

# Superplastic Forming (SPF) of Materials and SPF Combined with Diffusion Bonding: Technological and Design Aspects

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## Abstract

*The development of superplastic materials has provided new opportunities for designing and producing complex components and structures using superplastic forming methods, alone or in combination with diffusion bonding, which are not possible with conventional materials. Despite the considerable analytical attention which has been devoted to superplastic sheet forming, the process/material behaviour relationships are so complex that the techniques used are not yet very well defined quantitatively in any generally applicable manner. This paper discusses the techniques for the commercial forming of components and structures with particular emphasis on simple SPF methods using different superplastic billets, including pre-shaped and pre-welded ones, in order to obtain a variety of component shapes with higher aspect ratio. The rule of main economic parameters of SPF technology, with respect to conventional one, is discussed.*

## Riassunto

Lo sviluppo dei materiali superplastici ha offerto nuove opportunità per il progetto e la produzione di componenti e strutture complesse mediante i metodi di formatura superplastica, eventualmente associati alla saldatura per diffusione. A fronte del considerevole interesse rivolto alla formatura superplastica, le relazioni processo/equazione di stato del materiale sono così complesse che le tecnologie utilizzate non sono ancora ben definite quantitativamente da poter essere applicate in modo generale. In questo lavoro sono discusse le tecnologie di formatura superplastica di componenti e strutture; viene dato particolare rilievo a metodi semplici di SPF che si avvalgono dell'uso di billette diverse, comprendenti quelle pre-formate e pre-saldate, che consentono la realizzazione di una varietà di geometrie con più elevati rapporti di forma. Sono anche discussi i principali parametri economici della tecnologia di SPF rispetto ai processi convenzionali.

## Introduction

Superplasticity is the property of some materials to undergo plastic deformation without necking and with very large elongations under low flow stresses, at temperatures above  $0.4 T_m$  (where  $T_m$  is the absolute melting point) and with low strain rates ( $10^{-2}$  to  $10^{-5} \text{ s}^{-1}$ ). This behaviour, often observed in materials with an equiaxed fine microstructure ( $d \leq 10 \text{ } \mu\text{m}$ ) stable at the deforming temperature, is defined structural or micrograin superplasticity.

Since superplasticity is a diffusion-controlled process, grain growth could occur during deformation. A presence of two phases in about equal volume fractions (microduplex materials) or a small amount of a fine dispersion of the second phase (pseudo-single phase materials) inhibits the grain growth at elevated temperatures, because the second phase acts as a grain boundary stabilizer.

The viscous behaviour of a material during superplastic flow is related to the deformation mechanisms and evolution of the microstructure during the process. A constitutive equation of superplastic materials is generally expressed in terms of flow stress as a function of strain rate, temperature and microstructural parameters. The most widely used equation is a power-law relationship,  $\sigma = k \dot{\epsilon}^m$ , where  $\sigma$  is the flow stress,  $\dot{\epsilon}$  the strain rate,  $m$  and  $k$  the strain rate sensitivity and a constant which depend on temperature, rate-controlling deformation mechanisms and microstructural parameters of the material. The main characteristic of superplastic materials is a high strain rate sensitivity ( $m \geq 0.3$ ), which confers high resistance to neck development and leads to large tensile elongations ( $\delta > 1000\%$ ) without failure [1, 2].

Full advantage of these mechanical properties is possible only in technological processes with tensile deformation schemes such as superplastic forming, which is now widely used for the industrial fabrication of complex parts and structures mainly for aerospace applications.

A large number of materials exhibits superplastic behaviour, but only some of them such as aluminium, titanium, nickel and ferrous alloys, have found commercial applications. A summary of some superplastic materials is presented in table 1. The fine-grained structure in these materials is usually achieved by means of several general methods or their combination. These methods, including phase transformation, recrystallization, working of duplex alloys and phase separation in duplex alloys, are

illustrated in fig. 1 [25]. In the case of the first two methods, phase transformation and recrystallization, the aim is to nucleate several product (transformed or recrystallized) grains within each grain of the

**TABLE 1 - Summary of some superplastic materials**

Alloy	Max Elong. %	$\sigma$ MPa	Strain rate $s^{-1}$	Grain size $\mu m$	T $^{\circ}C$	References
Aluminium-base alloys and composites						
Al Ca	1500		$10^{-3}$		550	3
Alcan 08050	800	2.8	$10^{-3}$		540	3
SUPRAL 100 (T6)	1600	9	$10^{-3}$	2	470	3
SUPRAL 210 (T6)	1350		$10^{-3}$		440	3
SUPRAL 220 (T6)	1100		$10^{-3}$		450	3
7075	600		$10^{-4}$		510	3
7475	1000	2	$10^{-4}$	7-14	516	3
8091	1137	5.6	$6.10^{-4}$	<1	500 - 540	4
Al-2124 + 20% SiC <sub>w</sub>	300	10	$3.3.10^{-1}$	1	475 - 550	5
Al-2024 + 20% SiC <sub>w</sub>	300	15	$5.10^{-4}$		100 ↔ 450	6
Al-7475 + 12 - 15% SiC <sub>w</sub>	350	7	$2.10^{-4}$		520	7
PM-64 + 10% SiC <sub>p</sub>	250	1.4	$2.10^{-4}$		516	8
Iron-base alloys						
Fe-1.6C-1.5Cr	1500		$10^{-4}-10^{-3}$		650	9
IN-744	> 1000		$3.10^{-3}$		960	10
Avesta 3RE60	> 700		$10^{-3}$		1000	11
25Cr-7Ni-3Mo-0.14N	780		$0.7.10^{-4}$		700	12
AISI 630	500	45	$3.10^{-4}$	2	775	13
Titanium-base alloy						
Ti-6Al-4V	1600	6	$4.2.10^{-4}$	6	950	14
Nickel-base alloys						
IN-100 PM	> 850		$3.3.10^{-4}-8.3.10^{-3}$		920-1050	15
IN-738	500		$10^{-4}-10^{-3}$		900	16
Ni-39Cr-8Fe-2Ti-2Al	> 1000		$10^{-4}-10^{-3}$		980	17
IN-718	1050	70	$9.68.10^{-4}$	2	920	18
Copper-base alloys						
IN-836	200-680		$1.6.10^{-4}-6.6.10^{-2}$		460-620	19
Cu-10Al-5Fe-5Ni	1000 - 5500		$5.10^{-3}-10^{-2}$		750-850	20
59Cu-1Fe-1Mn	540-620	10-15	$1.2.10^{-2}$	4-5	550	21
62(63)Cu-0.2(0.4)Si	400	20	$1.2.10^{-2}$	7-8	650	22
Eutectoid alloy						
Zn-22Al	500-2900		$1.7.10^{-3}-1.7.10^{-2}$	<1	200-250	21
Ceramic materials						
Li <sub>2</sub> O-Al <sub>2</sub> O <sub>3</sub> -6SiO <sub>2</sub>	400		$10^{-2}-10^{-1}$		1100-1150	23
ZrO <sub>2</sub> -Al <sub>2</sub> O <sub>3</sub>	500		$10^{-2}-10^{-1}$		1400-1550	24

