UDC 539.4

Flow Characteristics of Metal with Phase Transformation and Prediction of Its Microstructure

T. Shirakashi[a] and M. Yoshino[b]

[a] Department of Precision Machinery Engineering, Tokyo Denki University, Tokyo, Japan

[b] Department of Mechano-Aerospace Engineering, Tokyo Institute of Technology, Tokyo, Japan

УДК 539.4

Реологические свойства металла с фазовым превращением и прогнозированием его микроструктуры

Т. Ширакаши[а], М. Йошино[б]

[а] Отделение точного машиностроения, Токийский университет, Токио, Япония

[б] Отделение механико-аэрокосмической техники, Токийский технологический институт, Токио, Япония

Предложена новая характеристика текучести стали SUS430F, учитывающая влияние температуры, скорости деформации и истории деформирования материала. В рамках данного подхода влияние истории деформирования на скорость деформации и температуру оценивается по величине накопленной энергии пластической деформации. Предложенная характеристика текучести (σ) может быть представлена в виде функции температуры (θ), скорости деформации (ε), накопленной энергии (W) или базового напряжения (σ_{st}). Энергия накапливается в процессе пластического деформирования, а выделяется при отжиге. Ее величина соотносится с пределом текучести, измеряемым в исходных условиях деформирования. Анализ предложенной характеристики распространен на данный материал для высоких температур (1073...1473 К) при наличии ($\alpha+\gamma$)-фазы с определенным соотношением фаз. Равновесное распределение соотношения α- или γ-фазы при любой температуре может быть оценено на основе диаграммы равновесия фаз. Новая характеристика текучести для случая фазового превращения может быть использована по предложенной формулировке с учетом скорости фазового превращения из α- в ($\alpha+\gamma$)-фазу при повышении температуры и из α- в ($\gamma+\alpha$)-фазу при охлаждении. При этом основой служит диаграмма время–температура–фазовое превращение, учитывающая также процесс закалки. Выполнена оценка предложенной характеристики текучести с учетом соотношения фаз для случая горячей ковки материала.

Ключевые слова: характеристика текучести, скорость деформации, температура, история деформирования, энергия деформации, фазовое превращение.

Introduction. The flow stress characteristic provides a very important information for the analysis of a metal forming process. During this process, a material is deformed under variable strain rate, temperature and their deformation histories, and when temperature is high enough, phase transformation is also to be expected. However, no useful flow stress characteristic equation, which can be applied to a complex deformation process, is available yet.

Metals deformed under various strain rates show different work hardening rates even if their total equivalent strains are the same [1–5]. This means that the deformation history affects the flow stress characteristic. The same feature is also present in the temperature history, because metallurgical phenomena in hot forming processes (e.g., recovery, phase transformation, or re-crystallization) can be expected. Since conventional flow stress equation is only a function of the equivalent strain, strain rate and temperature, but does not depend on deformation histories of temperature and strain rate, the equation is not used to analyze the usual hot forming process.

In this paper, the effects of strain rate and temperature histories on the flow stress are discussed, and a new flow stress equation, which can be applied to any kind of deformation process, is proposed. The equation is expressed to the hot forming process, where phase transformation is expected, and the microstructure (phase ratio) combined with the flow stress is also estimated.

Flow Stress Characteristics of Multiphase Metals with Effect of Strain Rate and Temperature Histories without Phase Transformation. In this paper, the flow stress characteristic of SUS430F metal (ferrite stainless steel) is discussed, as an example. Figure 1 shows the equilibrium phase diagram for SUS430F material, which has three regions: ferrite phase (α) for temperatures less than 1073 K, ferrite and austenite phase ($\alpha + \gamma$) for temperatures from 1073 to 1473 K, and ferrite phase (α) once again for temperatures over 1473 K.

