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Analytical and Experimental Investigations on Influential Parameters of Superplastic Forming of Titanium Based Workpieces

M. J. Nategh[1] **B. Jafari**[2]

Superplastic forming is a viable method for shaping supperalloys including titanium based materials which are otherwise awkward to shape. Further effort is, however, required to commercialize this process and introduce it to metal forming enterprises. Special facilities capable of providing controllable forming environment are needed for implementing this process. A hot isostatic/isothermal pressing machine possessing such a characteristic is an effective candidate for this purpose. Hot isostatic pressing has vastly been employed for diffusion bonding, powder metallurgy and investment casting, while its application to bulk- and sheet-metal forming needs far more investigation. Careful selection of processing parameters such as gas pressure, strain rate, temperature and process time is vitally important for superplastic forming of titanium based workpieces. In an attempt to advance the superplastic forming technology towards achieving a feasible process, the authors developed a low price hot isothermal pressing device with the aid of which numerous forming experiments were carried out. An additional objective pursued by the authors was to elaborate on the analytical method superplastic forming of lens-shaped components which have considerable industrial applications and to illustrate the close relation between the analytical results and the experimental achievements.

NOMENCLATURE

$\{A\}$	microstructural state
d	grain size
F_θ	peripheral force
F_φ	force acting along meridian direction
h	instantaneous depth of deformation
H	workpice's depth
$\bar{H}$	$=H/R_o$
K	material constant
m	strain rate sensitivity factor
m_s	$=m-2$
P	forming pressure
r	radius of workpiece profile
r_o	radius of the profile located in the surface perpendicular to the revolution axis
r_θ	radius of the profile perpendicular to the meridian
r_φ	radius of meridian
R_o	die mouth radius
S	workpiece's wall thickness
S_n	critical thickness
S_o	initial thickness of blank
t	$=-(\tau\varepsilon^o)/m_s$
T	temperature
T_{melt}	melting temperature
X	distance between centers of blank and workpiece's profile

Greek Symbols

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1. *(Corresponding Author), Tarbiat Modares University, Mechanical Engineering Department, Faculty of Technology and Engineering,P. O. Box 14115-143, Tehran, Iran E-mail: nategh@modares.ac.ir*
2. *Tarbiat Modares University, Mechanical Engineering Department*

α	angle between the surface perpendicular to the revolution axis and the surface of the profile perpendicular to the meridian
ε_e	effective strain
ε_n	wall thickness strain at the bottom of the workpiece
$\dot{\varepsilon}$	strain rate
ε_r	strain in r direction
ε_θ	lateral strain
ε_φ	meridian strain
θ	lateral angle
σ	flow stress
σ_s	flow stress
σ_θ	flow stress in the lateral direction
σ_φ	flow stress in the meridian direction
τ	process time
φ	meridian angle

INTRODUCTION

Superplastic alloys including titanium-based materials with fine-grained microstructures exhibit considerable ductility during superplastic forming (SPF), i.e. when shaping takes place at low strain rates and at elevated temperatures [1,2]. Titanium and its alloys exist in different categories consisting of low temperature α-phase with a close-packed hexagonal crystal structure, high temperature β-phase possessing a body-centered cubic structure, α-β phase, intermetallics $\mathrm{Ti}_x\mathrm{Al}$ ($x = 1$ or 3), $\mathrm{Ti_3Al}(\alpha_2)$ and $\mathrm{TiAl}(\gamma)$ [3-5]. Various properties ensue from these varieties giving the major cause for recent trend of widening application for titanium products. Corrosion resistance, good elevated-temperature service life, and high specific strength together with low density are the main reasons for the application of titanium alloys in various industries such as aerospace, biomedicines, chemicals, ship building, offshore structures [6-8], piping systems [8,9], nuclear power plants [10] and automotive industries [11].

They are also used as shape memory alloys [12, 13] and as wear-resistance material for coating of cutting tools [14]. It is awkward to shape titanium workpieces by conventional processes. Their low ductility and formability are considered as the major hurdles [16-20]. Titanium alloys are prone to crack, reaction with atmospheric elements, constitution of surface brittleness phases and some other defects during conventional forming under uncontrolled environment. Instead, superplastic forming is a cost effective and efficient process, especially for complicated shapes [21].