parent microstructure. In the third method, deformation of duplex alloys, grains of the two phases are broken-up and spheroidized. Deformation is usually accompanied by recrystallization in both phases, contributing to the overall grain refinement. In the fourth method, phase separation in duplex alloys, the starting microstructure is not the equilibrium duplex microstructure, but rather is usually either a martensitic or supersaturated solid solution. Phase separation of the non-equilibrium structure into the two equilibrium phases can produce a fine-grain duplex microstructure.

### **Superplastic Forming and SPF combined with diffusion bonding (SPF/DB)**

The low flow stresses, the large elongations and the high strain rate sensitivity values permit superplastic materials to be used in deformation processes similar to thermoforming of plastics [26, 27]. The most widely used superplastic forming method, female forming, is illustrated in fig. 2.

The sheet is placed into a die, heated to the deformation temperature and rigidly clamped around its periphery by hermetic elements (Fig. 2-b). A gas pressure (argon, nitrogen, air etc.) usually in the range 0.1-2.1 MPa is applied to the top side of the sheet. In the case of forming materials which exhibit cavitation during superplastic deformation, such as aluminium alloys, a back-pressure may be applied in order to reduce cavity nucleation and growth, by means of hydrostatic pressure, equal to the difference between the pressure values over and under the sheet [28].

During the initial stage of SPF, free forming, when the sheet is not in contact with the tool, deformation is concentrated at the pole of the dome and consequently this region exhibits the greatest flow stresses, strain-rates and strains. Ratio of the pole thickness to initial sheet thickness,  $S_p/S_0$ , as a function of the bulge height-to-base ratio,  $H$ , for free superplastic forming of two brasses into square die, with optimal gas pressure, is shown in fig. 3-a [29]. It can be seen that for these materials the changes of pole thickness depend on  $m$  values: for materials with high  $m$  the pole thickness changes slighter. This influence is more clear near the dome failure,  $H \approx 0.75 - 0.83$ . The stage of free forming ends when the pole comes into contact with the bottom of the die, the material is locked against the tool by friction and forming pressure and this prevents further deformation within the region. It is clear that the pole thickness at this moment is proportional to the  $S_p/S_0$  value corresponding to the pole height  $H$  (fig. 3-a).

Further deformation is therefore forced to occur in the unsupported zone, resulting in higher thickness gradients in the part being formed. Since the corners and fine elements of the die are the last to fill, the greatest subsequent thinning,  $(S_0 - S)/S_0$ , occurs in these regions. The minimum corner thickness decreases as the radius between the side wall (walls) and base of the component ( $r_{pl}$  = planar,  $r_t$  = three-dimensional) becomes smaller respect to the corresponding section radius of the dome ( $R_{pl}$ ,  $R_t$ ) after its contact with the bottom of the die (fig. 3 b-c). These corner effects are exaggerated if the corner is three dimensional rather than planar and also depend on the  $m$  values: for higher  $m$  values thinning is lower (Fig. 3 b-c) as for free forming of the dome (Fig. 3-a).

Hence the superplastic forming technology is limited by some technological parameters such as the aspect ratio of the formed component ( $H$  = height/width) and its thickness distribution. The latter is more uniform for materials with higher  $m$  values. An example of different deformation stages of the female forming carried out on a 250 kN universal hydraulic press is illustrated in fig. 4. The component has complex decorative elements and its manufacture by conventional pressing methods require 5 operations and expensive high-powered presses, such as a 25000 kN coining press [30].

From the thickness distribution of fig. 4 it is clear that with the female forming method it is not possible to shape high depth components nor to create a rather uniform wall thickness.

The limits of this method are the aspect ratio not higher than 0.3-0.4, the thinning up to 52% and 84%, for planar and three dimensional corners respectively, and the ratio of formed component area to blank area ( $A/A_0$ ) not higher than 2.2-2.6 [31]. For materials with  $\delta \geq 1000\%$  it is possible to shape higher

components, for example with  $H = 0.75$  and  $A/A_0 = 4$ , but in this case a thinning up to 97% was observed [29, 31].

A number of methods have been developed to increase the aspect ratio and obtain a more uniform thickness distribution [32]; the more interesting are illustrated in fig. 5. The upper part of this figure includes rather simple techniques, where deformation is only driven by a gas pressure. These methods make it possible to utilize universal presses for their realization [30]. The schemes of fig. 5-a and 5-c are also more suitable for SPF with a moving flange, such as is the case with a membrane forming (fig. 5-d) [33]. With this method a more uniform thickness distribution can be achieved and also it is possible to shape non-superplastic materials [34], thus reducing production costs of single to low volume sheet components because the male tools are no longer necessary.

The last three complex schemes of fig. 5, on the contrary, involve the use of a moving tool and enable higher aspect ratios to be achieved, up to  $H = 0.6$  for male forming (fig. 5-f) and  $H \approx 1$  for snap-back forming (fig. 5-g). However, the use of moving tools makes special press equipment necessary for SPF [32].

Tools for SPF, whether male or female, are single surface and may be readily and quickly modified during product development by simple machining operations [30]. In some instances, composite tools incorporating different profiles are used to produce similar parts without necessitating separate formers and these tools may incorporate sliding sections to produce re-entrant parts.

One major benefit of the single surface tools is that sheets of differing thickness may be formed to optimize strength, weight and cost parameters. Each will give parts which are dimensionally true to size on the tool side. This factor may influence the choice of forming method used. The cost of SPF tools is rather low and could be less than 1/10 of conventional matched tools [35].

