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Analysis of Deformation, Temperature, and Microstructure of Titanium Alloys During Hot Extrusion

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Abstract:

In the hot extrusion of a material with high flow stress, a large amount of heat is generated, which tends to locally change the microstructure and mechanical properties of the extruded material. It is therefore necessary to know in detail the strain, strain rate, and temperature distribution of the material during the hot extrusion. The strain, temperature, and microstructure of Ti-6Al-4V alloy billets being hot extruded at the heating temperatures of 950 and 1,100°C and extrusion ratios of 6 and 12 were investigated by the visioplasticity and heat analysis methods. On the same cross section of the billet being hot extruded, the strain was smaller in the center than in the surface, while the temperature was higher in the center than in the surface because the heated billet cooled down to a considerable extent before it was hot extruded. The microstructure was composed of α grains deformed according to these strain and temperature distributions.

1. Introduction

Commercially pure titanium and titanium alloys have excellent corrosion resistance and high specific strength so that they are extensively used as structural members in aircraft and other applications where high reliability is essential. Such structural parts are made in various shapes and diverse product types that call for small-lot production. This brings into highlight the hot extrusion process that can easily fabricate structural components with various cross-sectional shapes.

Hot extrusion is a kind of near net shape production technology whereby a part close in shape to the end product is made in one processing step, and thus is an extremely efficient hot working process. The severity of a single hot extrusion step is large, and a large amount of heat is generated in materials with high hot flow stress, such as titanium alloys. To homogenize the mechanical properties and microstructure of the hot-extruded product of interest, detailed survey must be made over the strain and temperature of the material at cross-sectional positions during the hot extrusion. It is also essential to pre-establish criteria for predicting the mechanical properties and microstructure of the material hot extruded under various conditions. Many of the past studies on hot extrusion are concerned with the metal flow analysis of materials during the hot extrusion. For example, Shabaik et al.[1] analyzed axisymmetric extrusions by the visioplasticity method. Non-axisymmetric extrusions were analyzed by Altan and Nagpal[2] using the flow function method and by Kiuchi et al.[3] using the upper bound elemental technique (UBET). These studies analyzed only the metal flow of hot-extruded products, paying little attention to the metallurgical effects of working strain and temperature changes on the mechanical properties and microstructure of hot-extruded products.

The authors focused attention on those titanium-base materials that were expected to meet increasing social needs in the future, and analyzed strain, strain rate and temperature distribution dur-

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ing hot extrusion in the representative titanium alloy Ti-6Al-4V. We observed the microstructure of the material in the deformation process, and investigated mutual relations between the factors involved. The material's deformation during hot extrusion is usually analyzed by the upper bound method, slip line field method or finite element method. Instead of these approximate methods, however, we used the grid method[1] that can clearly indicate the metal flow during hot extrusion and directly determine the deformation state of the material. The temperature of the material was analyzed by the method that introduces the mass transfer term and working-generated heat term as heat transfer terms[4]. The heat transfer coefficient between the billet and the container was separately measured in order to accurately estimate the temperature distribution during hot extrusion.

2. Experimental Methods

A Ti-6Al-4V billet forged in the $\alpha + \beta$ region was used as experimental material, and a 62 mm diameter and 155 mm long round billet for hot extrusion was machined from the starting billet. To measure the strain induced during hot extrusion, this billet was halved along the center line, and 5 × 5 mm grind lines of 0.3 mm thickness were scribed on the cross section of each half by electric discharge machining. The two billet halves thus scribed with grid lines were mated into the original condition, placed in a 64 mm diameter and 150 mm long cylinder made of 1 mm thick titanium sheet, and hot extruded.