Superplastic forming of titanium alloys, especially $\mathrm{Ti} - 6\mathrm{Al} - 4\mathrm{V}$ has been the subject of considerable research work [17, 22-25]. Components with special configurations such as spherical shells [26], domes, roll formed disks [27, 28] and thin circular diaphragms [28] have been dealt with. Analytical models have been developed for the latter components based on superplastic bulge forming of domes [28]. Far more research is, however, needed to verify the existing analytical results by shaping components with other configurations. Experiments with various components and resolving technological and economical problems are essential to commercialize superplastic forming of titanium-based components.

Hot Isostatic and Isothermal Pressing (HIP) machines provide protected and controllable environment and are good candidates as superplastic forming devices. Hot isostatic pressing was developed for manufacturing nuclear fuel element assemblies by diffusion bonding in the United States in the mid 50's [29]. Cold Isostatic Pressing (CIP) is HIP's counterpart process in which powder consolidation takes place at ambient temperature [30]. Diffusion bonding and powder metallurgy remained the main category of HIP application and benefited greatly from this process. Casting industries have also successfully employed this technique. In fact, HIP has had a revolutionizing role in investment in the casting industry [30]. HIP is also applied as a post process for isothermal forging and extrusion of HIPped powders to improve their mechanical properties [30]. Application of HIP to superplastic forming including bulk and sheet metal ones need further investigation. Superplastic forming of superalloys can lead to considerable saving in costly materials. A range of elongation from several hundreds up to thousands percent can be achieved by SPF. Fine grained alloys with an average grain size, $d < 10\mu m$, and with a high strain rate sensitivity factor, m, exhibit good superplasticity.

The grains of these alloys remain stable up to the superplasticity temperature usually amounting to 60% of the melting temperature, T_{melt}. A high value of m is the major obstacle to the progress of necking and causes uniform deformation to develop within the workpiece leading to enormous elongation before rupture occurs.

High values of m are achieved at low strain rates, within the range of 10^{-3} to $10^{-4}s^{-1}$ for titanium based materials.

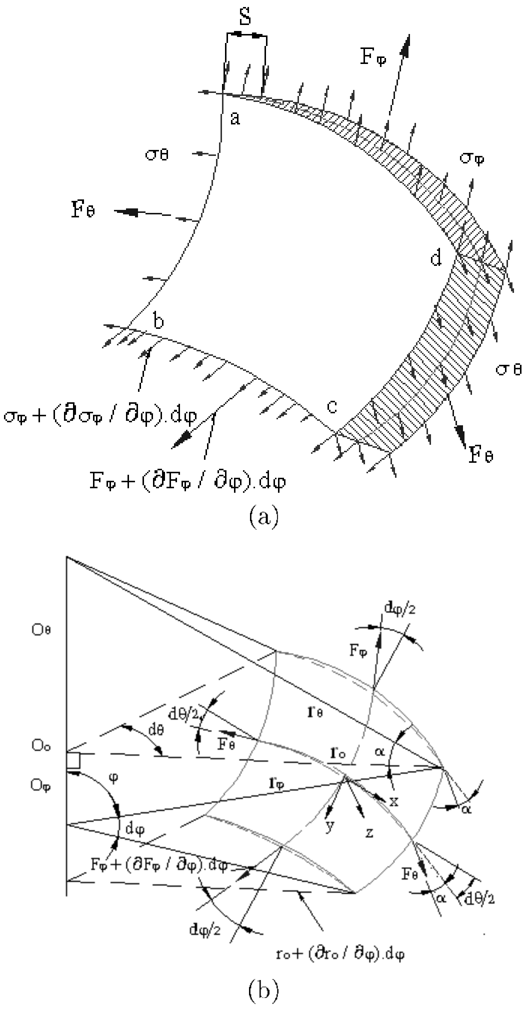
The authors have developed a laboratory HIP device for superplastic forming of titanium and titanium alloys. Several lens–shaped components possessing numerous industrial applications were successfully formed. The experimental achievements, including the process parameters, have been compared with analytical results already available for superplastic sheet metal forming, a report of which is presented in the following sections. It is noteworthy that careful selection of forming parameters such as temperature, gas pressure, strain rate, and process time is vitally important for obtaining sound components.