SPF equipment type depends both on the forming scheme used and on the volume of production. So, for a small number of shaping components, superplastic forming with the schemes of fig. 5 a-b-c-d is possible using only tools to contain the clamping forces and forming pressures, heating being achieved using conventional electric furnaces. On the contrary, for medium-volume production, forming can be carried out only by means of modernized universal or special hydraulic equipment [30, 32]. The availability of suitable presses for SPF is, however, a limiting factor in the production of full scale components.

An analysis of the force and work-space characteristics of the Russian universal hydraulic presses, for instance, showed that not a large number of presses are available for SPF. Many of them, designed for conventional deformation processes, have relatively high force characteristics which are not suitable for superplastic deformation.

The types of hydraulic equipment analyzed are shown in fig. 6, where (1) is the press scale for isothermal forging, (2) is the press scale for working of plastics, (3) and (4) are the press scales for pressing of sheet components. In this plot the x-value is the table area of the press, the y-value is the pressure achieved on the table. The horizontal line at  $p = 2.25$  MPa divides the field of pressure values in two regions. In terms of energetic characteristics, the lower region (pressure values less than 2.25 MPa) is the optimum region for SPF. The pressure value  $p = 2.25$  MPa was obtained by multiplying an average pressure value for SPF ( $p = 1.5$  MPa) with a coefficient ( $c = 1.5$ ) which takes account of the necessity of sure blank clamping. It is important to note that in this analysis an ideal case of SPF was assumed, with the forming blank area equal to the press table area.

This analysis clearly shows the necessity to design and manufacture special presses for superplastic forming, mainly in the range of work-space areas where universal presses with low force characteristics are absent.

A summary of general characteristics and demands for special SPF equipment has been given by D.B. Laycock [32], based on practical experience of the first special presses for superplastic forming



designed and manufactured by Tube Investments/British Aluminium, in 1974. The generalized (male) machine configuration is shown in fig. 7. Central to the machine design is a pair of insulated pressure chambers which can be moved relative to each other by a hydraulic system which also provides the clamping force for the superplastic sheet. Blanks of different sizes can be accommodated by the use of a modular range of auxiliary clamping plates, which transmit the clamping force from the chamber flanges to the superplastic sheet, located between the clamping plates. A mechanically driven table is provided within each pressure chamber to carry either forming tools or a device for sensing bubble heights. The more important characteristics of the special equipment are the following [32]:

- (\*) means of applying controlled pressure to either side of the sheet;
- (\*\*\*) ability to provide controlled tool movements;
- (\*\*) facility to accommodate blanks of different size within the machine;
- (\*\*\*) means of sensing bubble heights in free deformation, because bubble height is critical;
- (\*) machine motions such as opening, closing and clamping, as rapid as possible so that cycle times are minimized;
- (\*) self contained heating so that the forming environment is maintained at the desired forming temperature;
- (\*\*\*\*) specially built auxiliary sheet-heating equipment so that minimal time is taken bringing the blank to forming temperature within the machine.

Based on practical experience, some of these demands for the SPF equipment indicated as (\*) are the most important (necessary for all forming schemes), others (\*\*) are desirable, (\*\*\*) necessary for SPF schemes with moving tools, and finally (\*\*\*\*) have no influence on SPF machine construction.

In spite of the possibility to design and produce special equipment, corresponding to all these demands, which permits the use of complex SPF schemes with moving tools (fig. 5 e-f-g), female (drape) forming is generally preferred over other forming techniques. This trend can be explained by the relative simplicity of this method and its equipment which requires that only demands (\*) and (\*\*), leading to lower expenses, to be met.

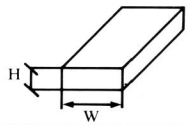
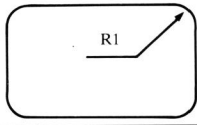

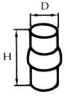
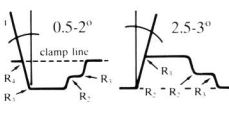
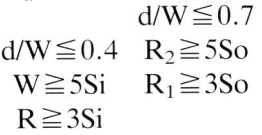
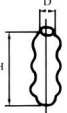
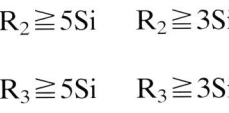
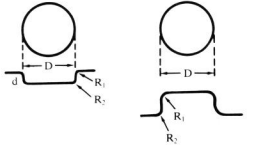
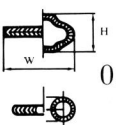
The attraction of this method is also clear because female (drape) forming permits the production of almost all shapes of components, also with re-entrant features, using billets of different types. The technological classification of SPF components in relation to type of billet and forming method is shown in table 2 [36]. In this table the component shape is described by the aspect ratio in column 3. These component shapes are divided into four technological groups and, for each of them, the more effective type of forming billet and SPF method are reported in column 6. Columns 4 and 5 indicate the dimensions of the radii between the main surfaces of the component and the measurements of fine elements, when present (Superform Limited recommendations were used for these characteristics [37]). To complete the technological picture, in columns 3 to 6 there are some data for the male forming method, which also could be used in some cases.

Thickness distributions can be improved for all groups in the classification using well known methods, such as: superplastic billets with higher  $m$  values and with shapes more similar to the component shape, reverse billowing, membrane forming, SPF with a variable temperature field, SPF of billets with different thicknesses, SPF with a variable friction coefficient, and others [32, 33].

The classification should be useful for machine and technology designers and its applications are shown in some examples for each technological group. The components of fig. 8 a-b-c [21, 30, 38] was obtained from sheet billets (group I), the component of fig. 8-d [39] from pre-shaped glass billet (group II), the components (multiple forming) of fig. 8-e from tube (group III), the components of fig. 8 f-g from edge welded envelopes (group IV). Although some product examples given here are only model components, the principles of technology design for their production can be extended for use in high-tech applications such as for the aerospace industry.

The field of use for the technological group IV, from edge welded envelopes, can be successfully extended by means of the diffusion bonding process for billet/component/structure fabrication.