The billet was heated in air at 950 or 1,100°C for 5 min, extruded on a hot extrusion machine with a 45° conical die, extrusion ratio of 6 (from 65 mm to 26.5 mm diameter) or 12 (from 65 mm to 18.7 mm diameter) and stem speed of 70 mm/s, stopped midway in the process, and examined for the conditions before, amid, and after extrusion. Silicate (SiO_2) glass was used as the hot extrusion lubricant. The cooling rate of the billet from extraction from the reheating furnace to hot extrusion was determined by attaching four thermocouples to another billet of the same shape at 12-mm radial intervals from the surface and by measuring the temperature of the temperature-measuring billet as it was uniformly heated to 950°C, cooled in air, loaded into the container, and extruded by the pressure of the stem.

After the hot extrusion, the outer titanium sheet cylinder was removed from the billet, the billet was opened at the center partition, the deformation of the grid lines scribed on the center section was measured, and the strain and strain rate of the billet were calculated from the grid line deformation measurements. The cross-sectional microstructure of the hot-extruded billet was observed, and the microstructural transformation and the primary α grain morphology were examined.

The strain and strain rate of the hot-extruded billet were obtained from the stem speed and grid line deformation measurements by the following procedure[1]. The coordinate system for the billet during hot extrusion is illustrated in **Fig. 1**. The flow line j of the material in steady-state axisymmetric extrusion is given by $\Psi_j = \pi R_j^2 V_0$ using the flow function Ψ, where R_j is the radius of the flow line before the deformation, and V_0 is the stem velocity. Since the flow function Ψ is expressed as a function of the distance in the radial direction r and the distance in the axial direction z, the radial velocity component u and the axial velocity component v at an arbitrary nodal point are given by Eq. (1).

$$u=\frac{1}{2\pi r}\frac{\partial\Psi}{\partial z},\quad v=-\frac{1}{2\pi r}\frac{\partial\Psi}{\partial r} \qquad \cdots\cdots(1)$$

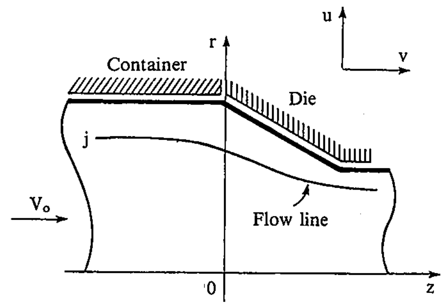


Fig. 1 Coordinate system and flow line

From the velocity components (u, v) at the point, the radial, circumferential, axial, and shear strain rates $\dot{\varepsilon}_r, \dot{\varepsilon}_\theta, \dot{\varepsilon}_z$, and γ_{rz} are given by Eq. (2).

$$\dot{\varepsilon}_r=\frac{\partial u}{\partial r},\quad \dot{\varepsilon}_\theta=\frac{u}{r},\quad \dot{\varepsilon}_z=\frac{\partial v}{\partial z},\quad \dot{\gamma}_{rz}=\frac{\partial u}{\partial z}+\frac{\partial v}{\partial r} \qquad \cdots\cdots(2)$$

The effective strain rate $\dot{\bar{\varepsilon}}$ is given by Eq. (3) and is integrated by time along the flow line to obtain the effective strain $\bar{\varepsilon}$ as given by Eq. (4). The numerical values of the effective strain rate $\dot{\bar{\varepsilon}}$ and the effective strain $\bar{\varepsilon}$ are calculated by the finite difference method.

$$\dot{\bar{\varepsilon}}=(2/3(\dot{\varepsilon}_r^2+\dot{\varepsilon}_\theta^2+\dot{\varepsilon}_z^2+1/2\cdot\dot{\gamma}_{rz}^2))^{1/2} \qquad \cdots\cdots(3)$$

$$\bar{\varepsilon}=\int\dot{\bar{\varepsilon}}\,dt \qquad \cdots\cdots(4)$$

The temperature distribution is numerically calculated from the above-mentioned strain rate and strain distributions by a two-dimensional heat transfer equation containing the mass transfer term and internal working-generated heat term of the material, using the finite difference method.

