JMEPEG (2010) 19:527–532
DOI: 10.1007/s11665-010-9619-z

Indirect Versus Direct Heating of Sheet Materials: Superplastic Forming and Diffusion Bonding Using Lasers

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(Submitted December 9, 2009; in revised form February 17, 2010)

Many from within manufacturing industry consider superplastic forming (SPF) to be 'high tech', but it is often criticized as too complicated, expensive, slow and, in general, an unstable process when compared to other methods of manipulating sheet materials. Perhaps, the fundamental cause of this negative perception of SPF, and also of diffusion bonding (DB), is the fact that the current process of SPF/DB relies on indirect sources of heating to produce the conditions necessary for the material to be formed. Thus, heat is usually derived from the electrically heated platens of hydraulic presses, to a lesser extent from within furnaces and, sometimes, from heaters imbedded in ceramic moulds. Recent evaluations of these isothermal methods suggest they are slow, thermally inefficient and inappropriate for the process. In contrast, direct heating of only the material to be formed by modern, electrically efficient, lasers could transform SPF/DB into the first choice of designers in aerospace, automotive, marine, medical, architecture and leisure industries. Furthermore, 'variable temperature' direct heating which, in theory, is possible with a laser beam(s) may provide a means to control material thickness distribution, a goal of enormous importance as fuel efficient, lightweight structures for transportation systems are universally sought. This paper compares, and contrasts, the two systems and suggests how a change to laser heating might be achieved.

Keywords laser cleaning, laser heating, laser induced superplasticity, SPF, SPF/DB, titanium

1. Introduction

In 2003, Peters and Leyens described SPF/DB as "…the most spectacular near-net shape process … within which … complex thin walled titanium components can be manufactured in a single step" (Ref 1). Indeed, the advantages of SPF/DB components and structures are well understood and recorded; for example, Kalpakjian and Schmid (Ref 2) list such advantages as:

- Lower strength is required of the tooling, because of the low strength of the material at forming temperatures; hence, tooling costs are lower.
- Complex shapes can be formed out of one piece, with fine detail and close tolerances, with elimination of secondary operations.
- Weight and material savings can be realized, because of the formability of the materials.
- Little or no residual stress occurs in the formed part.

In 2008, Werner Beck (Ref 3), Head of FormTech in Germany, listed the following benefits:

- Cost reduction
- Weight reduction
- Rapid prototyping
- Integral design of complex shapes
- Better material utilization
- Low assembly cost
- Reduced part number
- Lower die cost

Given the above, SPF/DB should be the first choice of designers and not, as is often the case, the last. Furthermore, many in the SPF/DB community feel the technology has still not reached its full potential. So what is holding back its progress?

In this paper, the advantages of directly heating materials to be SPF with a laser will be compared and contrasted with the

This article is based on a presentation at the AeroMat Conference, International Symposium on Superplasticity and Superplastic Forming (SPF) held in Austin, TX, June 23-26, 2008.

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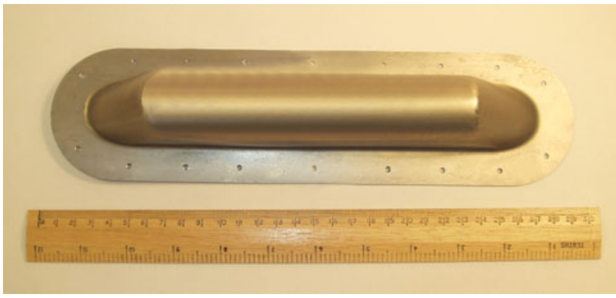

Fig. 1 Titanium protective cover

conventional indirect, isothermal methods currently, and almost universally, used to produce SPF parts. Production times and energy consumption will be considered, whilst improved quality through better control of material thickness distribution by differential heating will be discussed. To help illustrate the comparison, a current generic titanium aircraft component has been used (Fig. 1).

2. Process Problems

2.1 Tooling

Regrettably, perception is often regarded as truth and, consequently, when an SPF/DB component is less than perfect, many conclude that superplasticity itself is to blame; in reality, however, it is often the equipment or a related process that has caused the failure. For example, an out of tolerance component caused by mould distortion is likely to be caused by thermal creep due to cycling the mould in and out of a hot platen press, or furnace, during production, as the SPF process will faithfully reproduce the form in the tool, irrespective of its accuracy. In this quite common scenario, SPF is often cited as the problem when in fact it is the tool. However, if a process could be developed that significantly reduced the degree of thermal cycling, tool/mould life would be increased, at the same time maintaining any geometric features to a high degree of accuracy.

