reaches at almost 200 ℃, gas generant begins thermal decomposition abruptly. The superplastic temperature is about 520 ℃ for the alloy, A5083, the deformation resistance does not yet fall to the lower level. Thus internal pressure rises suddenly at thermal decomposition. There may not be any deformation at all at this instance. It seems that strain rate is also much higher than usual superplastic deformation. But in few minutes there occurs initial deformation, then steep descent in internal pressure is observed, as shown in Fig.4-5. The rise of pressure with increasing temperature should oppose with decrease of flow stress. As a result, very low but

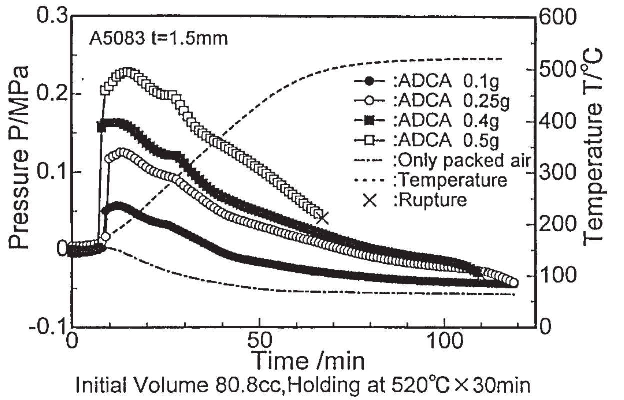

Fig.4-5. Generated pressure and temperature evolutions with time.

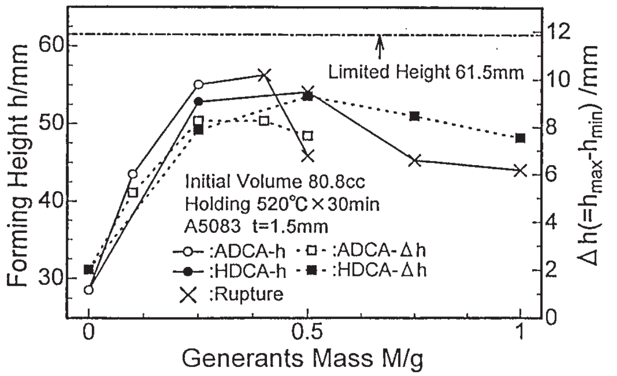

Fig.4-6. Average forming height vs used mass of gas generants.

significant forming pressure continues on in the forming. For the constant cavity volume, optimum amount of gas generant must be recognized in advance in this way of forming. The results shown in Fig.4-6 exhibits that average forming height can be reached at maximum in the range of gas generant mass 0.25 to 0.5g for both gas generants, and never says that the more the mass of gas generant, the higher the forming height up to failure.

4.4 RB/SPF by gas generant

The processing is composed of several stages. It involves cladding of similar/dissimilar metal with partial unbonded area at the interface. The geometry and the dimensions of this area should be calculated before rolling according to the structure of the component to be made. Within thin clearance a little amount of gas generant is inserted, which will act as a forming source in the next stage. By heating this clad sheets together with simple die, gas blow forming starts spontaneously to form the desired shape. Fig.4-7 shows a flow chart of making an auto-

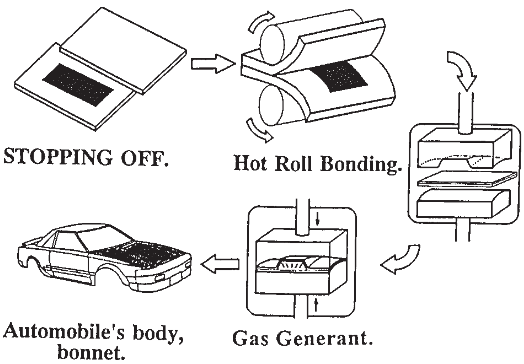

Fig.4-7 RB/SPF (Roll Bonding/SuperPlasticForming) may be available for fabricating, for instance, a component of automobile's body structure.

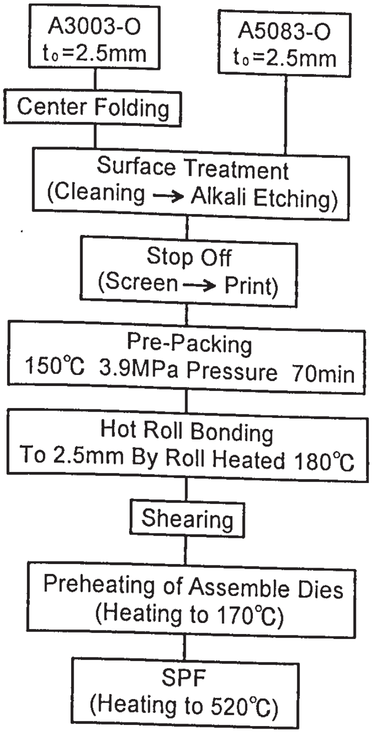

Fig.4-8. Making of clad metal by hot roll bonding for truss component.