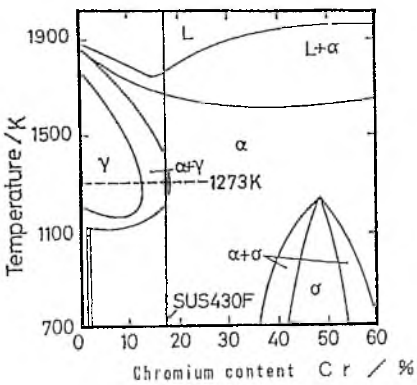

Fig. 1. Equilibrium phase diagram of Fe and Cr.

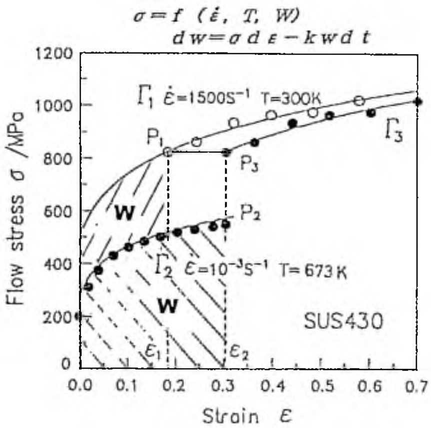

Fig. 2. Combined effect of strain rate and temperature on the flow stress.

If phase transformation is not expected (at temperatures less than 1073 K), the flow stress characteristics with effect of histories of both strain rate and temperature have been proposed as the function of strain rate/temperature at the moment of straining and material state (work hardening rate) shown by Eq. (1) [6], and the material state is estimated by the stored energy (W) in straining through the forming process shown in Fig. 2,

$$\sigma = f(\dot{\varepsilon}, T, W), \tag{1}$$

where $\dot{\varepsilon}$, T, and W are strain rate, temperature and stored energy, respectively.

The energy is stored through plastic deformation and released by annealing process as shown in Eq. (2),

$$dw = \sigma d\varepsilon - kw^{p} dt, \tag{2}$$

where σ, ε, k, p, w, and t are flow stress, strain, material constants, stored energy, and time, respectively. The energy released during annealing is shown in Fig. 3 and also expressed by Eq. (3) and Fig. 4,

$$dw/dt = -kW^{n}, \quad k = k_s \exp(-C/T), \tag{3}$$

where k_s and C are the material constants.

Equation (1) is also applicable to $\alpha+\gamma$ phase of given ratio under high temperatures between 1073 and 1473 K shown in Figs. 4 and 5. The stored energy (W) is uniquely estimated by the reference stress sst, which is measured under the reference condition such as room temperature and high strain rate 1500 s^{-1} shown in Fig. 5.

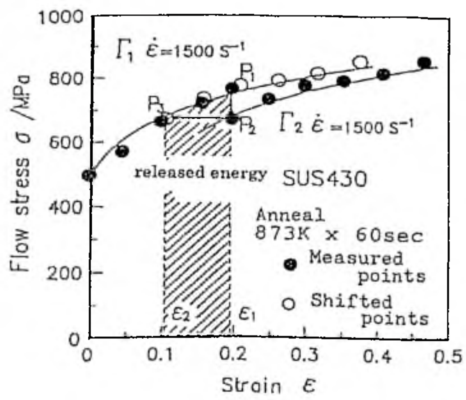

Fig. 3. Behavior of stress-strain relation by annealing (room temperature).

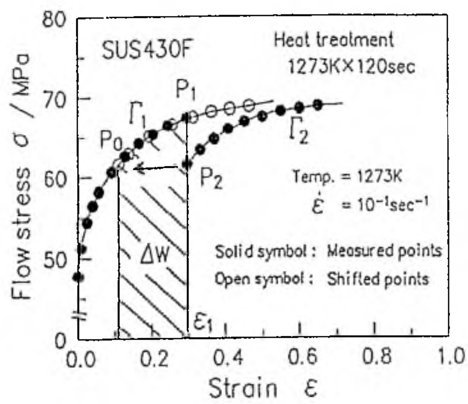

Fig. 4. Stress strain relation of $\alpha+\gamma$ phase (high temperature $T = 1273$ K).