2.2 The Hot Platen Press

SPF/DB relies on raising the temperature of the blank to be formed to about 50-60% of its melting temperature, which can be achieved by surrounding the part to be formed with electrical induction heater(s), or within a furnace but, most frequently, by the use of heated platens of an hydraulic press, a procedure which was patented, in 1795, by Joseph Bramah (Fig. 2). In 1985, the British Aircraft Corporation, Bristol, commissioned the large hot platen press (Fig. 3) which is a direct derivative of Bramah's concept. Such devices only heat isothermally, providing a single temperature to the work piece/tool which renders the material to be formed superplastic across its entire surface.

2.3 Isothermal Component Forming

As the gas pressure used to force the material into its mould is applied, progressive stretching occurs, resulting in thinning of the material. In those areas where the maximum deformation takes place, thinning is often severe, with a reduction in component thickness of 50% being quite common. However, to ensure component integrity, such areas have, of necessity, to be of a certain minimum thickness, leaving less stretched areas of material unnecessarily thick and overweight.

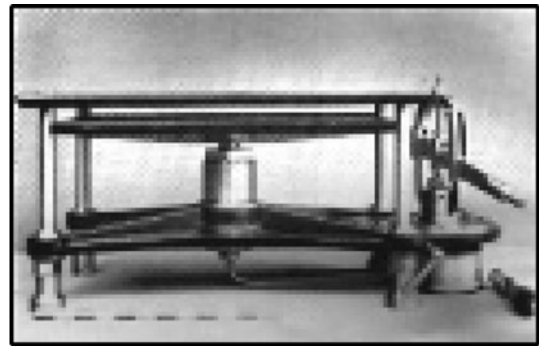

Fig. 2 First hydraulic press 1795

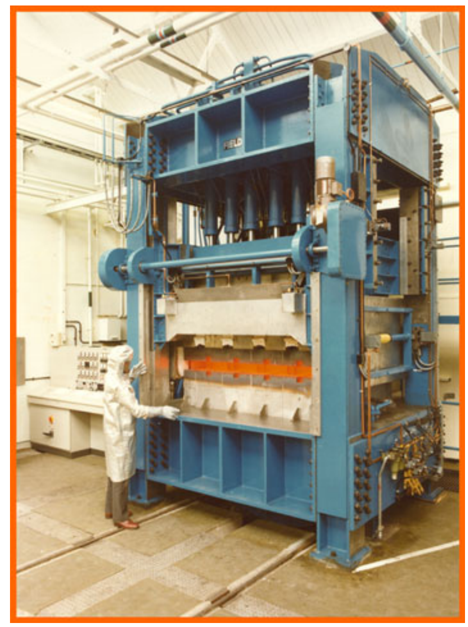

Fig. 3 SPF/DB hot platen press 1985

3. Thermal Characteristics of Indirect Heating

In addition to the above component limitations imposed by the use of a single temperature heat source, presses are not very energy efficient. Although conventional electrical heating elements used in appliances, such as household kettles and, indeed, hot platen presses heated by similarly designed elements, are very efficient, with conversion of electrical energy into heat in the range of 95-98% (Ref 4), the heating of press platens, followed by heating the mould and, finally, the blank to be formed, is very energy inefficient. Thus, initial studies suggest that perhaps less than 5%, and may be as little as 1%, of the total energy consumed in the process is actually used to heat the material.