ANALYSIS OF FORMING PARAMETERS

Internal Pressure

The supporting analysis of forming experiments for lens-shaped components is briefly presented in this section. This kind of components drawn from relatively thin sheets with $S/R << 1$ can be treated as shells with surfaces of revolution [31-33], where S and R are the thickness and profile radii of the component being deformed during the process, respectively. An element of the component is depicted in Figure 1. The equation of equilibrium in the z direction is

$$F_\varphi d\varphi + F_\theta cos\alpha d\theta = Pr_\varphi r_o d\varphi d\theta \tag{1}$$



(a)

(b)

Figure 1. A segment of the component with a surface of revolution, (a) stresses and forces acting on an element of the component, (b) the geometrical representation of the element

where F_φ is the resultant force acting on the upper side; F_θ, the resultant force on the lateral side; r_φ and r_θ, the radii of the two perpendicular surfaces of revolution; $r_\varphi d\varphi$ and $r_\theta d\theta$, the lengths of the element; and P, the internal pressure acting on the surface denoted by abcd in Figure 1.a. F_φ and F_θ are found as follows:

$$F_\varphi = S\sigma_\varphi r_o d\theta = S\sigma_\varphi r_\theta cos\alpha d\theta \tag{2}$$

$$F_\theta = S\sigma_\theta r_\varphi d\varphi \tag{3}$$

where S is the thickness of the component; and σ_φ and σ_θ are the flow stresses in φ and θ directions, respectively. By substituting F_φ and F_θ from Eqs. 2 and 3 into Eq. 1:

$$(\sigma_\varphi/r_\varphi)+(\sigma_\theta/r_\theta) = P/S \tag{4}$$

This relation is referred to as Laplace's equation [34]. For a homogeneous and isotropic material, at the bottom point of the workpiece, $\sigma_\varphi = \sigma_\theta = \sigma$; $r_\varphi = r_\theta = r$, and the gas pressure, P, from Eq. 4 is obtained as follows:

$$P = 2\sigma S_n/r \tag{5}$$

where S_n is the thickness of the workpiece's bottom. For a semi-spherical component, at its full deformation $r = R_o$, Eq. 5 can be stated as

$$P = 2\sigma S_n/R_o \tag{6}$$

where R_o is the radius of the die's mouth.

Radius of Workpiece's Profile

The configuration of a circular blank during various stages of shaping process is illustrated in Figure 2. By considering this figure, it can be written:

$$r = H + X \tag{7}$$

$$X^2 \approx r^2 - R_o^2 \tag{8}$$

From Eqs. 7 and 8, it is concluded that:

$$(2H/r) = (H^2/r^2) + (R_o^2/r^2) \tag{9}$$

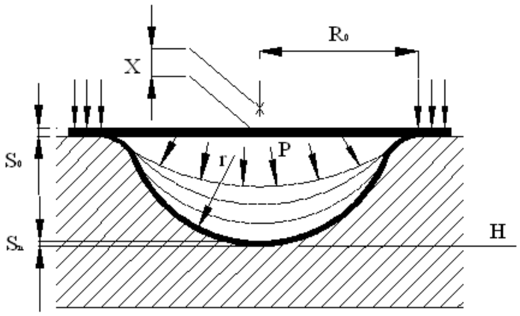


Figure 2. A circular blank during deformation process

By definition of

$$\bar{H} = H/R_o \qquad (10)$$

the radius of workpiece's profile is obtained from Eq. 9, as:

$$r = R_o(1+\bar{H}^2)/(2\bar{H}) \qquad (11)$$

Critical Thickness

For the strain, it follows from homogeneity and isotropy of the material that at the bottom of the workpiece:

$$\varepsilon_n = -2\varepsilon_\varphi = -2\varepsilon_\theta = Ln(S_n/S_o) \qquad (12)$$

where ε_φ, ε_θ are the strains in the φ, θ and r directions, respectively; ε_n, is the strain in the thickness direction; and S_o, the initial thickness of the blank. For a spherical segment such as the lens-shaped component, $r_\varphi = r_\theta = r$ (Figure 1(b) and Figure 2), and also $H_\varphi = H_\theta = H$ where H_φ, H_θ and H are the depths of the shell under deformation along r_φ, r_θ and r, respectively.

It is deduced from the classic analysis that the critical thickness, or in other words, the thinnest section occurs at the bottom of the workpiece. The thickness of the bottom of workpiece without considering the material property is obtained by the followings procedure.

