

[54] **LOW OIL-CANNING ALUMINUM ALLOY FORGINGS**

[75] Inventors: **Charles P. Furney, Jr.**, Delmont;
Richard Couchman, New Kensington, both of Pa.

[73] Assignee: **Aluminum Company of America**, Pittsburgh, Pa.

[22] Filed: **Sept. 4, 1973**

[21] Appl. No.: **393,954**

[52] U.S. Cl. **148/13.1**, 148/159

[51] Int. Cl. **C22f 1/04**

[58] Field of Search..... 148/11.5 A, 12.7, 13.1,
148/159

References Cited

UNITED STATES PATENTS

3,007,427 11/1961 Bryan et al. 148/11.5 A
3,392,568 7/1968 Garrity..... 148/11.5 A

3,568,491 3/1971 Bruner et al..... 148/11.5 A

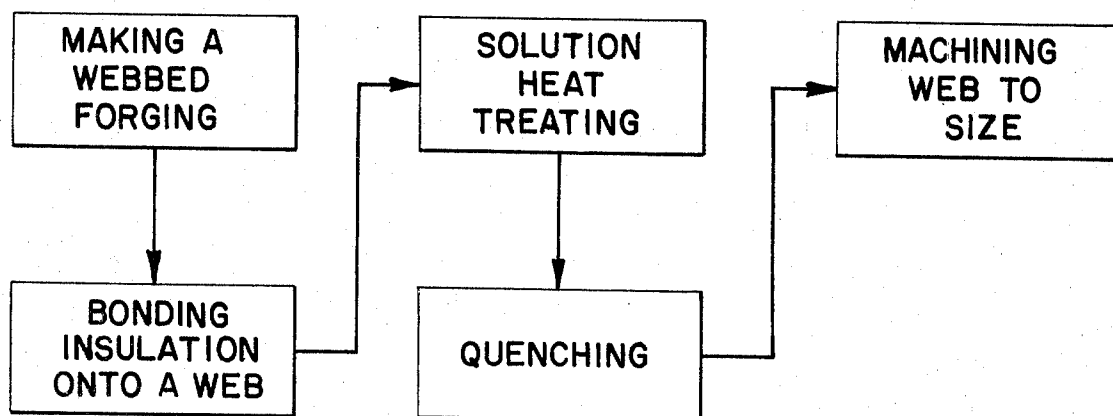
Primary Examiner—W. Stallard

Attorney, Agent, or Firm—Daniel A. Sullivan, Jr.

[57] ABSTRACT

The method of making a heat treated aluminum alloy forging exhibiting reduced "oil-canning" in "oil-canning"-susceptible sections upon machining, including bonding insulation onto an "oil-canning"-susceptible section of an age-hardenable aluminum alloy forging with a bonding agent effective for maintaining a bond during heating for solution heat treatment, solution heat treating the thus-insulated forging, and, with the insulation still on the section, subjecting the solution heat treated forging to a quench for maintaining precipitable components of the alloy in solution in the "oil-canning"-susceptible section, whereby upon machining, said section will exhibit reduced "oil-canning."