$$\lambda\left(\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+r\frac{\partial^2 T}{\partial z^2}\right)-\rho c\left(\frac{\partial}{\partial r}(T\cdot u\cdot r)+r\frac{\partial}{\partial z}(T\cdot v)\right)+\dot{q}\cdot r=0 \qquad \cdots\cdots(5)$$

where λ is thermal conductivity; ρ is specific gravity; c is specific heat; T is temperature; and q is internal working-generated heat. The working-generated heat $\dot{q}$ is given by $\sigma\cdot\dot{\bar{\varepsilon}}$, and the hot flow stress σ by Eq. (6).

$$\sigma=C_\beta\exp[-8.4546+(13457/T)]\cdot\bar{\varepsilon}^{-(1.319-0.001T)}\cdot\dot{\bar{\varepsilon}}^{-1.061+0.00104T} \qquad \cdots\cdots(6)$$

$$C_\beta=1.6-(0.00495T_0-3.953)$$

Since the deformation stress depends on the temperature, these calculations are made to converge with respect to the temperature. The physical properties of the titanium alloy Ti-6Al-4V are: λ = 14.8 J/ms°C, ρ = 4,510 kg/m³, c = 0.54 kJ/kg°C. In line with the results of the hot extrusion experiment by the visioplasticity method, the temperature distribution is concretely calculated by assuming that the heated billet is air cooled for 20 s, cooled for 2 s after contact with the container and hot extruded with the temperature falling from the center toward the surface and by considering the heat generated during the hot extrusion as well. A lubricant glass film, normally about 10 mm thick, is present between the Ti-6Al-4V titanium alloy and the die during the hot extrusion. No heat transfer is thought to occur through the glass film.

For cooling by the container and the like, the heat transfer coefficient from the surface of the billet is calculated from the measured data by Eqs. (7) and (8), and the temperature distribution of the billet is estimated from the heat transfer coefficient.

$$\frac{\partial T}{\partial t}=a\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial t}\right) \qquad \cdots\cdots(7)$$

$$\lambda\frac{\partial T}{\partial t}\bigg|_{r=R_0}=K(T_s-T_c) \qquad \cdots\cdots(8)$$

where T is temperature; t is time; r is radius; a is thermal conductivity ($\lambda/\rho c$); R_0 is billet radius; K is heat transfer coefficient between the billet and container; T_s is billet surface temperature; and T_c is container inside surface temperature (140°C).

3. Experimental Results and Discussion

Photo 1 shows an example of deformation mode as indicated by grid lines on the central cross section of a billet hot extruded at 950°C in the $\alpha + \beta$ region. The effective strain distributions calculated by Eqs. (1) to (4) from the amounts of deformation thus determined are shown in **Figs. 2(a)** and **2(b)** for the extrusion ratios of 6 and 12. From these diagrams, it is evident that the effective strain increases with the progress of extrusion and from the center to the surface of the billet and peaks at the die outlet surface. The effective strain for the extrusion ratio of 6 is about 1.2 times higher in the surface than at the center on the cross section at the die exit. The effective strain is smaller for the extrusion ratio of 6 than for the extrusion ratio of 12, and is about 30% smaller at the center at the die exit, for example.

The grid line deformation of Ti-6Al-4V during hot extrusion at 1,100°C in the β region and at the extrusion ratio of 6 was investigated next. Unlike extrusion in the $\alpha + \beta$ region, the grid line-scribed surface is considerably distorted and at the same time, considerable surface irregularities are produced in the vertical direction. The deformed grid lines are not clear enough so that some error is suspected in the measurement and calculation of the deformation. **Fig. 3** shows the effective strain distribution calculated by Eqs. (1) to (4) as is the case with hot extrusion at 950°C. As in the above-mentioned $\alpha + \beta$ hot extrusion, the effective strain increases from the center toward the surface of the billet. The internal strain distribution or the deformation of the material at the center is somewhat larger than observed during the $\alpha + \beta$ hot extrusion. When the extrusion ratio was 12, the deformed grid lines were so indistinguishable that the strain and other variables could not be calculated.