The strains are expressed as:

$$d\varepsilon_\varphi = d\varepsilon_\theta = dH/r_\varphi = dH/r_\theta = dH/r$$

or by considering definition 10 and Eq. 11:

$$d\varepsilon_\varphi = d\varepsilon_\theta = 2\bar{H}dH/(1+\bar{H}^2)$$

or

$$\varepsilon_\varphi = \varepsilon_\theta = Ln(1+\bar{H}^2) \qquad (13)$$

From Eqs. 12 and 13:

$$S_n = S_o(1+\bar{H}^2)^{-2} \qquad (14)$$

If the material property is taken into consideration, a constant thickness would be achieved for the workpiece shaped from a perfectly superplastic blank. By considering Figure 3, it can be written from the volume constancy principle that:

$$\pi R_o^2 S_o = 2\pi r H S \qquad (15)$$

From Eqs. 11 and 15:

$$S_n = S = S_o(1+\bar{H}^2)^{-1} \qquad (16)$$

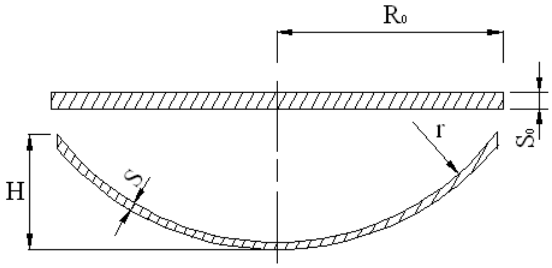


Figure 3. Shaping of a perfectly superplastic blank

The actual thickness, S_n , lies between the two limit values obtainable from Eqs. 14 and 16. In fact, without considering the superplasticity of the material ($m = 0$), the workpiece's thickness can be obtained from its geometry as expressed in Eq. 14. However, an ideal material with perfect superplasticity ($m = 1$) deforms according to Eq. 16. The strain rate sensitivity or superplasticity factor, m, is effectively less than 1. The actual thickness, S_n, is thus obtained from:

$$S_n = S_o(1+\bar{H}^2)^{m-2} \qquad (17)$$

The strain rate sensitivity factor, m, is an indication of the rate of flow stress change against the changes occurring in the strain rate. It is defined as follows:

$$m = (\partial Ln\sigma/\partial \ln \dot{\varepsilon})_{T,\{A\}} \qquad (18)$$

where $\dot{\varepsilon}$ is the plastic strain rate; T, temperature; and $\{A\}$, the state of component's microstructure. As is clear from Eq. 18, the partial derivative is defined at constant temperature and microstructural state. It is argued in the literature that a material well exhibits superplasticity, if its strain rate sensitivity factor is larger than 0.3 and $T > 0.4T_{\mathrm{melt}}$. The flow stress follows the following relation:

$$\sigma = K\dot{\varepsilon} \qquad (19)$$

where K is a constant dependent on the material.

Pressure – Time Relation

The process time, τ, is obtaind as follows:

$$\tau = (Ln(S_o/S_n))/\dot{\varepsilon} \qquad (20)$$

By substituting S_n from Eq. 17:

$$\tau = ((2-m)/\dot{\varepsilon})Ln(1+\bar{H}^2) \qquad (21)$$

Combining Eqs. 5, 11, 17 and 21 gives the pressure-time relation, as follows:

$$P = 4\sigma(S_o/R_o)(e^t-1)^{1/2}/(e^{t(1-m)}) \qquad (22)$$

where $m_s = m-2$ and $t = -(\tau\dot{\varepsilon})/m_s$.

HOT ISOTHERMAL PRESSING MACHINE

The laboratory hot isothermal pressing (HIP) machine developed by the authors operates on some basic principles. The forming area is evacuated from the atmosphere by flow of an inert gas; the die assembly and the workpiece under deformation have the same degree of temperature; a forming temperature of about 900^oC should be achievable; an inert pressurized gas is the forming agent; the gas pressure and thus the strain rate should be controllable all through the process; the die assembly and various components of the machine located in the vicinity of the forming area should resist the prevailing pressure and temperature circumstances. The die assembly is schematically depicted in Figure 4. A circular blank is fixed between the forming die with the final impression according to the workpiece geometry and the upper cover. The gap between the die and its cover is firmly sealed. Die assembly is placed inside an electric furnace and heated up continuously. The atmosphere surrounding the blank inside the die is evacuated by argon gas flow through two lines running above and beneath the blank. The evacuation takes place before the furnace temperature reaches 400^oC. It is recommended that the evacuation practice be repeated a few times during the process. Evacuation takes about five minutes.