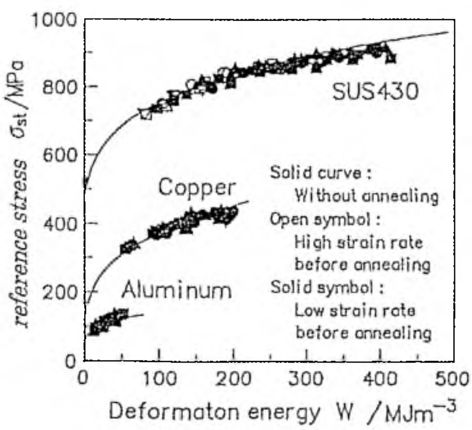

Fig. 5. Relation between plastic deformation energy and reference stress.

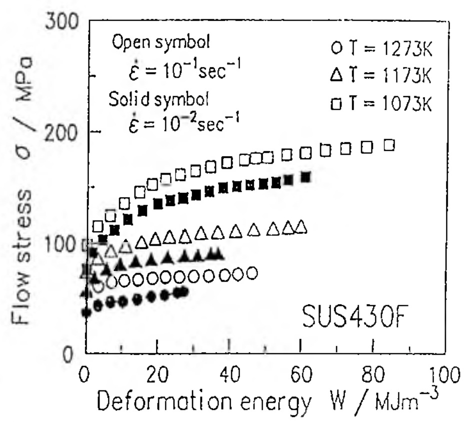

Fig. 6. Plastic deformation energy and reference energy relation of $\alpha+\gamma$ under high temperature.

The general flow stress characteristic under given phase ratio is expressed by Fig. 6 and Eq. (4) as follows:

$$\sigma = f(\dot{\varepsilon}, T, \sigma_{st}). \tag{4}$$

Phase Transformation Rate. The flow stress under given condition is easily obtained as shown by Eqs. (1) or (4) when the phase ratio is known. In order to estimate the flow stress, the phase ratio must be obtained.

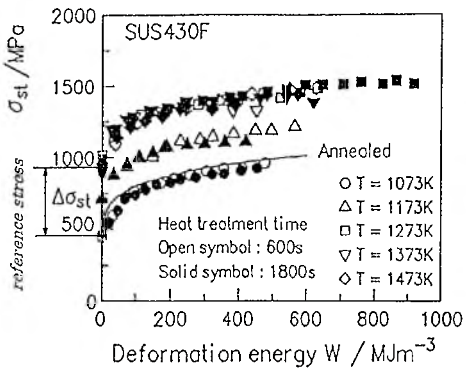

Fig. 7. Variation of reference stress for quenching at various temperatures.

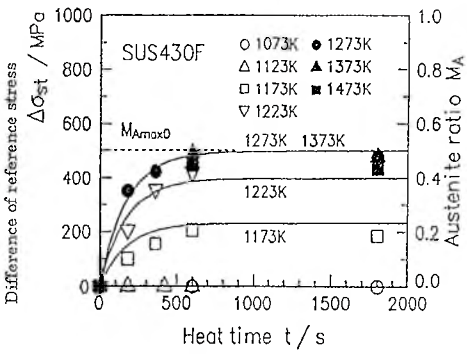

Fig. 8. Variation of $\Delta\sigma_{st}$ and austenite ratio annealed under various temperatures.

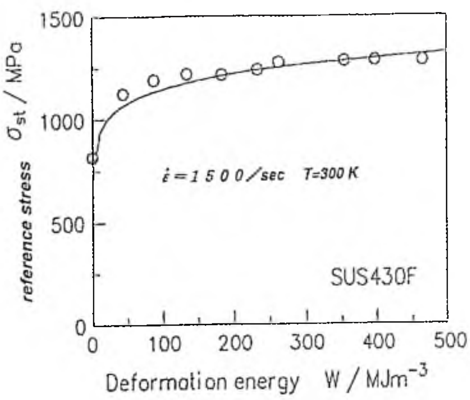

Fig. 9. Reference stress and stored energy relation (martensite phase).

