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Experiments with a Low-Cost Hot Isothermal Pressing Machine Developed for Superplastic Forming

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Hot isothermal/isostatic pressing machines are technically good candidates for superplastic forming (SPF) of otherwise hard-to-shape materials such as superalloys. These machines are, however, very expensive so that small or medium-size enterprises can not afford them. This has impeded widespread use of SPF processing. In an attempt to alleviate the problem, the authors have developed a laboratory model of an affordable hot isothermal pressing machine with differential gas pressure as the forming medium. Careful selection of process parameters such as temperature, gas pressure, strain rate, and process time as well as monitoring of thickness changes in a workpiece has a pivotal role in successful operation of such machine. It has been illustrated in this article that SPF can be successfully performed with this machine on the basis of process parameters estimated with existing analytical relations. The performance of this machine has been verified by several experiments on SPF of titanium-based sheets, as reported in this article.

Keywords hot isostatic pressing, hot isothermal pressing, superplastic forming, titanium, titanium alloys

1. Introduction

Hot isothermal/isostatic pressing (HIP) machines are technically good candidates for superplastic forming (SPF) of otherwise hard-to-shape materials such as superalloys. Superplastic forming requires controllable processing environment and HIP machines are capable of maintaining such environment. These machines are, however, very expensive so that small or medium-size enterprises can not afford them. This has limited the application of SPF processes. While HIP has been well developed for some processes such as powder metallurgy, investment casting, isothermal forging, and extrusion of HIPped powders to improve their mechanical properties, and isothermal forging of critical components such as aerospace forgings (Ref 1-3), far more development is needed in the area of sheet metal forming with HIP technology. Hot isothermal pressing is regarded as a new manufacturing method (Ref 4, 5). Therefore, efforts at developing low-cost HIP technology to form superalloys would be rewarding.

The authors have developed a laboratory model of a low-cost hot isothermal pressing machine with differential gas pressure as the forming medium. It has been used for SPF with process parameters estimated via existing analytical relations. Careful selection of process parameters such as temperature, gas pressure, strain rate, and process time has a pivotal role in the successful operation of such machine. Thickness changes of workpiece during the process should also be taken into consideration as excessive thinning of the workpiece can cause rupture.

The performance of this machine has been verified by several experiments on SPF of titanium-based sheets. Titanium alloys have found widening trends of application in the aerospace industry, as biomaterials for orthopedic and oral implantations, in chemical and ship building industries, in offshore structures for extraction of hydrocarbons and piping systems, in nuclear power plants and reactors, as shape memory alloys, in automotive components such as turbochargers and valves, and as coating materials for cutting tools (Ref 6-18). This increasing demand for titanium is attributable to its favorable properties including high specific strength, low density, corrosion resistance, weldability, and relatively elevated-temperature resistance (Ref 9, 19-21). Conversely, serious issues are posed by manufacturing difficulties of titanium products. Intensive effort has been expended overcoming these manufacturing issues when forming titanium components through conventional manufacturing processes. These manufacturing processes include conventional forging, drawing, extrusion, and machining (Ref 3, 22-26). Titanium alloys are prone to crack as a result of reaction with the atmospheric elements and the formation of surface-brittleness phases during the forming processes. These impose serious limits on the application of titanium alloys, in spite of their favorable mechanical properties and increasing demand for titanium components. The low ductility and formability are considered as the most serious impediments to the application of titanium-based products (Ref 15, 26).

It is, however, promising to note that hard-to-shape metals with fine-grained microstructures such as titanium alloys possess good superplasticity, i.e., exhibit considerable ductility at relatively low strain rates and elevated temperatures (Ref 27, 28). A superplastic elongation exceeding 1000% has been reported for Ti-6Al-4V (Ref 10). Superplastic forming can be cost-effective for complicated shapes (Ref 29). The scrap rate and material cost are considerably higher when titanium workpieces are shaped with conventional forming processes. It could be

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difficult to achieve profitable forming applications without utilizing the superplastic properties of titanium.