The temperature distribution that allows for the working-generated heat and billet cooling rate measurements is estimated by Eqs. (5) to (8) from the strain distributions shown in **Figs. 2** and **3**. First, the following measured data are taken into account as initial conditions for estimating the material temperature during hot extrusion. **Fig. 4** shows the thermal hysteresis of

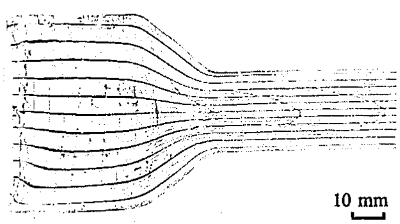
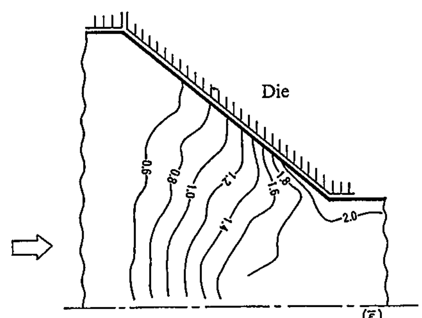
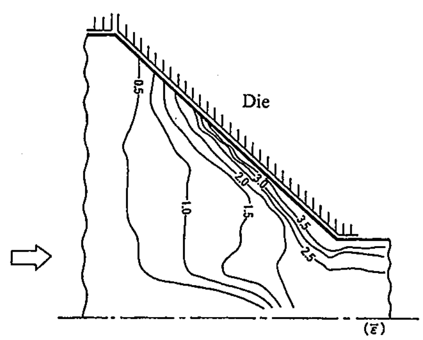


Photo 1 Grid line deformation during hot extrusion at temperature of 950°C and extrusion ratio of 6



(a) Extrusion ratio: 6



(b) Extrusion ratio: 12

Fig. 2 Effective strain distribution of billet hot extruded after heating to 950°C

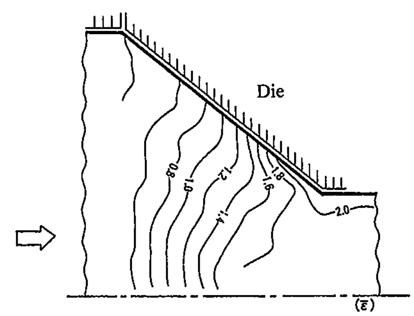


Fig. 3 Effective strain distribution of billet heated to 1,100°C and hot extruded to ratio of 6

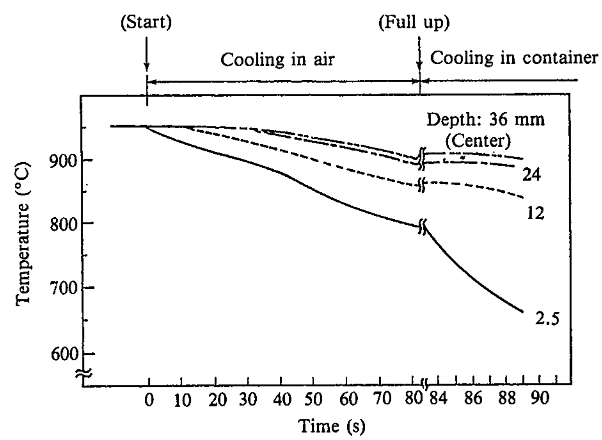


Fig. 4 Cooling curves of billet after heating to 950°C

a billet that was heated to 950° and hot extruded. It is clear from **Fig. 4** that the billet surface temperature decreases to a considerable extent after heating, especially through contact with the container. The heat transfer coefficient K of the billet surface in contact with the container is calculated to be 1.0 kJ/m^{2}s°C from the results of **Fig. 4**. The temperature distribution just before the hot extrusion of a billet heated to 950°C, cooled in air for 20 s, and rapidly cooled through contact with the container for 2 s is estimated using the billet-container heat transfer coefficient K, as shown in **Fig. 5**. This state is taken as the initial condition to estimate the temperature distribution during hot extrusion.