Die impression and its upper cover were machined from hot work steel H13. Pipes and connections made of Cr18 steel were selected. Some degrees of deformation were evidenced in spite of all precautions. Numerous experiments were conducted to achieve reliable sealing in the prevailing severe physical conditions of pressure and temperature. Special design was devised for the connections to give them the required resistance in the working conditions.

EXPERIMENTAL WORK

In order to verify the foregoing theoretical results of superplastic forming and to validate the process for shaping titanium based components with the HIP device developed by the authors, several experiments were carried out with circular titanium blanks.

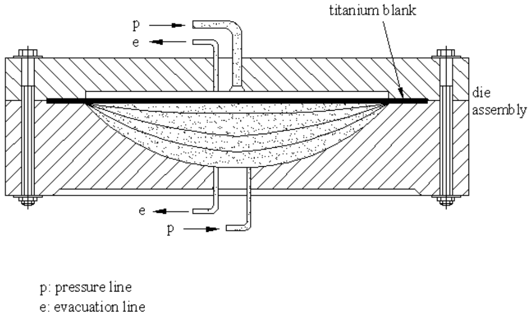


Figure 4. A schematic view of the die assembly

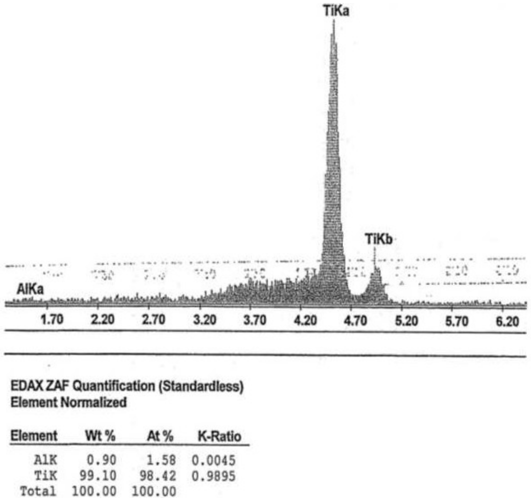
The results of tensile and metallographic tests of the titanium sheets used for the experiments, consisting of the mechanical properties and constituting elements are depicted respectively, in table 1 and Figure 5. It is evidenced from Figure 5 that the material is rather pure titanium with traces of aluminum. It is noteworthy that in spite of vast investigations already implemented by researchers on various titanium alloys, scarce results are available for processing of commercially pure titanium. The authors have thus partially undertaken this task.

Experiments, Results and discussion

The shaping pressure was adjusted to follow Eq. 22. A constant strain rate of $\dot{\varepsilon} = 0.002s^{-1}$ was achieved. The experiments were carried out at a temperature of 900^oC. Blanks with initial diameter, $R_o = 100$mm, were formed up to a depth of $H = 65$mm. Some sample workpieces from among many test components shaped out of these blanks with an strain rate sensitivity factor of $m = 0.4$ are shown in Figs. 6 and 7. A representative sample of products is depicted in Fig. 8 in which the

Table 1. Mechanical test results of sample sheets

	Sample Width mm	Tensile Strength kg/mm^2	Elongation %	Yield Strength kg/mm^2
1	80	43.87	21.25	29.5
2	80	44.26	22.5	31.2
3	80	44.70	29.1	35.9
4	80	44.83	17.25	37.7
5	80	44.11	23.5	30.3
6	80	43.60	30	38



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EDAX ZAF Quantification (Standardless)
Element Normalized

Element   Wt %     At %   K-Ratio
   AlK    0.90     1.58   0.0045
   TiK   99.10    98.42   0.9895
 Total  100.00   100.00
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Figure 5. Constituting elements of the titanium sheets used for the experiments

Figure 6. Lens-shaped workpieces shaped superplastically

Figure 7. Other sample workpieces with different configurations shaped superplastically

Figure 8. Samples before trimming the pressure and vacuum lines connections

pressure and vacuum line connections have not yet been trimmed away.

