The Importance of Adiabatic Heating in Flowforming Ti-6Al-4V

George L. Durfee
Consultant
Grafton, Mass.

Key to increasing the success factor of flowforming Ti-6Al-4V is enhancing the ductility using a suitable array of metallurgical practices to the preform before flowforming.

Flowforming is a cold metalworking process for manufacturing seamless tubular and rotationally symmetrical products (Fig. 1). A cylindrical work piece, or preform, is fitted over and secured at one end to a rotating mandrel. Typically, three CNC-controlled rollers compress the preform while moving along the length of it, which causes the metal to be plastically deformed and made to "flow" in the axial direction along the rotating mandrel. The work piece becomes lengthened according to the amount of reduction-in-wall thickness for the pass. Often, two or more passes are used to form the finished product with or without an intermediate annealing step between some of the passes.

Success Factors for Flowforming

It is useful to divide the subject into two major categories. The first and foremost success factor is the ductility of a metal. It is also the limiting characteristic. Next in importance, the forming and process variables must be established in a coordinated manner to minimize any adverse effects on ductility from the plastic deformation that could jeopardize the integrity of the flowformed part.

Chemical composition, conversion, microstructure, and heat treatment are the metallurgical tools used to maximize ductility of a metal. The second requirement deals with the thermomechanical properties and falls under the aegis of state-of-the-art know-how for flowforming. This success factor is dependent on the ability and experience of the engineer to use a database of experience to determine the design and operating parameters.

Nature of the Flowforming Process

A large amount of adiabatic heating is generated during plastic deformation. Although the plastic deformation zone is flooded with refrigerated emulsified oil-treated coolant to absorb part of the adiabatic heat, a significant amount of the deformation energy is transformed into heat in the deformation zone. This process is called the adiabatic, or deformation heating, effect. Based on a perusal of the literature and depending on the metal, between 90 and 100% of the deformation energy is transformed into heat, resulting in a rise in the temperature of the metal. Therefore, the rise in temperature of the metal during flowforming is an important parameter.

Thermomechanical Behavior of Metals during Flowforming

Plastic deformation of a metal may be quantitatively described by strain and strain rate. For many metals, cold plastic deformation produces a strain, or work hardening, effect often resulting in a significant decrease in ductility and a large increase in strength (both yield and ultimate strength). Strain rate effects on ductility and strength are usually less in magnitude, and they are confounded with adiabatic heating effects (see discussion below). The ultimate limit of strain hardening, or when ductility has been exhausted, is failure or cracking.

The next important characteristic of the thermomechanical behavior of metals is the effect of the adiabatic heating in the zone of the plastic deformation. For many metals, adiabatic heating has a dual beneficial effect on flowforming characteristics; that is, increasing the ductility (failure limit) and decreasing the strength or flow stress of the metal. Therefore, for such metals, the right combination of strain and strain rate in flowforming may produce an adiabatic heating effect of sufficient magnitude to largely negate the decrease in ductility from strain hardening and offset some of the increase in strength from the strain hardening effect.

Controlling the Adiabatic Heating Effect

The adiabatic heating effect of the metal during flowforming is mainly a function of the yield strength, or flow stress, strain, and strain rate. In addition, the strain rate is a function of the strain, revolutions per minute (rpm), and the feed rate (axial travel/revolution). Finally, the heat build-up in the zone of deformation is affected by the cooling effectiveness of the coolant in the zone of deformation, and the heat absorbed by the mandrel. These variables constitute the most important elements of the state of the art that affect the integrity of a flowformed part.

If a model and methodology could be developed that enables an engineer to establish the
forming and process parameters that mainly determine the adiabatic heating effect for a given alloy that has been proven to produce a satisfactory part, the engineer’s job is greatly simplified. Additionally, if the same model produces outputs that can be compared with other outputs from a historical database across a wide size range (even if only on a comparative basis), then the flowforming engineer can, with confidence, predetermine the design and operating parameters for improved productivity and optimal product results.