**TABLE 2 - Technological classification of components**

N°	Technological Group of Components	Aspect Ratio Height/Width	Corner Radius of Component	Parameters of Fine Elements	Billett and Method
1	2	3	4	5	6
I	Shallow Component With Bottom				Sheet Billet
		SPF	SPF	SPF	Female (Male) SPF (single/multiple) Thinning up to 80%
II	Deep Component With Bottom				Pre-shaped Glass Billet
		$0.4 \leq H/W \leq 60$	$R_1 \geq 15S$ $R_1 \geq 5S$	$d/W \leq 0.4$ $W \geq 5Si$ $R \geq 3Si$	Female (Male) SPF
III	High Deep Component Without Bottom				Pre-shaped Tube Billet
		$H/W \geq 0.3$	$R_2 \geq 5Si$ $R_3 \geq 5Si$	$d/D \leq 0.3$ $D \geq 10Si$ $R_1 \geq 3Si$ $R_2 \geq 5Si$	Female (Male) SPF (single/multiple)
IV	Thank-Type Component		$R_4 \geq 5Si$	$d/D \leq 0.6$ $D \geq 10Si$ $R_1 \geq 3Si$ $R_2 \geq 5Si$	Edge Welded Envelope Billet
		$0.4 \leq H/W \leq 0.8$			Female (Male) SPF

With regard to type of billet and its fabrication technology, it is important to note that the billet material must not only have good or excellent superplastic properties, but also must have good cold ductility and weldability (including DB).

The main characteristics of the diffusion bonding process are very similar to those of SPF [40]:

- the welding temperature is between 0.5 and 0.7  $T_m$ , in order to accelerate diffusion processes;
- a moderate gas pressure must be applied to develop an intimate contact between the billet surfaces to be bonded;
- a relative long time is necessary for the joining process;
- the bonding must be performed in vacuum ( $10^{-1}$  to  $10^{-3}$  Pa) or in a dry gas atmosphere (Ar, Ge,  $H_2$ );
- the roughness of the billet surfaces must be between 40 and 80  $\mu m$  for ductile materials and  $<2.5$   $\mu m$  for hard ones;
- interlayers in the form of metallic foils or coatings (electroplated, evaporated or sputtered) can be used.

The similarity of the technological parameters for both technologies makes it possible to combine SPF and DB, and thus highly complex structures are superplastically formed and diffusion-bonded within

the same heat-cycle [41]. The structures manufactured by concurrent superplastic forming and diffusion bonding can be divided into the following three main groups (fig. 9 [42]):

(1) Structures including forming of a single sheet into a die with pre-placed details followed by diffusion bonding. This allows the sheet material to be selectively thickened for stability or strength, or for attachment purposes. This can be used to avoid the need to start with forgings, extrusions or plate material and then machine these materials to sheet thicknesses over much of their surface area. As a result as much as 90% of the scrap material that would be generated during the machining operation is avoided and the cost of machining is eliminated.

(2) Panels including diffusion bonding of two sheets at selected locations followed by forming of one or both into a die (the reverse sequence can also be used); examples of such structures are shown in fig. 10 a-b.

(3) Structures involving diffusion bonding of three (or more sheets) at selected locations under gas pressure, followed by their expansion under internal gas pressure which forms the outer two sheets into a die while the centre sheet(s) is stretched into a core configuration.

In order to develop diffusion bonds in predetermined areas, a parting agent or stop-off material (*e.g.* graphite powder, yttrium oxide or boron nitride for titanium alloys) is placed between the sheets in the local areas where non-bonding is desired. The core configuration is determined only by the stop-off pattern; it can vary greatly and be modified without tooling change. The external shape of two and three sheet structures is determined by the tool cavity, which can be variable either in depth or in configuration (*e.g.* circular). The process inherently provides complete flexibility in edge closure design. This avoids what is frequently a significant cost factor in the fabrication of conventional honeycomb sandwich panels. In addition, the truss members of the SPF/DB core become integral with the edge member through the DB pattern, providing reduced cost and improved structural efficiency through simplified shear ties [43].

The superplastic forming and diffusion bonding process (SPF/DB) is an attractive manufacturing technology which is already coming into use for single and low volume production of primary structures for airframes and permits the manufacture of structures and components that could not otherwise be produced. In fact, since the latter are manufactured from high strength materials, such as titanium and aluminium alloys, the structures formed by the combined SPF/DB process provide higher rigidity and strength-to-weight ratio than conventional riveting assemblies, due to a large reduction in the number of components and higher structural efficiency. The process also provides excellent material utilization resulting in low buy to fly ratios.

## **Economics of component production**

The main design and manufacturing objectives associated with the selection of any processing route and component material are the achievement of maximum structural efficiency and minimum cost. Large cost and weight savings, up to 60% and 40% respectively, have provided the driving force for the development of SPF and SPF/DB in different industries such as the electronic, transport, architectural, medical, sport and mainly aerospace industries [21, 35, 38, 39, 42, 43]. In spite of the relatively low deformation rates, the SPF process can be economically attractive for low to medium volume production of sheet components. Primary cost savings are achieved through part consolidation, where structures with designed-in strength and stiffness are produced as a single component, rather than as built-up structures consisting of many details, and through a reduction in number of forming steps required to produce a component. Part consolidation also provides secondary savings, since a fewer number of parts leads to savings in design, inspection and production control.

The main advantages and disadvantages of the SPF technology with respect to conventional technologies can be summarized as follows [21, 32, 35]:

#### *Advantages:*

1. Liberty of design, with the possibility of forming complex components in a single operation, also from high-strength and low-ductile materials.
2. Reduction in tool costs because only one major tool is required, rather than an accurately matched pair of tools or multiple ones.
3. Reduction in capital costs of the production equipment because of the low deformation loads.

#### *Disadvantages:*

1. Long-time cycle related to the low strain rates.
2. Higher costs of die materials for high temperature superplastic deformation.
3. Higher costs of superplastic materials, resulting from thermal and mechanical treatments to induce a fine-grained microstructure.
4. Possible reduction in mechanical properties of shaped components because of cavitation.