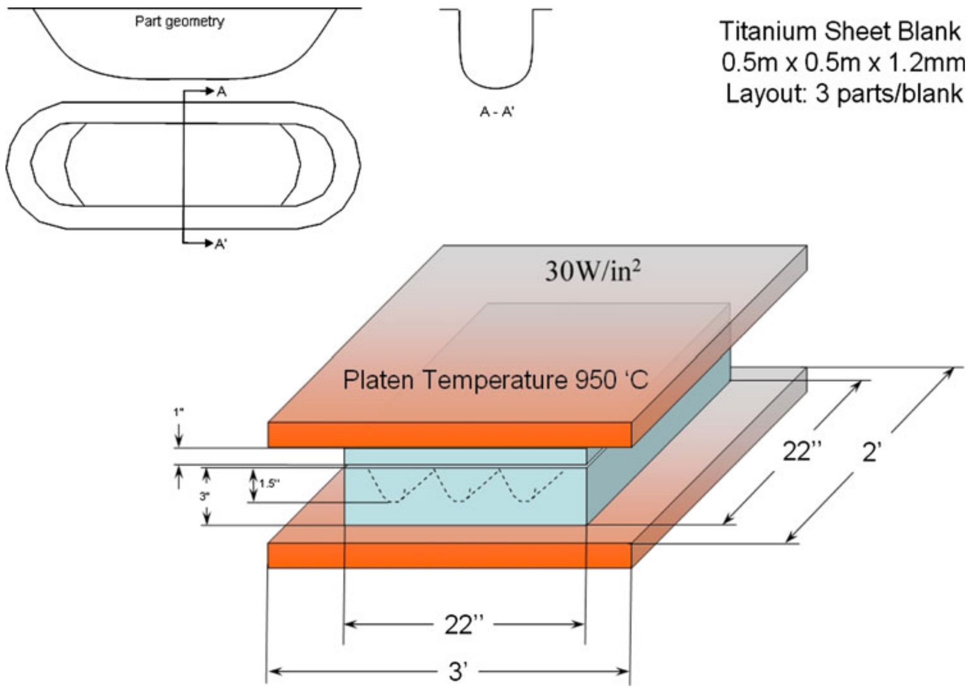

Fig. 4 Part formed using a hot platen press

Figure 4 shows the conventional process in which, after assembling an SPF/DB tool at ambient temperature, it is inserted into a hot platen press for indirect heating and subsequent forming. It is a typical single-sided component, formed from 1.2 mm sheet titanium alloy 6Al/4V (6/4). The tool and unformed blank are cold loaded into the hot platen press and, after forming, are allowed to cool in an inert atmosphere to prevent oxidation, thus eliminating post-forming operations. The more common practice of hot loading and unloading has not been chosen as no post-forming corrective shaping, nor alpha case removal, has been included in the scenario; such operations would introduce further energy and time considerations rendering the comparisons being made less accurate.

The cartridge heaters used in the above are 0.875 in diameter, and located in 1.250 in diameter gun drilled galleries in the steel platens of the press, which is kept at a constant 950 °C; no allowance has been included for heating up the press, which only normally happens once a year during annual maintenance. The electrical energy required to maintain this steady state temperature is 30 W/in^2 (Ref 5), which also provides a measure of heat loss through the fire doors surrounding the platens and the press structure.

Estimates of time and energy consumed are difficult because of uncertainties about heat transfer rates to the tool. For example, in the study it was assumed that the two halves of the steel tool were in intimate contact with the heated press platens, so heat was transferred with zero loss. In reality, oxidation, tool surface imperfections and undulated press platens act as barriers to heat transfer. However, initial calculations suggest the time required to bring the tool to forming temperature, whilst also compensating for heat losses, is approximately 120 min based on the heat treatment practice of steel soaking in a furnace for 1 h per inch of thickness to reach temperature. The forming time is known to be 100 min, thus giving a cycle time of 220 min. The steady state power density given above, over the platen area, represents about 25.9 kW which over the 220 min cycle represents an energy consumption of 342 MJ. Using estimated properties for the tool material, the energy required to heat the tool itself from cold to forming temperature was 97 MJ. Thus, the sum total of energy consumption for the total cycle was estimated to be 439 MJ.

4. Thermal Characteristics of Direct Heating

In marked contrast, the ‘wall-plug efficiency’ of modern lasers, that is the conversion of electrical energy into photon emission, or heat, from the laser delivery head is currently 25% (Ref 6), with many laser manufacturers predicting an increase up to 60% before long. Furthermore, if the correct laser beam wavelength is used, material absorption rates of 35% have already been recorded, with a potential of up to 70-75% with the development of effective heat shielding and secondary radiation devices. The combination of restricting direct heating to only the material to be formed, together with minimizing heat losses by good thermal design of the apparatus, would result in the development of a far superior energy regimen, initial studies suggesting the use of only half the energy employed in conventional SPF/DB. However, the prediction of saving 50% of electrical energy is based on a total laser system, or cell, that would be capable of carrying out most of the pre and post SPF/DB operations (Fig. 5). In this paper, only the actual SPF function of the cell is discussed which, although technically the most important element of the system, as it is the stage at which material thickness will be controlled, probably saves the least energy, but the most time, thereby increasing productivity beyond that which is currently possible.