12 Claims, 10 Drawing Figures



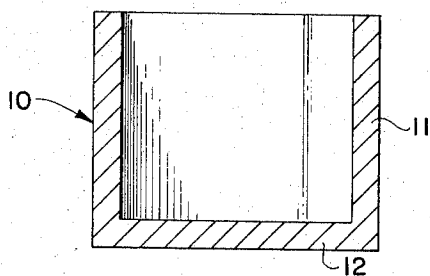


FIG. 1A

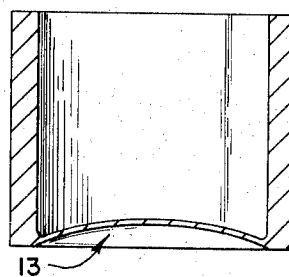


FIG. 1B

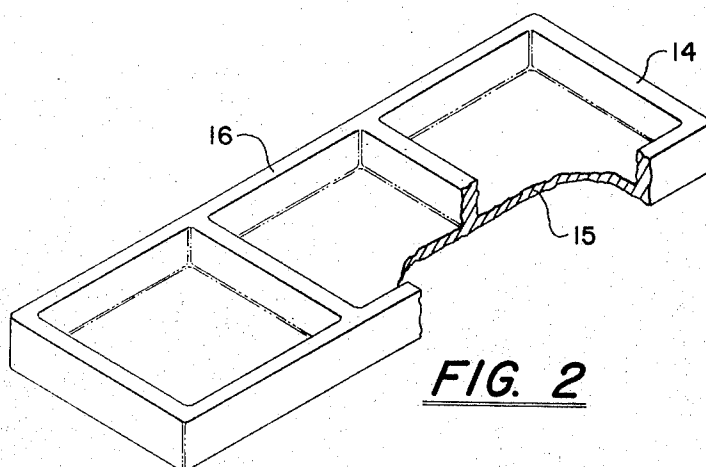


FIG. 2

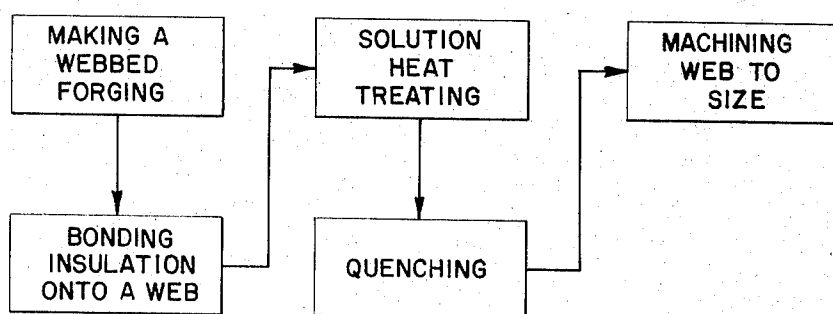


FIG. 3



FIG. 4

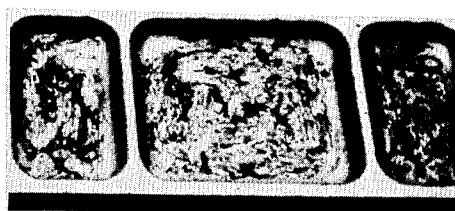


FIG. 7

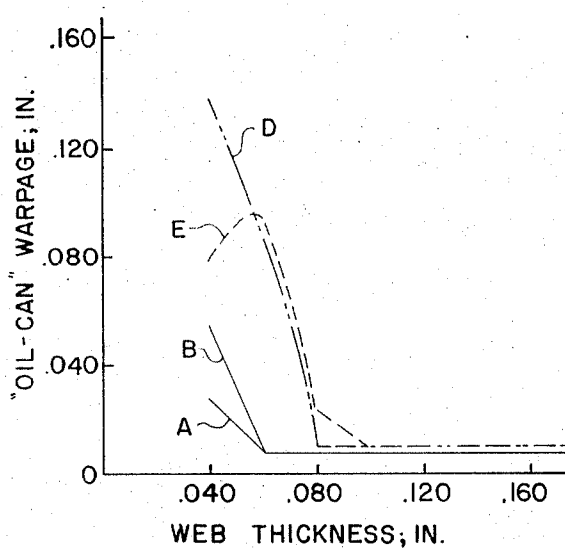


FIG. 5

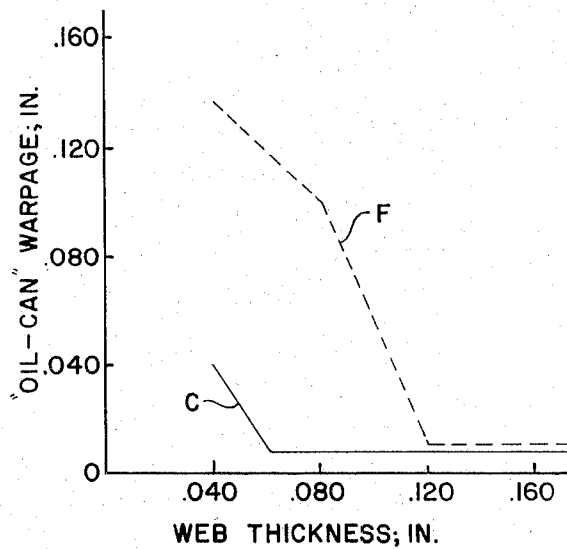


FIG. 6

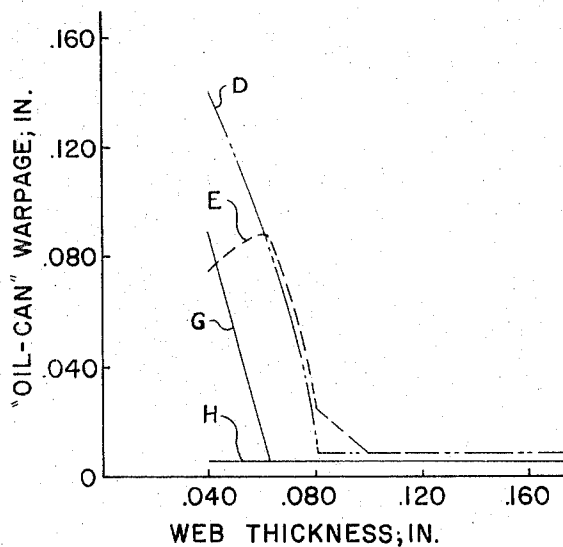


FIG. 8

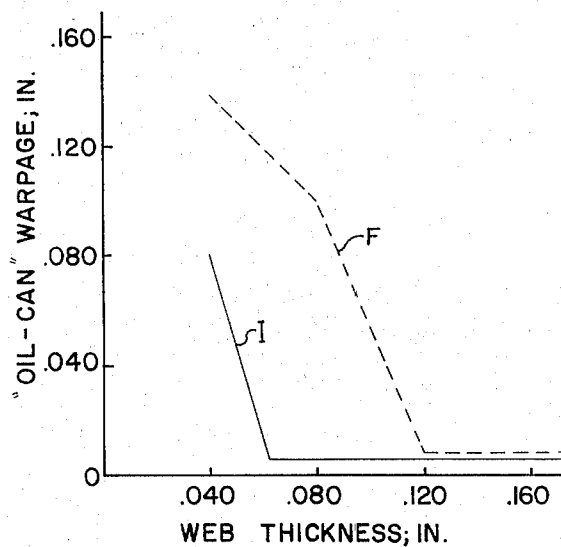


FIG. 9

LOW OIL-CANNING ALUMINUM ALLOY FORGINGS

BACKGROUND OF THE INVENTION

The present invention relates to the manufacture of aluminum alloy forgings, and, more particularly to the manufacture of aluminum alloy forgings exhibiting reduced "oil-canning" in "oil-canning"-susceptible sections.

If an aluminum forging having web sections surrounded by ribs is quenched after solution heat treatment and the web sections are then machined to a reduced thickness, a phenomenon called "oil-canning" may occur in which the web section may suddenly or slowly deflect away from the cutting tool. Deflection may also be toward the cutting tool, and this can result in a gouging or tearing of the web section. The metal deflection is much like that occurring on the bottom of an oil can when the bottom is being worked for dispensing oil onto an area to be lubricated — thus the term "oil-canning." Oil-canning can make it impossible to achieve desired thinness or tolerance in a production part.

SUMMARY OF THE INVENTION

In view of the above, it is an object of the present invention to provide a method for manufacturing aluminum alloy forgings exhibiting upon machining reduced oil-canning in oil-canning-susceptible sections.

It is a further object of the present invention to provide such a method having the additional advantage of reducing overall warpage in such forgings.