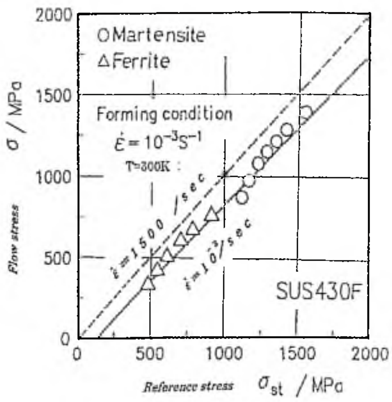

Fig. 10. Effect of strain rate on flow stress (α and martensite phase).

Temperature increase up to 1073 K results in α-phase transformation into $\alpha + \gamma$ phase, while in the case where the austenite phase is cooled down quickly enough (quenched), the phase transforms to martensite phase. The ratio of austenite phase is measured by the increase of the reference stress $\Delta\sigma_{st}$ caused by the transformed martensite as shown in Fig. 7. The maximum austenite ratio is determined by the temperature and annealing time as shown in Fig. 8. Based on latter, the transformation rate from ferrite phase (α) to austenite phase (γ) is expressed in Eq. (5)

$$dM_A / dt = h(M_{A\max} - M_A)^r, \tag{5}$$

where M_A and $M_{A\max}$ are, respectively, the austenite ratio and its maximum value which depends on temperature, while h is the material constant. For the martensite phase, the deformation energy can be measured by the reference stress shown in Fig. 9, and flow stress is also obtained from the reference stress, strain rate, and temperature as shown in Fig. 10. Equation (4) is also valid for the martensite phase.

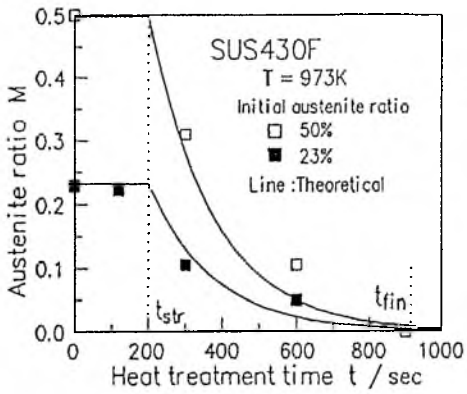

Fig. 11. Effect of annealing time on residual austenite ($\alpha+\gamma \rightarrow \alpha$ transformation).

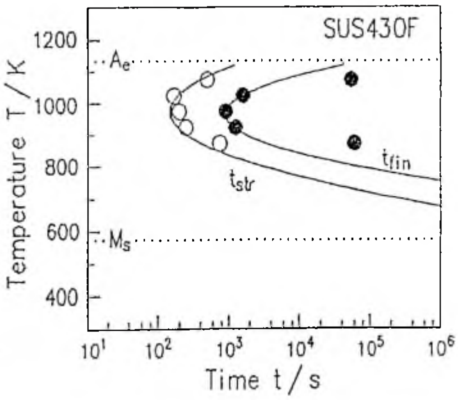

Fig. 12. "Time–temperature–transformation" diagram of ferritic stainless steel.

Under temperatures changing from 1123 K (point A_e) and 573 K (point M_s), the $\alpha+\gamma$ phase transforms to ferrite phase (α). Figure 11 shows variation of the austenite ratio with heat treatment time. This change in ratio is shown as "time –temperature–transformation" diagram in Fig. 12 plotted from Fig. 11. The austenite ratio (M_A) is represented with the use of nondimensional time χ defined from the following relation:

$$\chi = t/(t_{fin} - t_{str}), \tag{6}$$

where t_{fin} and t_{str} are the final and starting time of the transformation, respectively, and t is the transformation time.

$$M_A = (M_A)_{str} \exp(-\lambda \chi^{nt}), \tag{7}$$

where λ and n are the material constants. When temperature changes with time, χ in Eq. (6) is rewritten as follows,

$$\chi = \int dt/(t_{fin} - t_{str}). \tag{8}$$

The austenite ratio can be estimated using Eqs. (7) and (8).