In order to illustrate the competitiveness of SPF compared with other technological processes, a well known plot is often reported (fig. 11-a). In this plot the advantages and disadvantages of SPF process determine its application area. Below this interval it may be less expensive to use SPF for complex components with accurately reproduced curved surfaces, such as prototype automotive panels, radar reflectors or aircraft skin panels. Complex curves, intricate details and features such as ribs, bosses, depressions etc., often have little effect on forming cycle and price. The volume range over which superplastic forming is attractive increases with increasing complexity, particularly when multipiece fabrications can be replaced by a single superplastic component [35]. Thus the initial and final production levels for which the application of SPF is advantageous are not well defined. Mathematic models to predict the economic feasibility of the various technological application are useful. In this way the authors [44] have shown that it is possible to determine the influence of each economical parameter variation on the unit cost and production quantity. In fig. 11 b-f five plots are reported illustrating the quantitative influence of the main economic parameters on year volume cost efficiency of the SPF technology, with respect to conventional pressing technology (the y-value is the difference  $\Delta$  between the year volume unit cost of the pressing and SPF production).

The main technological parameters, in terms of their influence, are the following: time of SPF ( $t$ ); equipment price ( $P$ ); metal price ( $M$ ); die price ( $S$ ); die life value ( $D$ ). Hence, respective reductions in these parameters result in more efficient sheet component production.

## **Conclusions**

Superplastic forming and SPF combined with diffusion bonding are attractive technologies for single to low volume production of components and structures from specially prepared materials. The processes permit the manufacture of components and structures that could not otherwise be produced. These technologies provide the achievement of high structural efficiency and considerable cost and weight savings, up to 60% and 40% respectively.

Materials for SPF and SPF/DB processes should have, not only good or excellent superplastic properties (elongation and strain rate sensitivity), but also good cold ductility and weldability (including DB). These properties make it possible to fabricate components from superplastic materials using different types of billets, including sheet, pre-shaped and pre-welded ones. A variety of component shapes could be formed from these billets with simple SPF methods, using inexpensive modernized universal equipment.

Significant savings in cost for SPF and SPF/DB production result from the shorter times required in SPF and lower costs of the presses and metals used. However in the case of single component forming,



reduction of SPF time is possible through a better construction of equipment and/or better properties of superplastic materials, which are both certainly more expensive. Hence, it is the combination of the effects of these parameters which determines the extent of cost savings.

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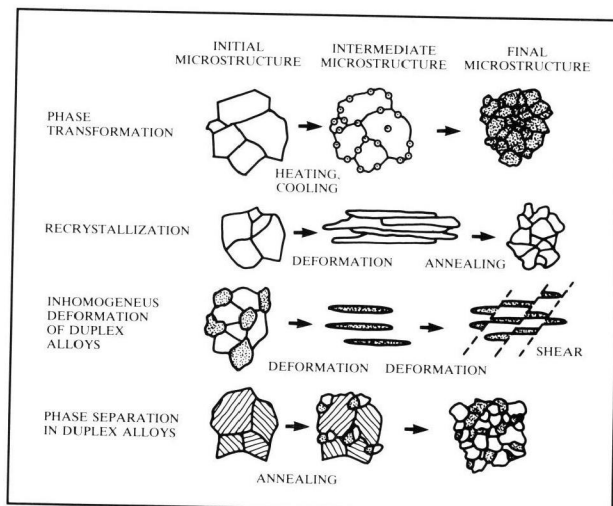


Fig. 1:  
Schematic illustration of the general mechanisms  
of grain refinement.

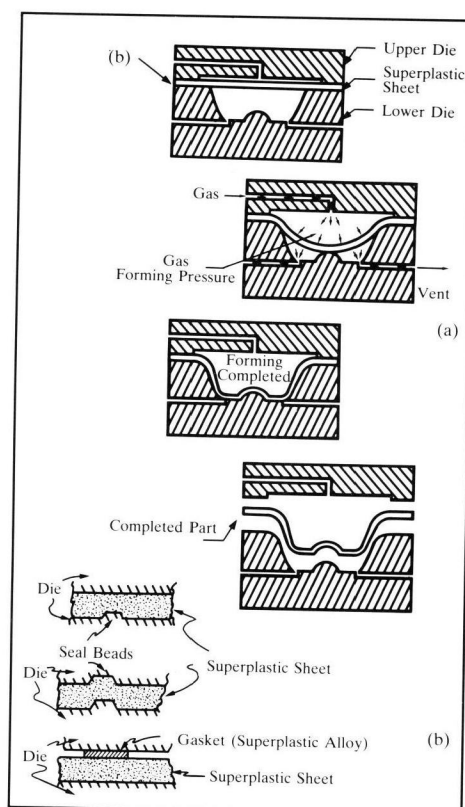


Fig. 2:  
Female forming: (a) process stages and (b) types  
of hermetic die elements.