The pressure change versus the process time based on the theory, i. e. on the basis of Eq. 22 for various strain rate sensitivity factors is plotted in Figure 9. The parameters are assumed to be the same as those of the experiments, i. e. $\dot{\varepsilon} = 0.002s^{-1}$, $H = 65$mm and $R_o =$ 100mm. The flow stress of the material at 900^oC is $\sigma_s = 20$MPa. It should be noted that the experiments could be successfully carried out on the basis of the theoretical pressure-time curve depicted in Fig 9. The same value was measured on the products for the strain rate, with the aid of visioplasticity relations. This implies that an acceptable agreement exists between theory and practice, as far as the process is concerned, and sound workpieces can be obtained on the basis of shaping parameters estimated by the analytical relations. An additional conclusion is that the HIPping process implemented on the device developed by the authors can viably be employed for the superplastic forming of sheet metals. This lays the foundation for manufacturing low-cost HIPping equipment and paves the way for commercial application of superplastic forming to superalloys and other hard-to-form metals.

For complicated shapes and components with rather sharp corners and intricate profiles, a rise occurs

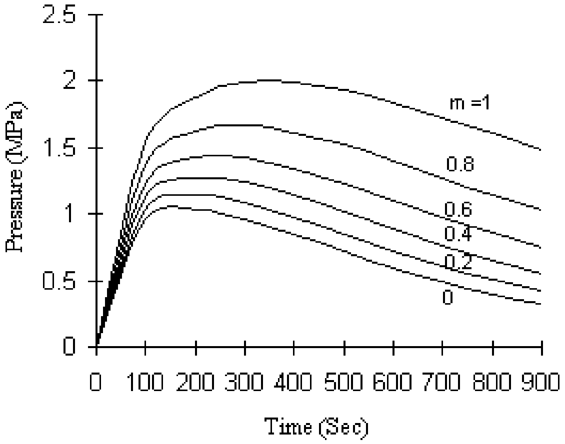

Figure 9. Pressure-time change during the process for various strain rate sensitivity factors

in the pressure-time curve at the corner filling stage, followed by a smooth descending curve. A typical pressure –time curve with a sharp pressure rise is illustrated in Figure 10. This curve has been plotted for a workpiece with a final cylindrical shape. The same values have been assumed for this case similar to lens-shaped experiments, i.e. $\dot{\varepsilon} = 0.002s^{-1}$, $R_o = 100$mm, $H = 65$mm, $m = 0.4$ and $\sigma_s = 20$MPa at 900^{o}C. Such a rise in the pressure – time curve has, indeed, been experienced for some test workpieces possessing a cylindrical profile rather than a lens shape. The pressure-time change would follow a different model at the corner filling stage from that governing the free forming of sheet metal.

It is inferred from Eq. 17 that S_n/S_o and, thus, the critical thickness, S_n, decreases as the material is distanced from perfect superplasticity. This implies that higher degrees of superplasticity deter necking and rupture of the workpiece under deformation, more

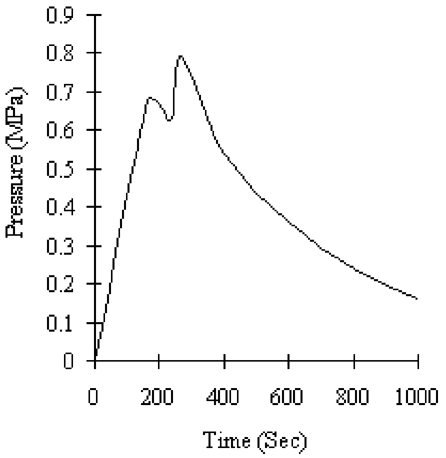

Figure 10. Typical pressure – time change with a pressure rise at the corner filling stage

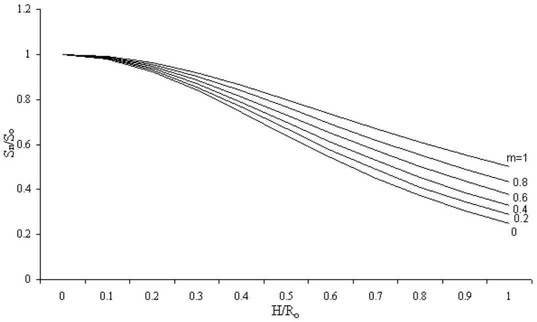

Figure 11. Variations of a workpiece critical thickness during superplastic forming

effectively. In other words, a workpiece can be shaped deeper before necking and rupture occurs when a material of a high degree of superplastiticity is employed. This is what one can expect from the theory based on the definition of superplasticity and strain rate sensitivity factor, as can be evidenced form Figure 11.