Superplastic forming of titanium alloys, especially Ti-6Al-4V, has been the subject of considerable effort (Ref 30-37). Components with special configurations such as roll-formed disks, spherical shells, and thin circular diaphragms have already been developed (Ref 33, 38, 39). Several lens-shaped components possessing numerous industrial applications were successfully formed from titanium blanks using the developed machine. The experimental achievements, including the process parameters, have been compared with analytical results already available for the SPF of sheet metals.

2. Forming Analysis

The relations already developed for pressure forming of sheet metals can be found in Ref 38-42. They are briefly presented here and in the appendix.

The configuration of a circular blank during different stages of a drawing process is illustrated in Fig. 1. The process time, T, forming pressure, P, and critical thickness, S_n, are given by

$$T = (2 - m)\text{Ln}\ (1 + \bar{H}^2)/\mathring{\varepsilon} \quad \text{(Eq 1)}$$

$$P = 4\sigma_s \frac{S_o(1+\bar{H}^2)^{m_s}}{R_o} \frac{\bar{H}}{(1+\bar{H}^2)} \quad \text{(Eq 2)}$$

$$S_n = S_o(1+\bar{H}^2)^{m_s} \quad \text{(Eq 3)}$$

where m = strain rate sensitivity factor, $\mathring{\varepsilon}$ = strain rate, $\bar{H} = H/R_o$, H = workpiece depth, R_o = die-mouth radius, S_o = initial thickness of blank, σ_s = flow stress, and $m_s = m - 2$. In Fig. 1, ρ denotes radius of lens-shaped workpiece, and X is the distance between the centers of the initial circular blank and the workpiece profile.

Processing time is found from Eq 1 for specific values of strain rate and die mouth radius when the workpiece reaches a specific depth of deformation. The processing pressure is then found from Eq 2 for different time intervals or in other words for different $\bar{H}$ values and for specific initial thickness and flow stress of the blank material. This gives the required pressure-time profile for implementing the experiments.

3. Hot Isothermal Pressing Machine

A HIP device is designed on the basis of the following requirements: Air should be evacuated from the forming area, in order to protect the hot workpiece against any detrimental effect such as oxidization and porosity. Working temperature should be maintained during the process. Since the workpiece is deformed inside the die cavity by gas pressure, this pressure should be controllable according to the pressure-time schedule of the process in order to deliver appropriate superplastic strain rates. Die assembly and other mechanisms should be robust and stable to avoid unacceptable deformations in critical pressure-temperature conditions in the processing area.

Taking these observations and other relevant design criteria into consideration, the authors have developed a laboratory version of a low-cost HIP device, which is schematically depicted in Fig. 2.

As is evident from Fig. 2, the device consists of one argon cylinder for supplying gas to evacuate air from the forming area, and another argon cylinder for supplying the forming gas. The pressure-time characteristic of the forming gas is manually controlled through the regulator. The gas pressure can be regulated up to 10 atmospheres. The furnace chamber can be heated up to 1200 °C. The blank is placed between the upper and lower dies and the die set is assembled and placed inside the furnace. High-temperature resistant sealing has been used in between the two halves of the die. The furnace chamber and the die set are heated up to the forming temperature delivering an isothermal environment.

A circular blank is fixed between the forming die with final impression and the upper cover. The impression accommodating the final product was created by EDM. The gap between the die and its cover is firmly sealed. The die assembly is placed inside an electric furnace and heated continuously. The atmosphere surrounding the blank inside the die is replaced by argon gas flow through two lines running above and beneath the blank. This inert environment is established before the furnace temperature reaches 400 °C and it only requires a few minutes. It is recommended to repeat the flow of argon several times, during the process and during cooling of the product.

The pressure-time schedule is controlled by the operator using a manual regulator shown in Fig. 2. The very low strain rates common in SPF permits such manual control.