Prediction of Flow Stress and Microstructure. Since phase ratio during forming process can be estimated through Eqs. (5) to (8), the flow stress characteristic can be also obtained using Eqs. (1) to (4). The average flow stress characteristic of mixed phase with given ratio is estimated using mixing rule as follows:

$$\sigma = M_f \sigma_f + M_a \sigma_a$$

or

$$\sigma = (1 - M_a / M_{a50}) \sigma_f + (M_a / M_{a50}) \sigma_{a50}, \qquad (9)$$

where M_f and M_a are the phase ratios of ferrite and austenite, respectively, while σ_f and σ_a are flow stresses of ferrite and austenite phases, respectively.

Now we can estimate changes in the flow stress and microstructure during the forming process. Figure 13 shows the outline of this method. When the stored energy and the phase ratio are known at the moment of forming process, the reference stress σ_{st} is obtained. The flow stress is also estimated based on the reference stress, temperature, and strain rate.

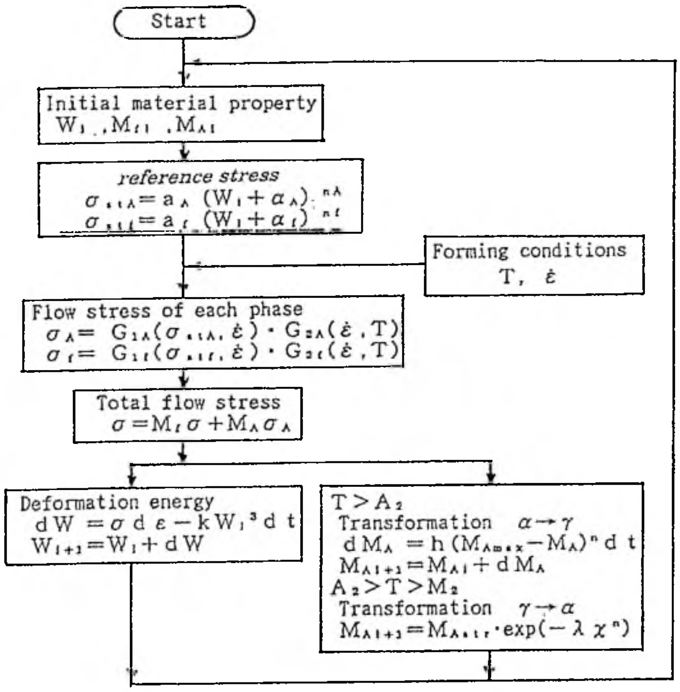

Fig. 13. Outline of the estimation system of the material structure and flow stress.

Figure 14 shows variation of the flow stress and ferrite ratio during the deformation process with the following loading program. SUS430F material is initially annealed under 1273 K for 1800 s, then it is cooled down to 973 K with cooling speed of 2 K/s, after that the material is compressed with a strain rate of 0.001 s^{-1} at constant temperature of 973 K. Under these conditions, both work hardening and annealing effects are expected, while phase transformation also occurs. In Fig. 14, both solid lines show the estimated results for the flow stress and ferrite ratio, whereas symbols represent the experimental results for the flow stress and ferrite ratio. Good correlation can be seen between the estimated and experimental results.