This as well as other objects, which will become apparent in the discussion that follows, are achieved according to the present invention by a method of making a heat treated aluminum alloy forging including the steps of bonding insulation onto an oil-canning-susceptible section of an age-hardenable aluminum alloy forging with a bonding means for maintaining a bond during heating for solution heat treatment, solution heat treating the thus-insulated forging, and, with the insulation still on the section, subjecting the solution heat treated forging to a quench for maintaining precipitable components of the alloy in solution in the oil-canning-susceptible section, whereby, upon machining, said section will exhibit reduced oil-canning.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1A and 1B are elevational cross sections, the cutting planes for which contain vertical axes of cylindrical symmetry.

FIG. 2 is a perspective view of an aircraft forging with a portion broken away to reveal the relative position and thickness of its web sections.

FIG. 3 is a process flow diagram.

FIG. 4 is a photograph of one web section, with surrounding rib portions, of a forging as illustrated in FIG. 2 at a certain stage in a process according to the present invention.

FIGS. 5 and 6 are graphs of "oil-can" warpage in inches versus web thickness in inches.

FIG. 7 is a photograph of a forging as in FIG. 2 at a certain stage in a process according to the present invention.

FIGS. 8 and 9 are graphs as in FIGS. 5 and 6.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

A. The Drawings

Referring now to FIG. 1A, there is shown a forging 10 formed by a cylindrical wall or rib section 11 and a base or web section 12. If forging 10 is provided in, for example, 7075 aluminum alloy with rib and web thicknesses of one inch, solution heat treated at 870°F, and quenched in water at 60° to 80°F, age-hardened at 250°F for 24 hours, and the lower side of web 12 in FIG. 1A is then gradually machined off, a certain web thickness is eventually reached at which web 12 suddenly becomes unstable and pops upwards in FIG. 1B, away from the cutting tool, into an "oil-canned" position 13.