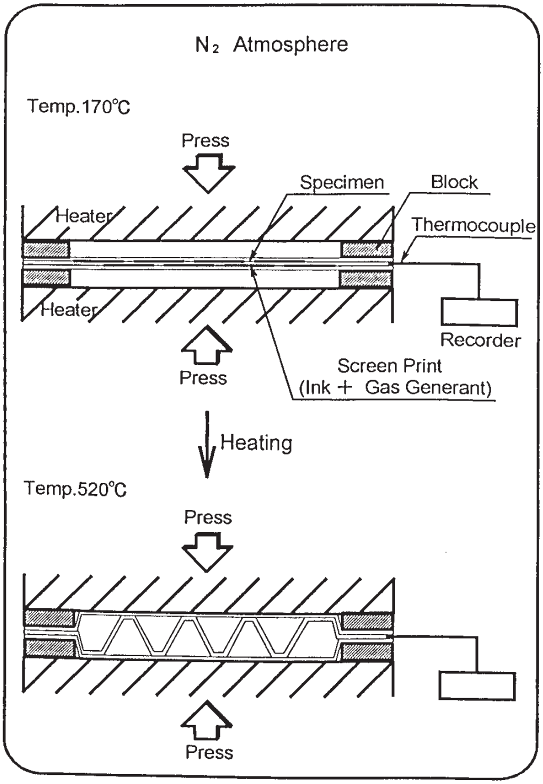

Fig.4-9. Gas blowing to make hollow structure like truss spontaneously.

mobile's bonnet as a practical component schematically. RB/SPF will be very effective for making this kind of hollow structure. A three layer sandwich structure, which is of a common type made by SPF/DB of Ti alloy sheets[5], was selected as a typical model. As a core material A5083, initial thickness to=2.5mm and as skins A3003-O (to=2.5mm) were also selected. After appropriate surface cleaning and mechanical brushing of the area to be packed, solution with water solved gas generant plus carbon fine particle was roller-printed by using screen pattern.

Then pre-packing procedure and hot roll bonding by thickness reduction by 67% were done. Final step of the processing is shown in Fig.4-9. With very simple dies and slight clamping force, the objective structural shape can be blown formed in the die cavity by rising the temperature spontaneously. Sectional cut of formed truss sheet is shown in Fig.4-10. A tiny shortcoming came out after forming. It is the wavy surfaces of this structure sheet. It will be extinguished, however by selecting appropriately the amount of gas generant and the clamping load.

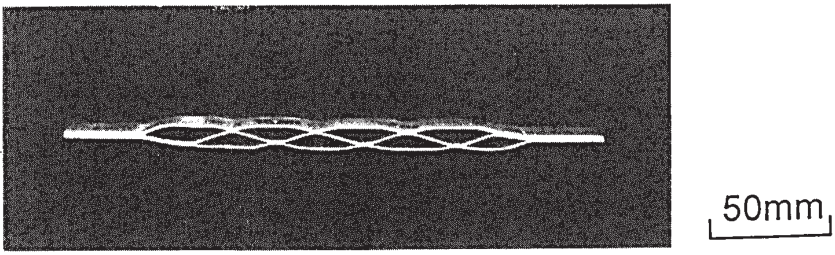

Fig.4-10. Sectional cut of formed hollow structure component by RB/SPF, by using ADCA 10% solution as STOP OFF and the source of gas pressure simultaneously.

5. CONCLUDING REMARKS

Pure aluminum and Al alloys have some intrinsic issues on sheet forming, as mentioned at the beginning of the article. Stretcher strain of Al-Mg accompanied by serrated yielding is one of the difficulties that we need to overcome someday. Although the idea of pre-coating for protecting soft surface of aluminum and improving the poor formability has come from pre-coated steel sheet, the future demand and use will develop on its own terms. Development of superplastic forming and concurrent diffusion bonding to Al alloy appears to be a distinct possibility. Diffusion bonding can not be applied to this metal but roll bonding instead will be successful if reduction rate is taken high enough. This is basis for the development of the new technique. Although the fundamental idea on RB/SPF was first available in Japanese Patents [6] , [7] in the early '60s, since then a very few number of components has been made by employing this technique. The fertile field still remains unexplored.

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REFERENCES

[1] E.Pink,Leoben and A.Grinberg:ALUMINIUM,60 (1984) ,601.

[2] A.K.Ghosh:Trans.of the ASME, (1977-7) ,264.

[3] S.Storen and J.R.Rice:J.Mech.and Phys.of Solids, 23 (1975), 421.

[4] H.Ohsawa and H. Nishimura:TRANS. of the JSME, 147 (1981), 654.

[5] E.J.Tuegel, M.O.Pruitt and L.D.Hefti, ADVANCED MATERIALS & PROCESSES, 17 (1989), 36.

[6] M.Koyanagi, T.Amitani,I.Yanagisawa and I.Hayashi, JAPANESE Patent, 10458,1959.

[7] I.Yanagisawa,I.Hayashi, M.Koyanagi, and T.Amitani, JAPANESE Patent, 13615,1961.