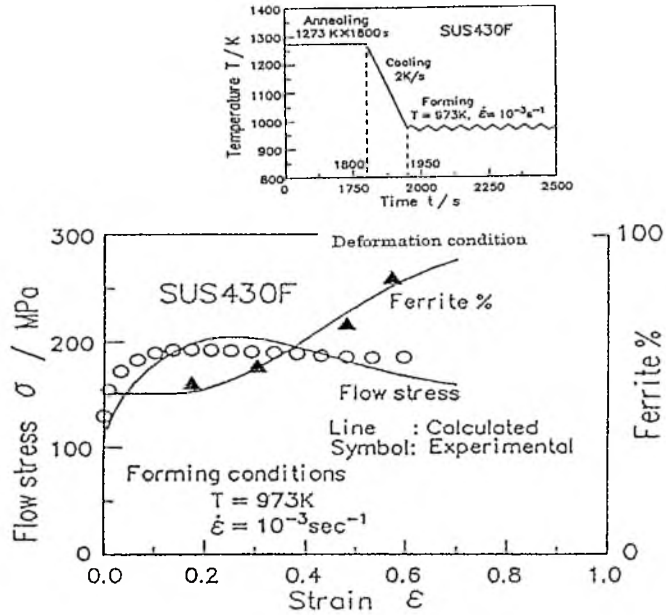

Fig. 14. Estimated structure and flow stress.

It can be concluded that the proposed flow stress characteristic including phase transformation and deformation history is available to estimate flow stress and microstructure.

Conclusions. In order to provide numerical simulation of the deformation process under given condition, mechanical properties of material, such as flow stress during deformation, should be obtained. In this paper, the effects of strain, strain rate, temperature, and their histories on flow stress are discussed, and the available flow stress equation is proposed. In the equation proposed, the energy accumulated during the deformation process, which can take account for the effect of strain rate and temperature histories on flow stress, is included combined with strain rate and temperature at the moment of deformation. The energy is also estimated by the reference stress, which is measured under the reference condition such as high strain rate 1500 s^{-1} and room temperature. The equation is also applied to the condition with phase transformation, when the phase ratio is given during forming process based on both equilibrium phase diagram and “time–temperature–transformation” diagram. Using this approach, both the flow stress and microstructure during forming process can be estimated. The flow stress equation is applied to simulate a forming process. Moreover, changes in microstructure and phase ratio are also simulated using the proposed system. Good agreement between the simulated and experimental results is shown.

Резюме

Запропоновано нову характеристику текучості сталі SUS430F, яка враховує вплив температури, швидкості деформування та історії деформування матеріалу. У рамках даного підходу вплив історії деформування на швидкість

деформації і температуру оцінюється по величині накопиченої енергії пластичної деформації. Характеристика текучості (σ) може бути представлена у вигляді функції температури (θ), швидкості деформації (ε), накопиченої енергії (W) або базового напруження (σ_{st}). Енергія накопичується в процесі пластичного деформування, а виділяється при відпалу. Її величина співвідноситься з границею текучості, що вимірюється в початкових умовах деформування. Аналіз запропонованої характеристики розповсюджується на даний матеріал для високих температур (1073...1473 К), якщо має місце $(\alpha+\gamma)$-фаза з визначеним співвідношенням фаз. Рівноважний розподіл співвідношення α- або γ-фази за любої температури можна визначити на основі діаграми рівноваги фаз. Нова характеристика текучості у випадку фазового перетворення може бути використана за запропонованим формулюванням з урахуванням швидкості фазового перетворення з α- у $(\alpha+\gamma)$-фазу при підвищенні температури та з α- у $(\gamma+\alpha)$-фазу при охолодженні. При цьому за основу береться діаграма час–температура–фазове перетворення, яка враховує також процес загартування. У випадку гарячого кування матеріалу оцінено характеристику текучості з урахуванням співвідношення фаз.

1. S. S. Hecker and M. G. Stout, *Met. Trans.*, **13A**, 619 (1982).
2. K. S. Chan, *Trans. ASME*, *J. Eng. Mater. Technology*, No. 110, 1 (1988).
3. K. E. Hughes, K. D. Nair, and C. M. Sellars, *Metal Technology*, **1**, No. 14, 161 (1974).
4. J. Klepaczko and C. Y. Chiem, *Mech. Physics Solids*, No. 34, 29 (1986).
5. J. Klepaczko, *Mechanics for Working Technologist*, No. 5, 143 (1987).
6. T. Shirakashi and E. Usui, *Int. J. JSPE*, **4**, No. 4, 91 (1970).

Received 14. 11. 2001