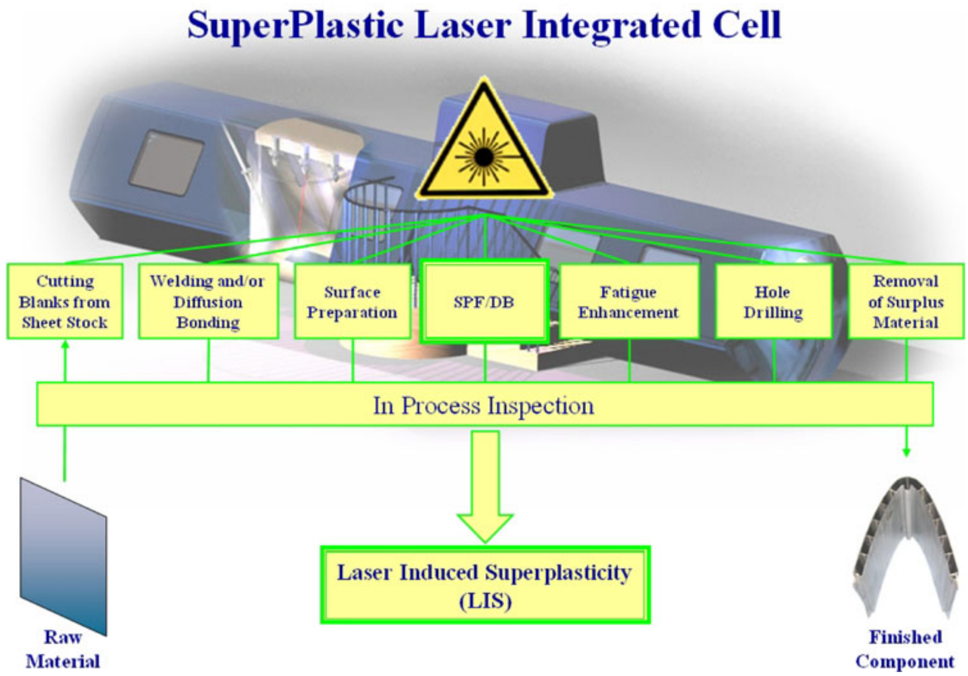

Fig. 5 Diagrammatic illustration of full laser manufacturing system

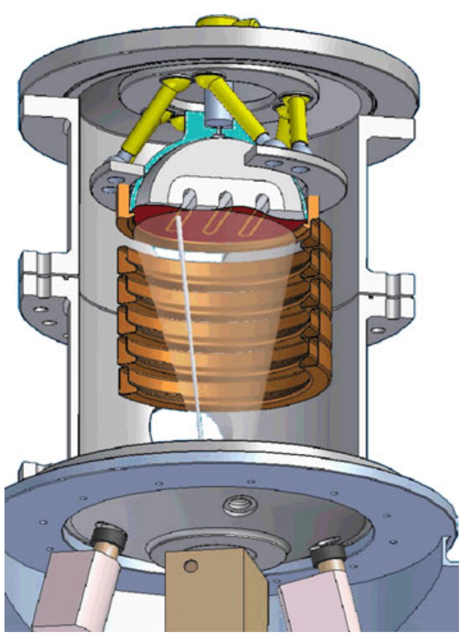

Fig. 6 Part formed using direct laser heating

Figure 6 shows a ceramic tool being used with a steel clamping ring to produce a gas tight seal between the titanium blank and tool surface, instead of the conventional steel plate. The laser beams heat only the blank and the ceramic tool absorbs radiant heat considerably less than the steel tool. Indeed, the tool surface will only reach the blank temperature in the final moments of the forming cycle when heat is radiated from the nearly fully formed blank, in marked contrast to the conventional process where the tool is the first to reach the forming temperature, which has to be maintained throughout the forming cycle.