CONCLUDING REMARKS

Superplastic forming is the most viable and economical method for deformation of sheet metals possessing some degrees of superplasticity. Hot isostatic/isothermal pressing is an efficient process for implementing superplastic forming. A HIP device was devised by the authors to lay the foundation for a feasible and low price machine. Several successful experiments were carried out repeatedly with this machine. The experiments were carried out on sample titanium based circular blanks. Workpieces with lens-shaped and some other similar profiles were produced. The processing parameters such as the pressure and strain rate were adopted from the theoretical estimations. Sound components could also be produced indicating the effectiveness of the developed HIP device's operation and the forming process and also close the relation exiting between the theory and practice. Both the theory and experiment suggest that the critical wall thickness increases as the material assumes a higher degree of superplasticity to the benefit of achieving larger elongations.

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REFERENCES

1. J.N. Wang, Yong Wang, "An investigation of the origin of the superplasticity of cast TiAl alloys", *International Journal of Plasticity*, **22**, PP 1530–1548(2006).

2. T. Rajagopalachary, V. V. Kutumbarao, "Superplastic behaviour of a titanium alloy IMI685 under uniaxial compression", *Scripta Materiala*, **35**, PP 305-309(1996).
3. F. Pirwitz, M. Dahms, G.-X. Wang, S. W. Hulsmann, D. Nerger, "Hip synthesis of gamma-base titanium-aluminide composites", *Proceedings of the Int. Conf. on Hot Isostatic Pressing-HIP'93*, Antwerp, Belgium, PP 91-98(1993).
4. M. Nakamura, M. Nobuki, T. Tanabe, T. Kumagai, I. Mutob, E. Abe, "Microstructure control and high temperature properties of TiAl base alloys", *Intermetallics*, **6**, PP 637-641(1998).
5. F. Warchomicka, M. Stockinger, H.P. Degischer, "Quantitative analysis of the microstructure of near b titanium alloy during compression tests", *Journal of Materials Processing Technology*, in Press, (2006).
6. Masafumi Kikuchi, Masatoshi Takahashi, Osamu Okuno, "Elastic moduli of cast Ti–Au, Ti–Ag, and Ti–Cu alloys", *Dental Materials*, **22**, PP 641–646(2006).
7. Shahab Faghihia, Fereshteh Azari, Huolong Li, Mohammad R. Batenic, Jerzy A. Szpunar, Hojatollah Vali, Maryam Tabrizian, "The significance of crystallographic texture of titanium alloy substrates on pre-osteoblast responses", *Biomaterials*, **27**, PP 3532–3539(2006).
8. Li Changyun, Wu Shiping, Guo Jingjie, Su Yanqing, Bi Weisheng, Fu Hengzhi, "Model experiment of mold filling process in vertical centrifugal casting", *Journal of Materials Processing Technology*, **176**, PP 268–272(2006).
9. G. Wang, K.F. Zhang, D.Z. Wu, J.Z. Wang, Y.D. Yu, "Superplastic forming of bellows expansion joints made of titanium alloys", *Journal of Materials Processing Technology*, in Press, (2006).
10. J. Chen, P. Jung, M. Nazmy, W. Hoffelner, "In situ creep under helium implantation of titanium–aluminium alloy", *Journal of Nuclear Materials*, **352**, PP 36–41(2006).
11. Klaus Gebauer, "Performance, tolerance and cost of TiAl passenger car valves", *Intermetallics*, **14**, PP 355–360(2006).
12. Wenyi Yan, "Theoretical investigation of wear-resistance mechanism of superelastic shape memory alloy NiTi", *Materials Science and Engineering*, **A 427**, PP 348–355(2006).
13. Xinhua Wu, "Review of alloy and process development of TiAl alloys", *Intermetallics*, **xx**, PP 1-9(2006).