A comparison between this machine and its existing HIP counterparts provides an idea about the economic benefit associated with it. A hot isothermal machine is usually a

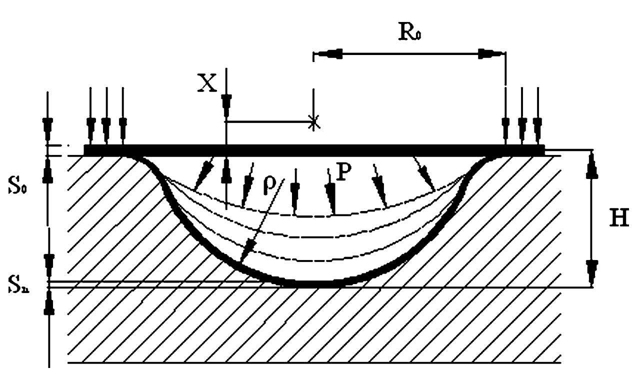

Fig. 1 A circular blank during deformation

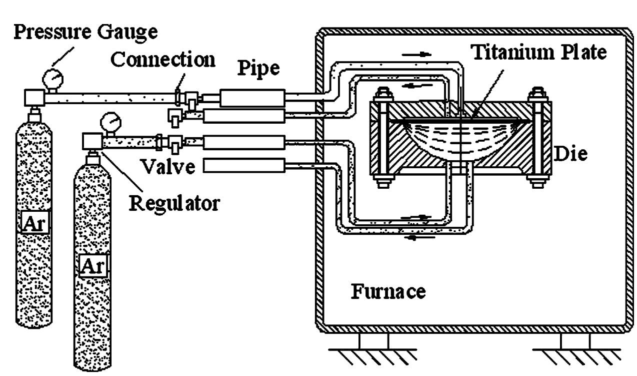

Fig. 2 A schematic view of the forming device

hydraulic press equipped with an isolated forming chamber to accommodate the dies and the billet/blank. This chamber is heated so that isothermal condition is established within the forming area. The forming power is applied through the press ram. When gas pressure is used as the forming medium then no other pressing equipment is required. This means considerable reduction in the equipment price when considering that a hydraulic press costs much higher than a low-pressure gas supply system like the one employed in the proposed machine. Isothermal pressing is a variation of SPF; however, the existing isothermal presses operate at higher strain rates than those used in SPF, although these rates are about one-tenth to one-hundreds those common in conventional forming (Ref 43). Deformation or ram velocities and strain rates within the ranges of 0.001-500 mm/s and 10^{-3}-1 s^{-1} have been, respectively, reported for isothermal forging presses (Ref 44, 45). Therefore, it is doubtful that one can take full advantage of superplasticity of materials when using existing isothermal machines. It can thus be concluded that the proposed machine is more feasible for SPF than existing isothermal presses from both the economical and technical view points. Sheet metal working presses for SPF under superimposed isostatic pressure are even more expensive than isothermal machines. An isostatic press is essentially equipped with a pressure vessel of high safety standards, as its forming chamber to resist high pressures is common in isostatic pressing. This considerably adds to its price.

Based on the above-mentioned differences, it is envisaged that the market value of the industrial version of the proposed machine would be at least three to four orders of magnitude lower than the market prices of its existing HIP counterparts.

4. Forming Experiments

The mechanical properties of the titanium sheets used for the experiments were as follows: Tensile strength = 436-448 N/mm^2, YS = 295-380 N/mm^2, and El = 17.2-30%. The constituent elements consisted of Al with almost 0.90 wt.% and Ti with 99.10 wt.%. Other constituents were negligible.

In order to ensure the operation in the superplastic range, the pressure-time characteristics were manually adjusted to follow Eq 2 and the relevant pressure-time plots. As an example, the pressure-time characteristic plotted for samples with $H = 65$ mm, $R_o = 100$ mm, $S_o = 3$ mm, $\overset{\circ}{\varepsilon} = 0.002$ 1/s, and $\sigma_s = 20$ MPa at 900 °C is shown in Fig. 3. Similar plots were obtained for other workpieces and experiments. Two sample workpieces among many test components with different configurations shaped out of these blanks with $m = 0.4$ (according to the supplier) are shown in Fig. 4. It should be noted that the long process time being common in SPF allows the manual control of the pressure at different time intervals. Taking advantage of this merit of the process was a major factor of cost-effectiveness of the developed device.