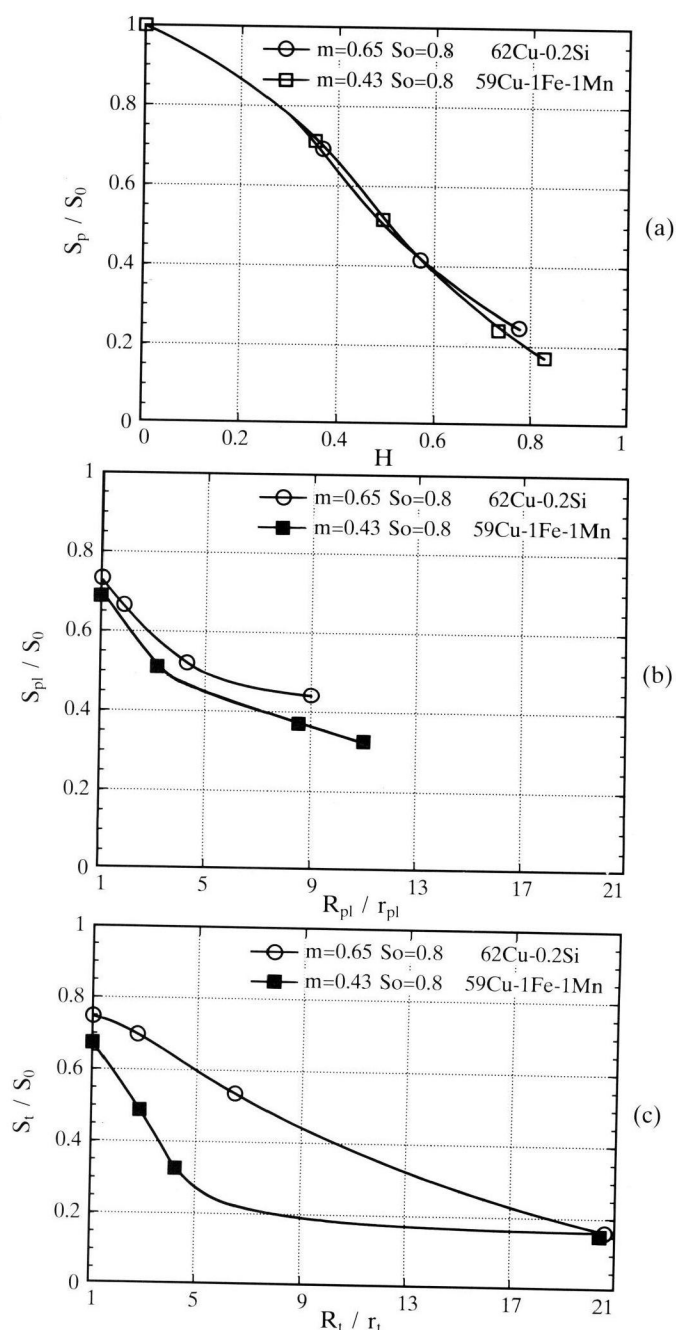


Fig. 3:  
Ratio of current component thickness to initial  
sheet thickness  $S_0$  as a function of the shape  
development parameter for SPF of brasses into  
square die during free forming up to failure (a)  
and during shaping of box components with  
 $H = 0.33$  (○) and  $H = 0.42$  (■) (b, c):  
(a) pole thickness  $S_p/S_0$  as a function of the bulge  
height-to-base ratio  $H$ ;  
(b) planar corner thickness  $S_{pl}/S_0$  as a function of  
the ratio of sectional radius  $R_{pl}$ , at the contact  
moment between dome and die bottom, to the  
current radius in this section;  
(c) three-dimensional corner thickness  $S_t/S_0$  as a  
function of the ratio of sectional radius  $R_t$ , at the  
contact moment between dome and die bottom,  
to the current radius in this section.

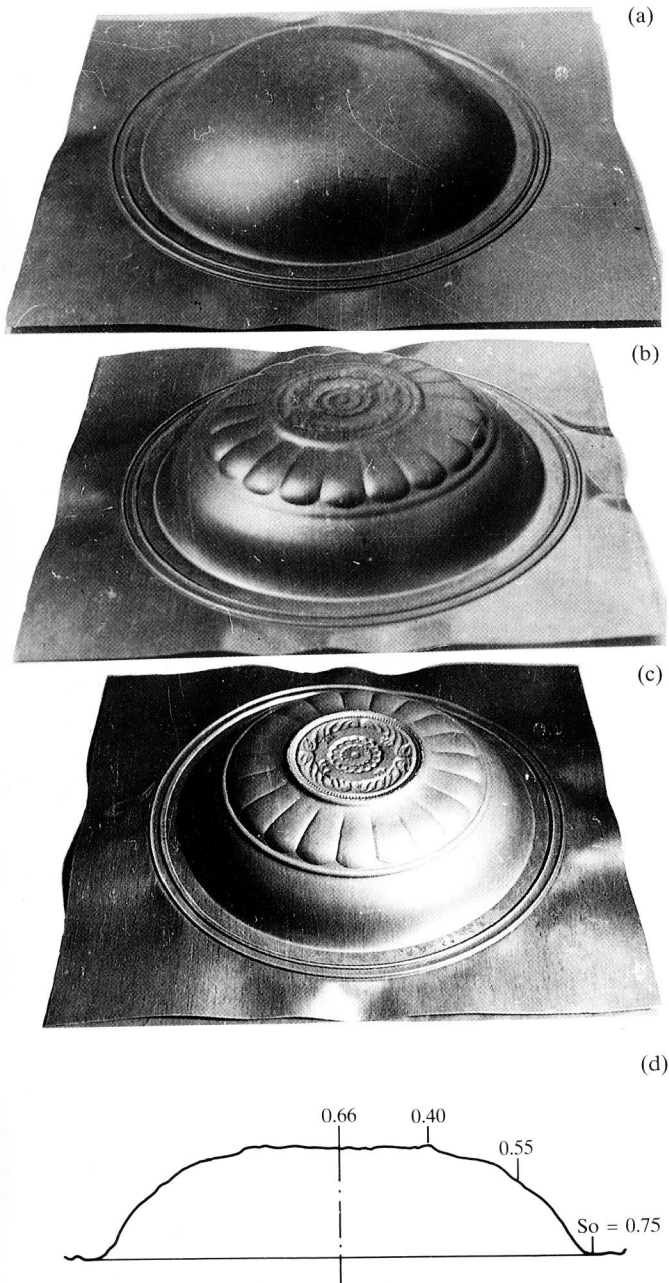


Fig. 4:

Female SPF stages and thickness distribution of brass decorative plate: initial plate shaping with gas pressure 0.1 MPa after 30 s (a) and 45 s (b); final plate shaping with gas pressure 1.3 MPa after 90 s (c); thickness distribution of the formed plate (d).

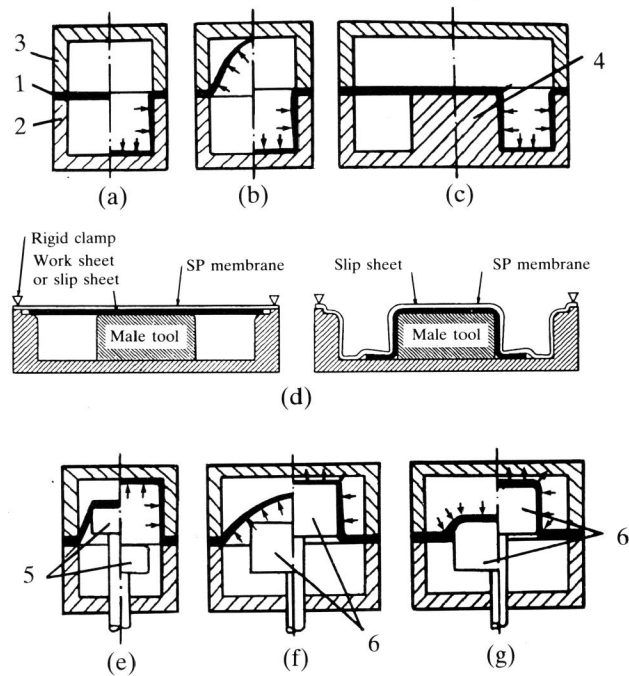


Fig. 5:

Main SPF methods: (a) female forming, (b) reverse billowing, (c) drape forming, (d) membrane forming, (e) plug-assisted forming, (f) male forming, (g) snap-back forming.