The temperature distributions of billets heated to 950°C and hot extruded to the ratios of 6 and 12 are shown in **Figs. 6(a)** and **6(b)**, respectively. When the extrusion ratio is 6, the heat generated by the hot extrusion raises the temperature of the material. At the exit of the die, the center temperature is higher than the surface temperature, but does not exceed the β transus temperature. When the extrusion ratio is 12, the heat generated by the hot extrusion raises the temperature of the material. At the die exit, the center temperature surpasses the β transus temperature, but the surface temperature does not.

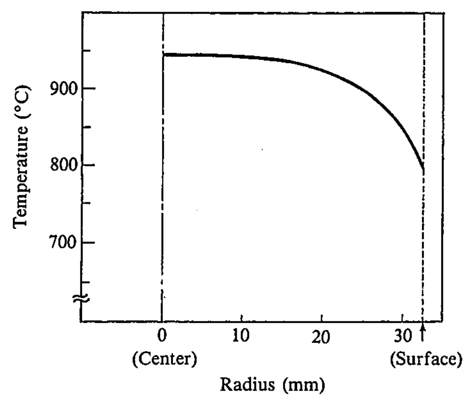
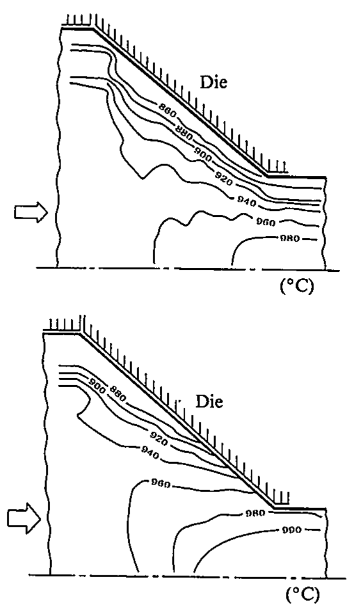


Fig. 5 Radial temperature distribution of billet heated to 950°C immediately before hot extrusion



(a) Extrusion ratio: 6

(b) Extrusion ratio: 12

Fig. 6 Temperature distribution of billet heated to 950°C and hot extruded

Photo 2 shows the change in the microstructure of Ti-6Al-4V heated to 950°C in the $\alpha + \beta$ region and hot extruded to the ratio of 6. The α grains in the undeformed region were longitudinally extended by subsequent deformation and remained throughout from the undeformed region to the die exit. These results mean that when the extrusion ratio was 6, the material temperature did not rise above the β transus temperature. This agrees with the temperature distribution estimated as discussed above. When Ti-6Al-4V was heated to 950°C in the $\alpha + \beta$ region and hot extruded to the ratio of 12, α grains in the undeformed region were also longitudinally extended by subsequent deformation. At the die exit, the α grains remained in the surface, and the center was an acicular microstructure where β transformed to $\alpha + \beta$. The heat generated by the hot extrusion is considered to have raised the center temperature above the β transus temperature of 990°C. When Ti-6Al-4V was heated to 1,100°C in the β region and hot extruded to the ratio of 6 or 12, its microstructure was acicular before, during, and after the hot extrusion.

Homogenizing the microstructure of a hot-extruded product is important in improving its properties. When Ti-6Al-4V is heated and hot extruded in the β region, its microstructure is acicular overall. When Ti-6Al-4V is heated and hot extruded in the $\alpha + \beta$ region, equalizing the shape and size of α grains is important in improving the fracture toughness and fatigue strength of the product. **Photo 3** quantitatively shows relationships among the