For complicated shapes with sharp features and intricate profiles, a rise occurs in the pressure-time curve at the feature filling stage, followed by a smooth descending curve. A typical pressure-time curve with a sharp pressure rise is plotted in Fig. 5. Such rise in the pressure-time curve has, indeed, been experienced for some test workpieces. These workpieces had flat surfaces at their bottom centers sharply joined to the spherical-shape walls. The sudden rise in pressure is attributable to the increase in the deformation load needed for sharp features forming stage similar to the increased force experienced during the die corner filling stage in conventional forging.

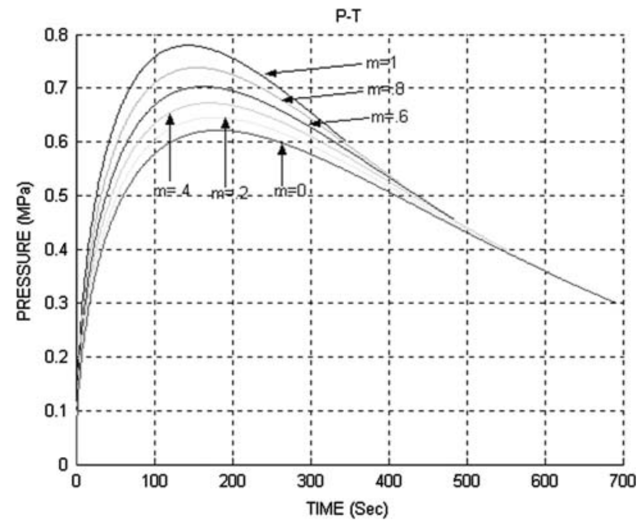

Fig. 3 Pressure-time change during the process

Fig. 4 Workpiece shaped superplastically

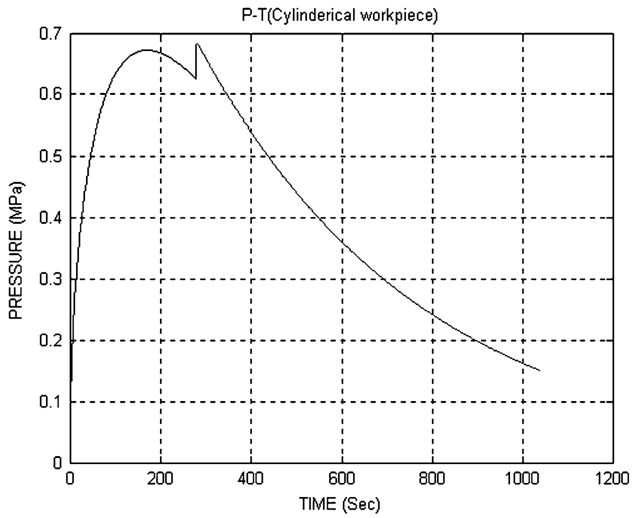

Fig. 5 Typical pressure-time change with a pressure rise at the feature filling stage

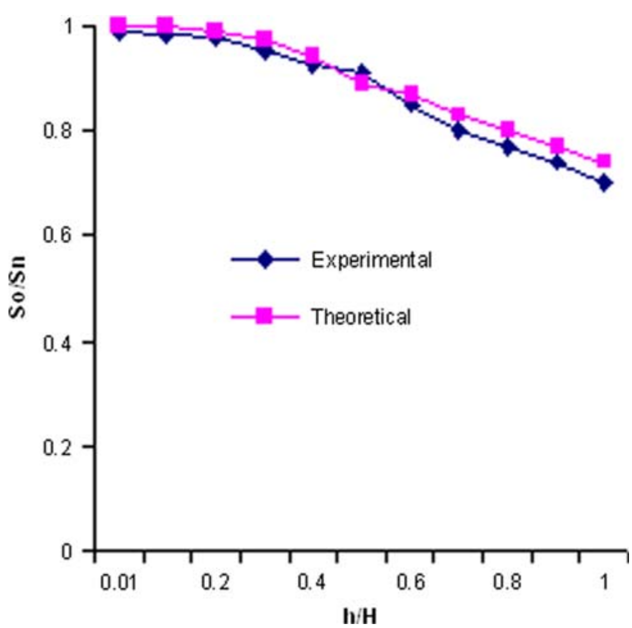

Fig. 6 A comparison of the experimental results and the theoretical estimates for a workpiece thickness variations during SPF

The experiments indicate that sound workpieces can be obtained on the basis of shaping parameters estimated by analytical relations.