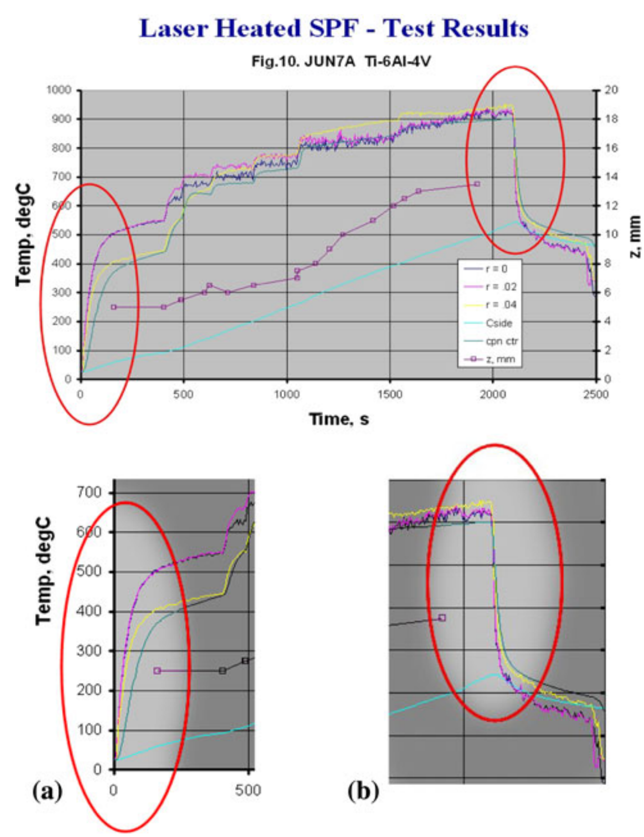

Fig. 7 Thermal history of laser heating 2 mm 6/4 titanium: (a) temperature rise and (b) temperature drop

Computer modelling, supported by over 40 laser forming tests, has shown that direct heating of the blank can achieve incredible heat up rates. For example, Fig. 7 shows the thermal history of a 120 mm diameter, 2 mm thick titanium alloy 6/4 sample that reached 400 °C from an ambient temperature of 20 °C in just 80 s and, subsequently, fell 300 °C in 20 s when the laser was switched off. The graph shows the temperatures recorded using three thermocouples attached to the upper surface of the sample and a centrally positioned one on the underside. A fifth thermocouple measured the temperature of the stainless steel capsule which held the ceramic mould.

Figure 7(a) shows the rate of temperature increase, which slows at about 480 °C at which point power was reduced to restrict thermal gradients within the mechanical apparatus. However, the overall thermal environment of the ceramic tool and surrounding metal structure started to absorb radiant heat from the hot blank at an increasing rate. To reduce this effect, and keep the thermal mass as low as possible so that energy efficiency is maintained and rapid cooling achieved (Fig. 7b), careful design and choice of materials of the cell is critical and requires further development.

To minimize heat transfer into the ceramic tool, and thus loss of energy, the surface may be made from, or coated with, an alternative material such as molybdenum or titanium nitride. These have a very low coefficients of thermal expansion and thus similar to silliminate, whilst being very reflective, thereby retarding the transference of heat from the radiating blank to the tool. In addition, the bulk of the mould tool would be produced from aerated silliminate (Ref 7) with about 50% porosity, thus reducing its thermal mass by half.

In addition, to maximize photon absorption into the surface of the material being formed, it is necessary for the laser beam to be perpendicular to the component surface, or as close to perpendicular as is practicably possible. To achieve this, the tool is mounted on a 6-axis parallel-kinematic hexapod micro-positioning system, often referred to as a 'wobble table' (Ref 8). A computer controls the table movements, maintaining the optimum beam to surface angle as the material progresses toward the tool cavity under gas pressure.

Apart from having a substantially lower thermal mass than the conventional hot platen press process, the proposed more energy efficient laser system could have a device, known as a concentrator tube (CT), which would provide additional thermal benefits. Thus, in the first instance, the CT would act as a highly effective thermal shell surrounding the component, thereby virtually eliminating heat loss to surrounding equipment. Secondly, a proportion of any secondary radiation present through both beam reflection and heat radiation from the component surface would be reflected back on to the material being formed, thus creating a very thermally efficient environment.

Simple computer modelling, developed by the academic team, suggests that providing such thermally efficient chambers within which the SPF/DB is carried out, heating up and forming cycle times would be reduced to 120 min and energy consumption to only 100 MJ.

5. Comparisons

Because of the many variables in each process that can affect the energy and time required to superplastically form titanium, evaluating and comparing direct and indirect heating is difficult. For example, it has been observed that the component and its mould tool are often much smaller than the press being used, so that a considerable amount of surplus energy is consumed (Fig. 8) (Ref 9).

Perhaps the clearest way to compare energies required by the two processes is as follows.