Scheme elements: (1) superplastic billet, (2) female mould; (3) upper die; (4) male tool, (5) auxiliary tool, (6) moving male tool.

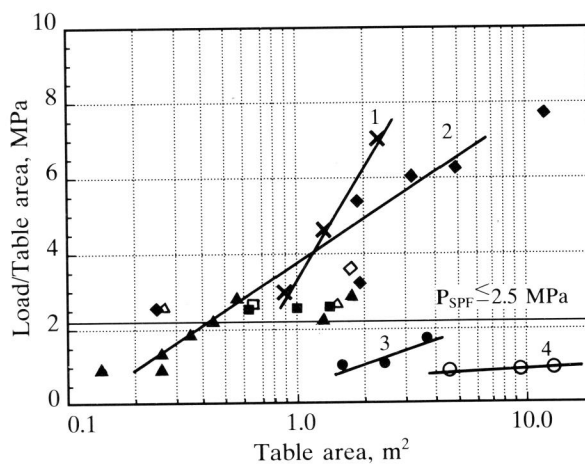


Fig. 6:

Characteristics of Russian universal hydraulic equipments; work pressure as a function of the press table area:

- 1(X) - presses for isothermal forging;
- 2(▲ ◆ ■ △ ◇ □) - presses for working of plastics;
- 3(●) and 4(○) - equipment for pressing.



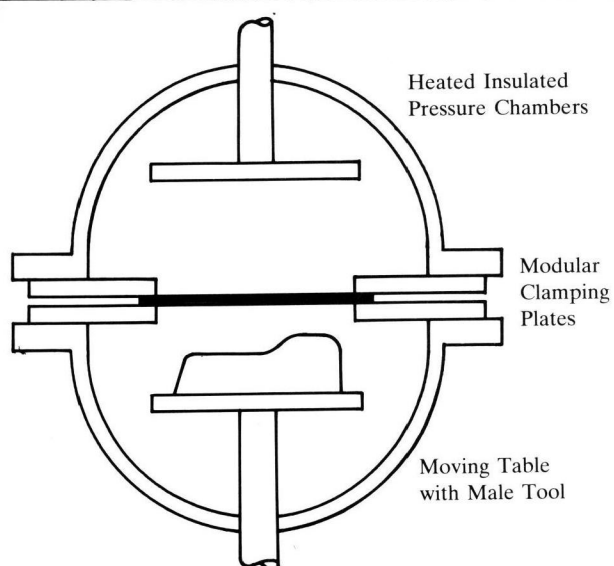


Fig. 7:  
Scheme of special SPF machine.



Fig. 8:

Female (drape) SPF components from blank (a-b-c), pre-shaped glass billet (d), pre-shaped tube (e), and edge welded envelope (f-g):

(a) computer keyboard cover from Al-5Zn-5Ca (Schetmash Corporation, Kursk, Russia); (b-c) female and drape formed decorative plates from 59-Cu-1Fe-1Mn, 62Cu-0.2Si (Non ferrous Metal-working plant, Kirov, Russia); (d) cream-jag, with reentrant features, from 62Cu-0.2Si (Non ferrous Metal-working plant, Kirov, Russia); (e) multiple formed model components (scheme); (f-g) model components formed without tools from 26Cr-6Ni-1Ti.

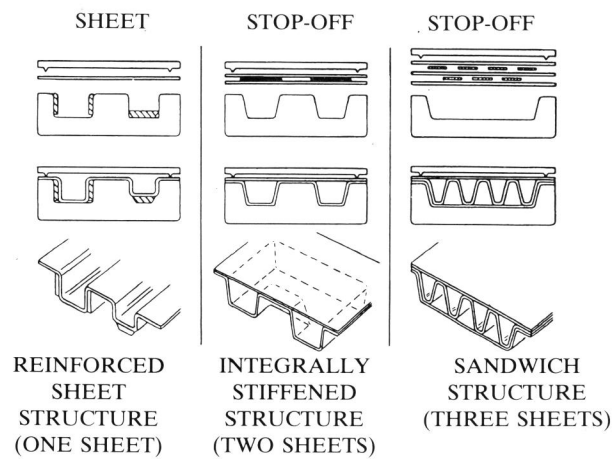
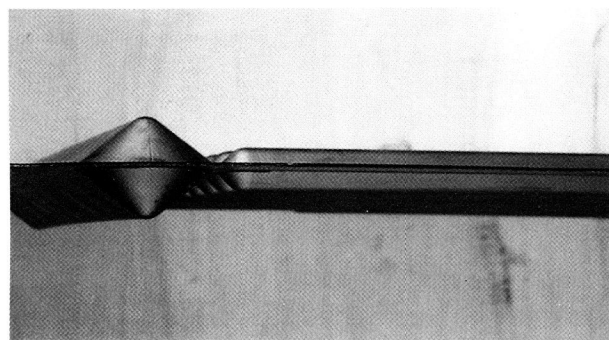
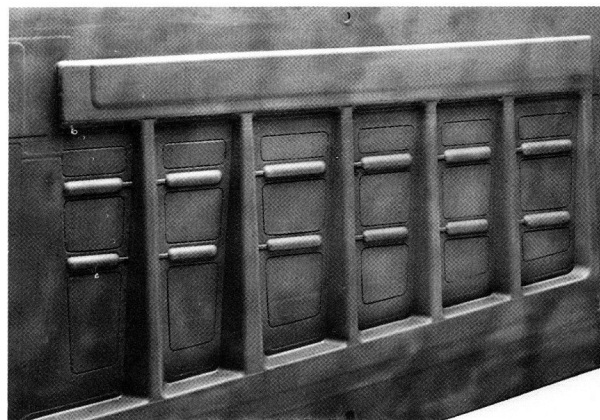
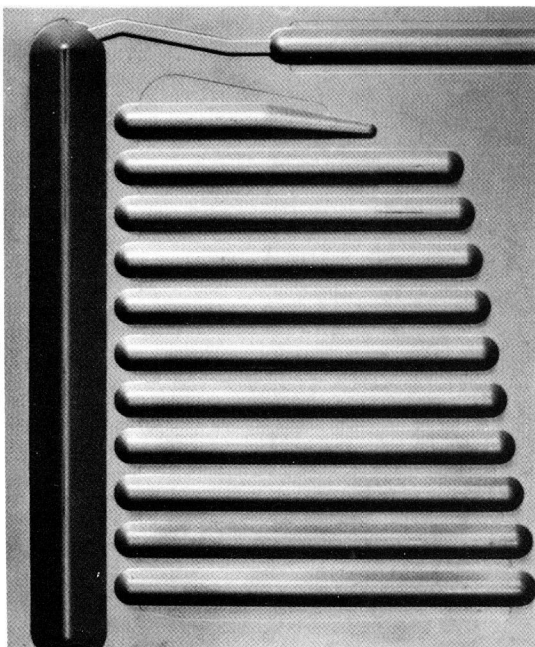