It should be noted that the workpiece would undergo some variations in wall thickness, during the forming process. These variations should be evaluated and taken into consideration when designing the workpiece dimensions. This is especially important for load-carrying components. Based on experiments, the bottom of workpiece would undergo the largest reduction in thickness, which is in agreement with theoretical estimates. In order to further investigate the viability of analytical results for the developed device, comparison is made between the

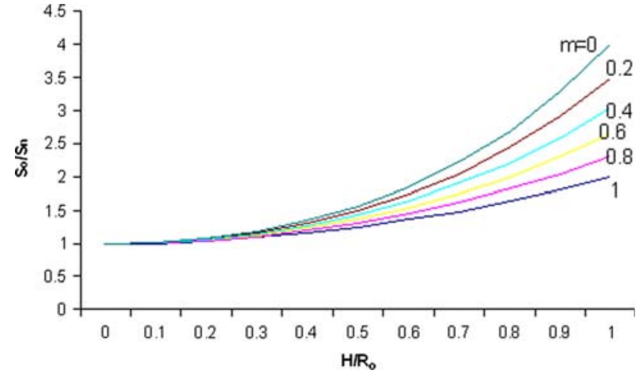

Fig. 7 Variations of workpiece thickness during SPF

theoretical S_o/S_n vs. h/H, and experimental results. The result is illustrated in Fig. 6 for the workpieces shown in Fig. 4, where h = the instantaneous depth of workpiece. Visioplasticity technique was employed to measure the instantaneous height. Each time the workpiece was removed from the die, it was cooled, measured, and returned to the forming area for further deformation to the next depth. Figure 6 shows that the experimental and theoretical results are closely related to each other. The amount of variation in the thickness depends on the geometry and material of the component. Larger variations occur with greater depths of forming (Fig. 7). These variations diminish as the superplasticity of the material increases.

5. Conclusion

The performance of a laboratory device developed by the authors as a model of affordable hot isothermal pressing machine has been verified in this article, based on which the following conclusions can be drawn:

Experiments carried out on sample titanium-based circular blanks drawn to lens-shaped workpieces indicate close relation existing between the experimental and theoretical achievements. This illustrates that the device proposed in this article can efficiently maintain the controllable environment required for SPF. Sound components could be produced, indicating the effectiveness of the forming processes being implemented with the proposed machine. Some variations were noticed in the thickness of components, the amounts of which were in good agreement with theoretical estimates. These variations depend on the geometry and the material of the component. Larger variations occur with greater depths of forming. The variations diminish as the superplasticity of material increases.

The market value of the industrial version of the proposed machine is envisaged to be at least three to four orders of magnitude lower than the market prices of its existing HIP counterparts.

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Appendix

Considering Fig. 1, process time, T, forming pressure, P, and critical thickness, S_n, for a spherical component are found as follows [38, 42]:

Maximum thickness strain is

$$\varepsilon_S = \frac{S_o - S_n}{S_o} \times 100 \quad \text{(Eq A1)}$$

$$\rho = H + X \quad \text{(Eq A2)}$$

$$\rho = H^2 + 2HX + X^2 \quad \text{(Eq A3)}$$

X can be approximated as follows:

$$X^2 = \rho^2 - R_o^2 \quad \text{(Eq A4)}$$

From Eq A2-A4 and considering that $\bar{H} = H/R_o$:

$$\rho = R_o \frac{1 + \bar{H}^2}{2H} \quad \text{(Eq A5)}$$

Considering Fig. A1 illustrating a spherical segment under the deformation pressure, P, it can be written from equilibrium of forces:

$$\pi r^2 P = 2\pi r S \sigma_s \cos(\pi/2 - \alpha) \quad \text{(Eq A6)}$$

From the geometry of Fig. A1:

$$r = \rho \sin\alpha \quad \text{(Eq A7)}$$

Substituting r from Eq A7 into A6:

$$P = \frac{2S\sigma_S}{\rho} \quad \text{(Eq A8)}$$

where S is the workpiece's wall thickness. From (A5) and (A8):

$$P = 4\sigma_S \frac{S}{R_o} \frac{\bar{H}}{1 + \bar{H}^2} \quad \text{(Eq A9)}$$

For the final stage of forming at the bottom of workpiece where $S_o = S_n$, and considering Eq 3:

$$P = 4\sigma_S \frac{S_o(1 + \bar{H}^2)^{m_S}}{R_o} \frac{\bar{H}}{1 + \bar{H}^2} \quad \text{(Eq 2)}$$

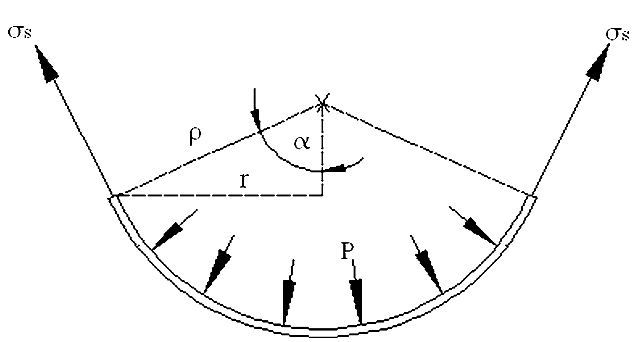

Fig. A1 A segment of a spherical component under deformation pressure

Process time is obtained as follows:

$$T = \frac{1}{\mathring{\varepsilon}} \mathrm{Ln} \frac{S_o}{S_n} \quad \text{(Eq A10)}$$

Considering Eq 3 and A10:

$$T = (2 - m)\mathrm{Ln}\,(1 + \bar{H}^2)/\mathring{\varepsilon} \quad \text{(Eq 1)}$$