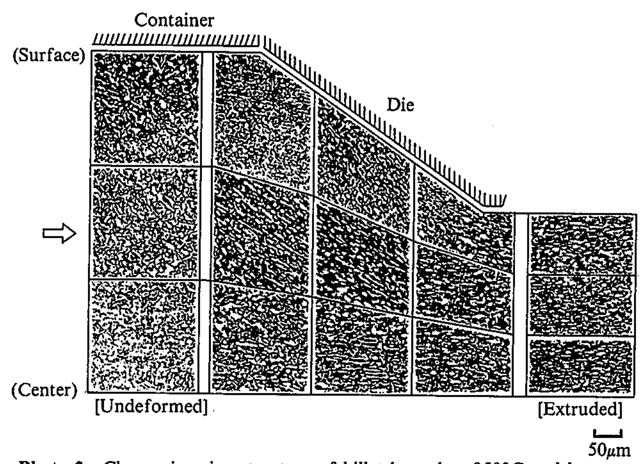


Photo 2 Change in microstructure of billet heated to 950°C and hot extruded to ratio of 6

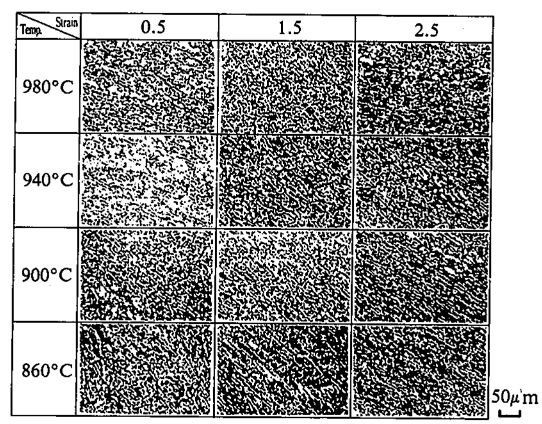


Photo 3 Effects of strain and temperature on microstructure of billets heated to 950°C and hot extruded

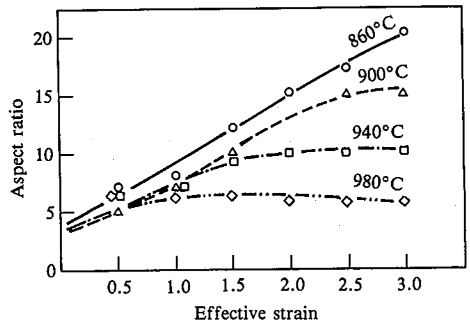


Fig. 7 Effects of strain and temperature on aspect ratio of primary α phase grains in microstructure of billet heated to 950°C and hot extruded

strain, temperature, and microstructure of Ti-6Al-4V heated to 950°C and hot extruded in the $\alpha + \beta$. The data used were derived from the above-mentioned quantitative determination of the deformation degree (extrusion ratio), temperature and α grains during the hot extrusion. The temperature being equal, the equiaxed α grains increasingly deform and elongate with increasing strain. **Fig. 7** shows the effects of strain and temperature on the aspect ratio of α grains. The α grains become increasingly elongated and equiaxed with increasing strain and temperature. This is probably because, as the β transus temperature is approached, the volume fraction of the α phase diminishes to make the α grains appear to be more equiaxed.

4. Conclusions

The strain, temperature, and microstructure of Ti-6Al-4V billets hot extruded at the heating temperatures of 950 and 1,150°C and extrusion ratios of 6 and 12 were investigated by the grid method and the thermal analysis method. On the same cross section of a Ti-6Al-4V billet during hot extrusion, the strain increases from the center toward the surface, while the temperature decreases from the center to the surface because the billet is cooled to a considerable extent in between the heating and hot extrusion steps. The microstructure comprises α grains deformed according to the strain and temperature distributions. The hot extrusion of Ti-6Al-4V is strongly influenced by the cooling of the billet and contact with the container, let alone the billet heating temperature and extrusion ratio. A heterogeneous microstructure often ensues. There is the possibility that the temperature of hot-extruded products may be homogenized through a judicious utilization of the nonuniform strain and temperature distributions. If the billet temperature immediately before hot extrusion is controlled to graduate from the center down to the surface so as to offset the differential heat generation by the hot extrusion strain, it will be possible to oftain a uniform cross-sectional temperature distribution at the die exit.

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