**Historical Perspective of Flowforming Ti-6Al-4V**

In the 1970s, the author witnessed some flowforming trials that produced a Ti-6Al-4V hollow tube about 4 ft long by 6 in. in diameter. The preform was preheated to about 540°C, and transferred to an in-house designed 2-roller machine having an array of gas-fired burners that impinged on the surface of the preform before it entered the rollers. No coolant was used. Several passes were required to make the part. The finished tube was displayed in the lobby of the parent company. However, later the whole development project was abandoned and the parent company sold the plant, equipment, and know-how to another company specializing in aluminum products. In 1993, M. Koch, et. al., were able to produce seamless Ti-6Al-4V titanium tubes using a flow-forming process only by conducting the flowforming process at temperatures above the recrystallization range. Thus, based on early history, traditional cold flowforming of Ti-6Al-4V remained an elusive and problematic challenge. Early in this decade, the author was retained as a metallurgical consultant to find a way to achieve the goal of cold flowforming Ti-6Al-4V without limitations on the grade. This paper is the outgrowth of that experience. The author first reported the commercial production of flowformed Ti-6Al-4V alloy seamless tubes in *The Fabricator* (February 14, 2002). Later, the solution of the most important success factor (enhancing the ductility) for flowforming α-β titanium alloys was presented to the public in U.S. Patent No. 7,601,232 B2. The main purpose of this article is to describe the potential role for modeling the main variables (strain, revolutions/minute, and axial travel/revolution) contained in the state of the art—the second most important success factor for flowforming.

**Thermomechanical Behavior of Ti-6Al-4V and Flowforming**

Ti-6Al-4V is an excellent candidate for demonstrating the importance of adiabatic heating for successfully flowforming through modeling. The alloy has a high yield point-to-tensile strength ratio resulting in a high strength with relatively limited ductility. The low ductility, especially elongation, limits its cold plastic formability to a narrow range, thereby resulting in the general belief (as reinforced by practical experience) that Ti-6Al-4V is unsuitable for use in many traditional cold-forming processes. Indeed, sheet forming of Ti-6Al-4V has traditionally been performed in the warm-working range often above 480°C. However, the yield strength of Ti-6Al-4V starts to drop off significantly at temperatures above about 200°C, and the ductility also starts to increase. In addition, there is a greater separation between the yield strength and ultimate tensile strength, which also promotes cold forming. These characteristics strengthen the relationship between the adiabatic heating intensity and ductility for success in cold flowforming.

It is difficult to measure the surface temperature in the zone of deformation. This is where modeling comes into play. If a model could be developed that results in a calculated temperature rise in the zone of plastic deformation for one part, then the model could be used to calculate the temperature rise for another part. And, if the model and its methodology could be validated by actual data for an alloy such as Ti-6Al-4V, which requires a significant adiabatic heating effect to avoid cracking during flowforming, then the model could be used with confidence for new candidate parts. Furthermore, the same flowforming model and methodology could also be used for other alloys.
in a similar manner, or, in the case of some metals that need to be flowformed with minimal adiabatic heating, and/or for avoiding excessive adiabatic heating intensity for a given amount of strain.

**Mark I Flowform Model**

The principle output of the Mark I Flowform Model is a calculated (estimated) rise in temperature in the zone of plastic deformation. There are other outputs that are used to ensure that the forming and process parameters determined in the modeling process are in balance and conform to historical modeled data. Although horsepower can be estimated on a comparative basis for new parts based on the assumed flow stress value used in calculating the estimated temperature rise in the zone of plastic deformation, this capability is not presented in this paper because of lack of reliable actual power data that could be used for validation purposes.

The model is based on the physics of the thermomechanical plastic deformation process including the physical characteristics of the metal. It also includes heat losses from coolant and the heat sink of the mandrel. The calculated heat losses can be modified for reduced coolant flow. In principle, external heating could be included in the overall methodology but no job data was available to validate this feature.

**Validation of the Mark I Flowform Model**

Data was available for two passes of 24 different parts produced from a large number of heats of metal. The range of outside diameters was more than 13 cm. The parts were flowformed on machines having different capacities, but all of the machines had three rollers and were similar in design. Among the parts, 14 were forward flowformed and 10 were reverse flowformed. The 24 parts were considered “good” parts. No outliers were excluded in the population of good parts because all of the jobs represent the state-of-the-art and a homogeneous population after the development of the metallurgical know-how to achieve cold flowforming.

Using the methodology of the model, job data from the 24 parts (equal to 48 passes) was translated into two variables: strain and temperature rise (Figs. 3 and 4). The temperature rise (expressed in °C) is plotted on the y-axis vs. strain on the x-axis using MS Excel software. The power curve option was used to plot regression curves including the equation and R² option for the power regression plots. The curves are mildly nonlinear. For flowforming Ti-6Al-4V, both regression power curves are considered to be the minimum calculated temperature rise goal for new jobs, although there were some jobs having a calculated temperature rise less than the power curve.