14. Urban Wiklund, Bego˜na Casas, Nils Stavlid, "Evaporated vanadium nitride as a friction material in dry sliding against stainless steel", *Wear*, **261**, PP 2-8(2006).
15. Baiyun Huang, Zhongyong Deng, Yong Liu, Xuanhui Qu, Yuehui He, "Superplastic behavior of a TiAl-based alloy", *Intermetallics*, **8**, PP 559-562(2000).
16. K. Tokaji, "High cycle fatigue behaviour of Ti–6Al–4V alloy at elevated temperatures", *Scripta Materialia*, **54**, PP 2143–2148(2006).
17. A. Majorell, S. Srivatsa, R. C. Picu, "Mechanical behavior of Ti-6Al-4V at high and moderate temperatures- part I: experimental results", *Materials Science and Engineering*, **A326**, PP 297-305(2002).
18. R. C. Picu, A. Majorell, "Mechanical behavior of Ti-6Al-4V at high and moderate temperatures- part II: constitutive modeling, Materials Science and Engineering", **A326**, PP 306-316(2002).
19. Xinhua Wu, "Review of alloy and process development of TiAl alloys", *Intermetallics*, **xx**, PP 1-9(2006).
20. Toshimitsu Tetsui, Kentaro Shindo, Satoshi Kaji, Satoru Kobayashi, Masao Takeyama, "Fabrication of TiAl components by means of hot forging and machining", *Intermetallics*, **13**, PP 971–978(2005).
21. X.J. Zhu, M.J. Tan, W. Zhou, "Enhanced superplasticity in commercially pure titanium alloy", *Scripta Materialia*, **52**, PP 651–655(2005).
22. R. S. Mishra, V. V. Stoyarov, C. Echer, R. Z. Valiev and A. K. Mukherjee, "Mechanical Behavior and Superplasticity of a Severe Plastic Deformation Processed Nanocrystalline Ti-6Al-4V Alloy", *Materials Science and Engineering*, **A298**, PP 44-50(2000).
23. B. P. Bewlay, M. F. X. Gigliotti, F. Z. Utyashev and O. A. Kaibyshev, "Super-plastic Roll Forming of Ti Alloys", *Materials and Design*, **21**, PP 287-295(2000).
24. Abhijit Dutta and D. Siva Kumar, "Predictions of the Phase Ratio at the Lowest Flow Stress in Super-plastic Titanium Alloy", *Materials Science and Engineering*, **A194**, PP L1-L4(1995).
25. Zhang Shaoqing, and Zhao Linruo, "Effect of Hydrogen on the Super-plasticity and Microstructure of Ti-6Al-4V Alloy", *J. Alloys and Compounds*, **218**, PP 233-236(1995).
26. A. A. Kruglov, F. U. Enikeev, and R. Ya Lutfullin, "Superplastic Forming of a Spherical Shell ??out of a Welded Envelope", *Materials Science and Engineering*, **323**, PP 416-426(2002).
27. M. Frary, C. Schuh, D. C. Dunand, " Gas pressure forming of titanium alloys and composites by transformation superplasticity", *ASM Int. Symposium on Superplasticity and Superplastic Forming, Indiapolis*, UCRL-JC-146024, (2001).
28. F. U. Enikeev, and A. A. Kruglov, "An Analysis of the Super-plastic Forming of a Thin Circular Diaphragm", *Int. J. Mech. Sci.*, **37**, PP 473-483(1995).
29. K. Uehara, T. Ishi, Y. Inoue, T. Fujikawa, "Recent advances in HIP equipment technology", *Proceedings of the Int. Conf. on Hot Isostatic Pressing-HIP'93*, Antwerp, Belgium, PP 481-491(1993).
30. Robert Widmer, "Hot isostatic pressing in competition and in combination with other consolidation processes", ibid, PP 581-590.

31. S. Timoshenko, S. Woinowsky- Krieger, *Theory of plates and shells*, McGraw-Hill Int. Book Co., (1984).
32. A. G. Pashkevich, "A Study on the Feasibility of Super-plastic Forming of Sheet Metals (in Russian)", Ph.D. Thesis, Mati University, Moscow(1984).
33. Varzandeh, "Super-plastic Forming of Components Used in Aerospace Structure (in Russian)", M.Sc. Thesis, Mati University, Moscow(2002).
34. V. A. Zharkov, *Theory and practice of deep drawing*, Mechanical Engineering Publications Ltd., (1995).