References

1. R.M. Govindarajan and N. Aravas, Finite Element Analysis of Cold- and Hot-Isostatic Pressing, *Proceedings of the Int. Conf. on Hot Isostatic Pressing-HIP '93*, April 21-23, 1993 (Antwerp, Belgium), Elsevier Publishing Company, 1994, p 29–36
2. R. Widmer, Hot Isostatic Pressing in Competition and in Combination with Other Consolidation Processes, *Proceedings of the Int. Conf. on Hot Isostatic Pressing-HIP '93*, April 21-23, 1993 (Antwerp, Belgium), Elsevier Publishing Company, 1994, p 581–590
3. G. Shen and D. Furrer, Manufacturing of Aerospace Forgings, *J. Mater. Process. Technol.*, 2000, **98**, p 189–195
4. J. Tang, A. Wu, X. Mao, S. Li, W. Gao, and Y. Du, Effects of Hot Isothermal Pressing on the Microstructures and Soft Magnetic Properties of Nanocrystalline Fe86Zr7B6Cu1 ribbons, *J. Phys. D: Appl. Phys.*, 2004, **37**, p 151–154
5. J. Tang, L. Zhou, D. Tan, and Y. Du, Crystallization Process of Amorphous Fe86Zr7B6Cu1 Alloy Under Hot Isothermal Pressing, *J. Alloys Compds.*, 2005, **394**, p 215–218
6. F. Warchomicka, M. Stockinger, and H.P. Degischer, Quantitative Analysis of the Microstructure of Near β Titanium Alloy During Compression Tests, *J. Mater. Process. Technol.*, 2006, **177**(1–3), p 473–477
7. M. Kikuchi, M. Takahashi, and O. Okuno, Elastic Moduli of Cast Ti-Au, Ti-Ag, and Ti-Cu alloys, *Dent. Mater.*, 2006, **22**, p 641–646
8. S. Faghihia, F. Azari, H. Li, M.R. Batenic, J.A. Szpunar, H. Vali, and M. Tabrizian, The Significance of Crystallographic Texture of Titanium Alloy Substrates on Pre-osteoblast Responses, *Biomaterials*, 2006, **27**, p 3532–3539
9. C. Li, S. Wu, J. Guo, Y. Su, W. Bi, and H. Fu, Model Experiment of Mold Filling Process in Vertical Centrifugal Casting, *J. Mater. Process. Technol.*, 2006, **176**(1–3), p 268–272
10. G. Wang, K.F. Zhang, D.Z. Wu, J.Z. Wang, and Y.D. Yu, Superplastic Forming of Bellows Expansion Joints Made of Titanium Alloys, *J. Mater. Process. Technol.*, 2006, **178**(1–3), p 24–28
11. M.K. Miller, K.F. Russell, and D.T. Hoelzer, Characterization of Precipitates in MA/ODS Ferritic Alloys, *J. Nucl. Mater.*, 2006, **351**, p 261–268
12. J. Chen, P. Jung, M. Nazmy, and W. Hoffelner, In Situ Creep under Helium Implantation of Titanium-Aluminium Alloy, *J. Nucl. Mater.*, 2006, **352**, p 36–41
13. S. De la Flor, C. Urbina, and F. Ferrando, Constitutive Model of Shape Memory Alloys: Theoretical Formulation and Experimental Validation, *Mater. Sci. Eng. A*, 2006, **427**, p 112–122
14. W. Yan, Theoretical Investigation of Wear-Resistance Mechanism of Superelastic Shape Memory Alloy NiTi, *Mater. Sci. Eng. A*, 2006, **427**, p 348–355
15. X. Wu, Review of Alloy and Process Development of TiAl Alloys, *Intermetallics*, 2006, **14**, p 1114–1122
16. K. Gebauer, Performance, Tolerance and Cost of TiAl Passenger Car Valves, *Intermetallics*, 2006, **14**, p 355–360
17. U. Wiklund, B. Casas, and N. Stavlid, Evaporated Vanadium Nitride as a Friction Material in Dry Sliding against Stainless Steel, *Wear*, 2006, **261**, p 2–8
18. B. Podgornik, S. Hogmark, and O. Sandberg, Proper Coating Selection for Improved Galling Performance of Forming Tool Steel, *Wear*, 2006, **261**, p 15–21
19. B. Huang, Z. Deng, Y. Liu, and X.Q. Yuehui He, Superplastic Behavior of a TiAl-based Alloy, *Intermetallics*, 2000, **8**, p 559–562
20. K. Tokaji, High Cycle Fatigue Behaviour of Ti-6Al-4V Alloy at Elevated Temperatures, *Scripta Mater.*, 2006, **54**, p 2143–2148