As a starting point, the energy estimated to raise the Cronite tool to forming temperature is 97 MJ, based upon estimated properties, whilst the thermal mass of an equivalent solid silliminate tool would be about 90% of the Cronite tool. Thus, working from this point, Table 1 shows how the various

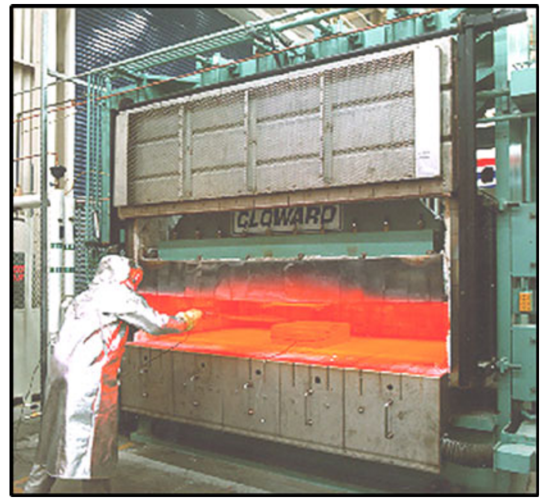

Fig. 8 Press in use at Triumph Fabrications—Hot Springs, Inc

Table 1 Estimated energy requirements for laser heating

Process considerations	Energy multiplying factor	Energy required in MJ
Cronite tool		97
Sillimanite properties	0.9	87
No tool lid	0.75	65
Tool support structure	2	130
Transient heating	0.5	65
Laser efficiency 25%	4	260
Blank energy absorption 35%	2.9	754

Table 2 Effects of thermal improvements in apparatus and laser efficiency

Process improvements	Energy multiplying factor	Energy required in MJ	% compared to hot platen process
Base case from above		754	172
Shorter cycle time	0.85	641	146
Future laser efficiency 50%	0.5	321	73
Bulk tool material with 50% voids	0.5	160	36
Heat shielding etc to improve energy absorption of blank	0.5	80	18
Reflective mould coatings	0.5	40	9

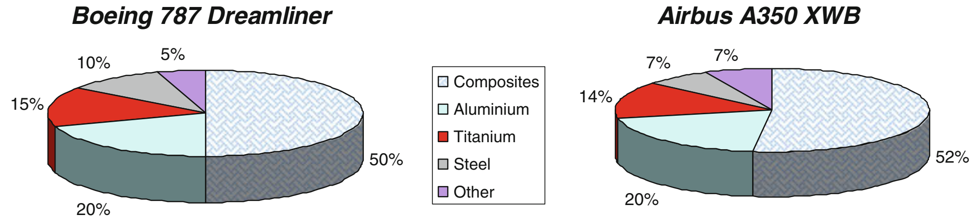

Fig. 9 Proportions of materials used in new civil aircraft

different aspects of the laser heating process change the energy requirements.

This study apparently showed the energy required for indirect heating amounted to about 70% (439 MJ:754 MJ) more than for the estimated hot platen process, but was based on extrapolation of energy multiplying factors from earlier, but rudimentary, experimental results. However, Table 2 shows that once the improved engineering, CT and expected laser wall plug gains were taken into account, calculated energy requirement levels fell dramatically as follows.

6. Conclusion

Assuming that the engineering improvements listed above are achieved, less than 10% of the energy required for indirect heating would be consumed in the laser process; such savings would be achieved irrespective of the size of the component being formed. In fact, the size of component is only limited by available laser power although modelling suggests 100 kW/m^2 is the maximum power needed only for the initial ramping up to forming temperature. Power required during forming would be considerably less.

In addition, if more titanium were formed using lasers, there would be even greater savings, which is particularly relevant because, for over 60 years, airframes have been made predominantly from alloys of aluminium, but these are now being superseded by carbon composites and titanium, with an increase from an average of 3 to 14/15% in the two latest aircraft from Airbus and Boeing (Fig. 9). Carbon composites provide lightweight and high levels of corrosion resistance, whilst titanium provides strength, stiffness and a means to join composite parts together. Thus, Boeing's Dan Sanders states that "Titanium alloy 6Al-4V is more compatible with composite materials than aluminium alloys because of its superior corrosion resistance and closer match to the coefficient of thermal expansion. In addition, many components that are used for the newer composite based aircraft, and are subject to high service temperatures, are fabricated from titanium using superplastic forming and diffusion bonding" (Ref 10).

Furthermore, as oil prices rise, the demand for light weight structures seems likely to escalate, resulting in a rapid growth in the requirement for titanium in aircraft, aluminium for automobiles, and of more SPF products. Consequently, the world will, increasingly, be looking to manufacturing technologists to provide low energy processes and improved product performance at reduced cost. The use of lasers to speed up the process of SPF, currently considered a slow "batch-forming process" (Ref 2), using markedly less energy than present day processes, and with the capacity to control material thickness distribution, could elevate laser induced superplasticity to the principal manufacturing technique of the 21st century.

LISTechnology Limited, with support from the Universities of the West of England, Bristol, UK, and Central Florida, US, has a major programme to develop laser induced superplasticity.

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