In the historical job data for reverse flowforming, two parts were not included in the plot. Cracking was encountered on one of the jobs. Using the equation in Fig. 3 and plugging in the before and desired finish dimensions of the cracked part into the model, the feed rate used on the cracked part would have to be increased by 25% to prevent cracking. Another part required some external heat to get the material to flow. This part had a thinner starting wall thickness compared with the part showing cracking. In a similar manner, using the power
curve to calculate the minimum temperature rise and plugging that temperature rise into the model, the feed rate should be increased by 10% to meet the minimum model temperature rise goal. Based upon the author’s past experience, it is believed that the projected feed rates thusly derived would have been sufficient to ensure good flowforming outcomes.

Also, it should be noted that in validating the model for reverse flowforming, it was assumed that the configuration of the rollers and the cooling effectiveness was uniform across the machines that were used to flowform the 10 parts. No data were available to validate the model for forward flowforming. However, because the core principles of the model are the same for both forward and reverse flowforming and the plots for both methods show a $R^2$ value over 0.99, the author believes that the model is valid for comparing the model temperature vs. strain for both forward and reverse flowforming when applied to a historical database of forming and process parameters.

**Discussion**

The model and methodology discussed above produces outputs that reflect an estimate of the energy of plastic deformation in the zone of plastic deformation during flowforming that is transformed into heat energy minus an estimate of the heat losses. It uses an assumed flow stress. For reverse flowforming, the heat balance equations of the model are adjusted to include the axial driving force as a source of energy for transformation into an adiabatic heat energy. The net intensity of the heat energy of the plastic deformation is expressed as temperature rise using the physical properties of the metal. Because the output is used in a comparative manner using historical data, a fixed flow stress value appears to be adequate for using the model for most metals. However, if actual horsepower data is available for a few jobs, it should be possible to develop an empirically derived equation for the flow stress for better accuracy in power projections and for establishing forming and process parameters for new jobs.

**Conclusions**

The first, and foremost, success factor for flowforming Ti-6Al-4V is enhancing the ductility by using a suitable array of metallurgical practices to the preform before flowforming. The next most important success factor is to choose the right combination of strain and strain rate to produce an adiabatic heating intensity to offset any loss in ductility from the plastic deformation of the process that would jeopardize the integrity of the flowformed part. These design and operating variables fall under the general aegis of state of the art of the flowforming process.

Based on historical information on the flowforming of Ti-6Al-4V, it was predictable that the loss in ductility produced by the work hardening effect of the plastic deformation of flowforming could be offset by an adequate amount of adiabatic heating intensity (= temperature rise). This prediction was born out by modeling the flowforming process and the subsequent validation of the model and methodology by plots of calculated model temperature rise vs. strain for flowform passes on 24 good flowformed parts or jobs.  

**Continued**
The graphical plot for 10 reverse flow formed parts was analyzed using MS Excel regression software to produce a power curve and equation for the temperature rise vs. strain. The model, power curve equation, and methodology were applied to two parts not classified as good parts because of problems incurred during flow forming. Using the temperature rise equation to determine the minimum temperature rise for the same amount or strain and the model, it was determined that the feed rate for one of the problem parts that cracked during flow forming should have been 25% greater to prevent cracking. For the other part that required external heat to get the metal to flow and applying the same methodology, the feed rate should have been 10% greater. Thus, the reverse flowform model was validated by both application to good parts and by demonstrating that the feed rates associated with the problem parts were significantly less than meeting the minimum feed rates per the model and the temperature rise vs. strain power curve equation for Ti-6Al-4V. Because the core principles of the model are the same for both flowforming methods, the author presents the argument that the model is valid for comparing the model temperature rise vs. strain for both forward and reverse flowforming when applied to a historical database of forming and process parameters.

References

For more information: Consultant George L. Durfee is a life member of ASM International, P.O. Box 168, Grafton, MA 01519; tel/fax: 508/839-4689; e-mail: flowformscientific@verizon.net. Durfee holds a B.S. degree from Michigan Technological University and was a Tau Beta Pi Fellow at MIT. Prior to his consulting work on flowforming titanium alloys in this decade, he pioneered the α-β forging of Ti-6Al-4V and the use of ceramic coatings as a precoat for forging at Wyman-Gordon Co. in 1955. In the early 1960s, he also invented (U.S. Patent No. 3,339,27) and put into production the use of electroseless nickel plating of titanium forging blanks for preventing surface cracking critically important for successfully forging the crack-prone titanium alloy used for the structural forgings on Lockheed’s SR-71 Blackbird spy planes.