21. S. Ankem, H. Margolin, C.A. Greene, B.W. Neuberger, and P.G. Oberson, Mechanical Properties of Alloys Consisting of Two Ductile Phases, *Prog. Mater. Sci.*, 2006, **51**, p 632–709
22. M. Mulyadi, M.A. Rist, L. Edwards, and J.W. Brooks, Parameter Optimisation in Constitutive Equations for Hot Forging, *J. Mater. Process. Technol.*, 2006, **177**(1-3), p 311–314
23. X. Li and M. Li, FE Simulation for the Forging Process of TC6 Alloy Disc Utilizing a Microstructural Model, *Mater. Character.*, 2005, **55**, p 362–370
24. J. Satoh, M. Gotoh, and Y. Maeda, Stretch-Drawing of Titanium Sheets, *J. Mater. Process. Technol.*, 2003, **139**(1-3), p 201–207
25. K. Muler, Extrusion of Nickel-Titanium Alloys Nitinol to Hollow Shapes, *J. Mater. Process. Technol.*, 2001, **111**(1-3), p 122–126
26. T. Tetsui, K. Shindo, S. Kaji, S. Kobayashi, and M. Takeyama, Fabrication of TiAl Components by Means of Hot Forging and Machining, *Intermetallics*, 2005, **13**, p 971–978
27. P.S. Bate, N. Ridley, B. Zhang, and S. Dover, Optimisation of the Superplastic Forming of Aluminium Alloys, *J. Mater. Process. Technol.*, 2006, **177**(1-3), p 91–94
28. J.N. Wang and Y. Wang, An Investigation of the Origin of the Superplasticity of Cast TiAl Alloys, *Int. J. Plast.*, 2006, **22**, p 1530–1548
29. X.J. Zhu, M.J. Tan, and W. Zhou, Enhanced Superplasticity in Commercially Pure Titanium Alloy, *Scripta Mater.*, 2005, **52**, p 651–655
30. S. Rhaipu, The Effect of Microstructural Gradients on Superplastic Forming of Ti-6Al-4V, *J. Mater. Process. Technol.*, 1998, **80–81**, p 90–95
31. 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, *Mater. Sci. Eng.*, 2000, **A298**, p 44–50
32. Y. Yang, X. Zhang, Z. Li, and Q. Li, Localized Superplastic Behavior in Titanium at High Strain-Rate, *Scripta Metall. Mater.*, 1995, **33**, p 219–224
33. B.P. Bewlay, M.F.X. Gigliotti, F.Z. Utyashev, and O.A. Kaibyshev, Superplastic Roll Forming of Ti Alloys, *Mater. Des.*, 2000, **21**, p 287–295
34. A.V. Sergueeva, V.V. Stolyarov, R.Z. Valiev, and A.K. Mukherjee, Enhanced Superplasticity in a Ti-6Al-4V Alloy Processed by Severe Plastic Deformation, *Scripta Mater.*, 2000, **43**, p 819–824
35. A. Dutta and D. Siva Kumar, Predictions of the Phase Ratio at the Lowest Flow Stress in Superplastic Titanium Alloy, *Mater. Sci. Eng.*, 1995, **A194**, p L1–L4
36. Z. Shaoqing and Z. Linruo, Effect of Hydrogen on the Superplasticity and Microstructure of Ti-6Al-4V Alloy, *J. Alloys Compds.*, 1995, **218**, p 233–236
37. B.H. Cheong, J. Lin, and A.A. Ball, Modelling of Hardening due to Grain Growth for a Superplastic Alloy, *J. Mater. Process. Technol.*, 2001, **119**(1-3), p 361–365
38. A.A. Kruglov, F.U. Enikeev, and R. Ya Lutfullin, Superplastic Forming of a Spherical Shell out of a Welded Envelope, *Mater. Sci. Eng.*, 2002, **A323**, p 416–426
39. F.U. Enikeev and A.A. Kruglov, An Analysis of the Superplastic Forming of a Thin Circular Diaphragm, *Int. J. Mech. Sci.*, 1995, **37**, p 473–483
40. Z.X. Guo and N. Ridley, Modelling of Superplastic Bulge Forming of Domes, *Mater. Sci. Eng. A*, 1989, **114**, p 97–104
41. M.K. Khraisheh, On the Failure Characteristics of Superplastic Sheet Materials Subjected to Gas Pressure Forming, *Scripta Mater.*, 2000, **42**, p 257–263
42. Y. Aoura, D. Ollivier, A. Ambari, and P.D. Santo, Determination of Material Parameters for 7475 Al Alloy From Bulge Forming Tests at Constant Stress, *J. Mater. Process. Technol.*, 2004, **145**, p 352–359
43. Report of NRC: Titanium: Past, Present and Future, National Academy Press, Washington, DC, 1983
44. S. Bednarek, J. Sińezak, and P. Skubisz, Modelling of Near-Net Forging of Thin-Walled Parts of Strain Rate Sensitivity Alloys, *Metall. Found. Eng.*, 2005, **31**, p 87–94
45. P. Cavaliere and E. Evangelista, Isothermal Forging of Metal Matrix Composites: Recrystallisation Behaviour by Means of Deformation Efficiency, *Compos. Sci. Technol.*, 2006, **66**, p 357–362