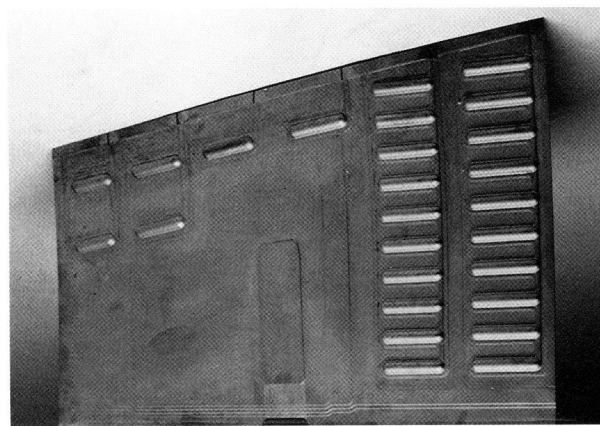
Fig. 9:  
Three basic types of sheet SPF/DB structures.



(a)



(b)



(c)

Fig. 10:  
Titanium SPF/DB structures (courtesy of ALENIA, Italy): (a) rear fuselage keel (from two sheets);  
(b) upper and (c) lower flaperon panel (from three sheets).

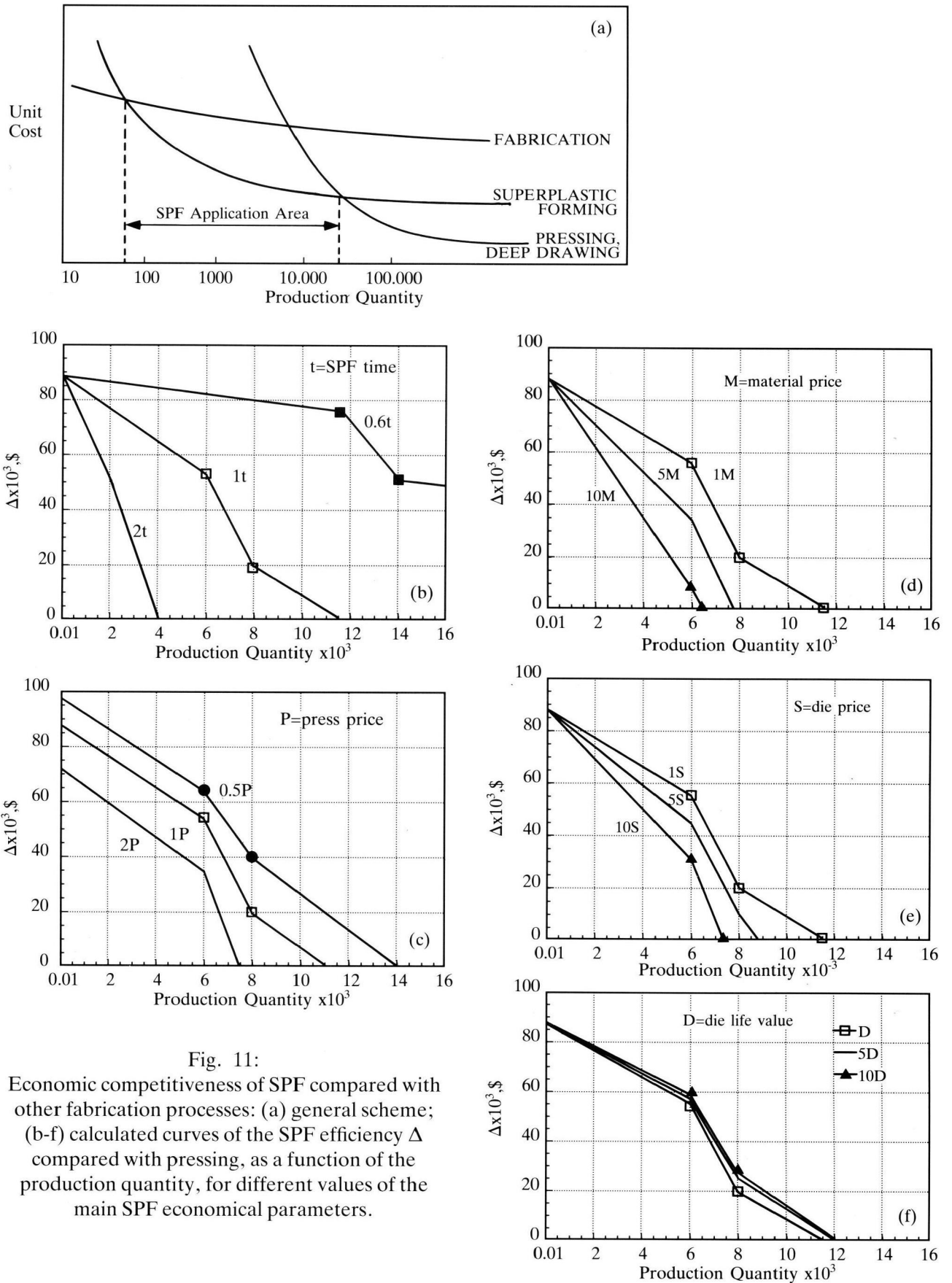


Fig. 11:  
Economic competitiveness of SPF compared with other fabrication processes: (a) general scheme; (b-f) calculated curves of the SPF efficiency  $\Delta$  compared with pressing, as a function of the production quantity, for different values of the main SPF economical parameters.