It is known to reduce this oil-canning effect by, subsequent to the quenching, cooling forging 10 to minus 100°F and restriking forging 10 in the same die members originally used in its formation. The restriking causes a stretching of the ribs which places web 12 in tension.

FIG. 2 illustrates a ribbed and webbed forging of a precipitation hardenable aluminum alloy material. The design is such as may be used in airplane manufacture. As in FIGS. 1A and 1B, the ribs 14 and 16 are, in this example, only on one side of the webs 15. Typically, following forging and age-hardening, such a forging may be machined all around, including both sides of the webs, to tolerance. The problem of oil-canning can make it impossible to achieve a desired thinness with tolerance at desired strength levels and endangers the economic viability of aluminum alloy forgings for certain applications.

We have discovered that the provision of proper amounts of insulation on both sides of the webs of aluminum alloy forgings during quenching can reduce oil canning in the webs sufficiently to permit machining to tolerance, while nevertheless maintaining sufficient web hardenability in a precipitation hardening step following quenching. We have also discovered that the placing of such insulation operates to reduce overall warping of a forging.

A process according to the present invention is illustrated by a flow diagram in FIG. 3. First, a webbed forging is made, then insulation is bonded onto a web, following which the forging is heated to the solution heat treatment temperature. With the insulation still on the web, the forging is quenched, for example, with water of temperature between 60° and 80°F. It is then possible to machine the web without experiencing unacceptable warping during machining to tolerance.

FIG. 3 is a flow diagram of only one embodiment of the present invention. Thus, for example, the forging may receive a preliminary machining before the step of bonding. Also, the forging may, for example, be age-hardened after the step of quenching and before the step of machining.

B. The Insulation

Insulation can be provided on the forging in the form of a coating of a suitable cement. Another technique is to use the cement to bond an additional insulating material, such as glass cloth, to the forging. Considerable perseverance was required to find satisfactory cements. Thus, we found that a number of cements, including sodium silicate, 85 percent phosphoric acid, a mixture of 1) 40 percent of minus-325 tabular alumina and 2) 60

percent of 85 percent phosphoric acid, and calcium aluminate cement, together with a number of proprietary cements, would fall off of a forging during its solution heat treatment in a furnace. Cements which were found to give best bonding are, firstly, Johns-Manville Fibrous Adhesive, a paintable mixture which gave on analysis, on a dry weight basis, essentially 80 percent sodium silicate (silicon to sodium weight ratio equals 2.1) and 20 percent asbestos fiber shorts and, secondly, Johns-Manville Fireite Cement, a paintable mixture, which gave on analysis, on a dry weight basis, essentially 2 percent asbestos fiber shorts, 15 percent kaolinite, 45 percent silica powder, remainder sodium silicate of silicon to sodium weight ratio equals 1.4. Percentages are on a weight basis. Asbestos fiber shorts are asbestos material whose fibers have lengths below approximately 1 millimeter. Good bonding was achieved with Sauereisen No. 31 cement available commercially from the Sauereisen Cements Company. Poor bonding was exhibited by Sauereisen No. 1 cement.

Besides insulating just with cement material itself, the cement material may be used to bond, for example, glass cloth in place on forging webs to act as insulation. Exemplary glass cloth suitable in the practice of the present invention is a cloth having a weave of 16 filaments by 14 filaments, a thickness of 0.0138 inches, and a weight of 9.55 ounces per square yard available commercially as Burlington Industries glass cloth No. 7500, a 42 × 32 weave of 0.0070 inch thickness and 5.95 ounces per square yard weight available commercially as Burlington Industries glass cloth No. 1528, and a glass cloth off weave 32 × 29, 0.0060 inch thickness, and 4.90 ounces per square yard weight available as Burlington Industries glass cloth No. 1510.

For any given forging, it is possible without undue experimentation to arrive at a proper amount of insulation for reducing oil canning while nevertheless obtaining sufficiently high mechanical properties, for example, yield strength. However, choice of the correct amount of insulation can be helped by engineering analysis as follows, according to another feature of the present invention.

C. Analysis

One first chooses a yield strength σ which he is willing to accept for a web section of a forging. A suitable quench to achieve this yield strength is determined by use of the following equations:

$$\sigma = \sigma_{max} \exp[\ln \sigma_x / \sigma_{max} \tau] \quad (1)$$

$$\tau = \int_{t_0}^{t_f} \frac{dt}{C_{\tau_x}(T)} \quad (2)$$

These equations and their use will become clear from the following discussion of their theory.

C.1. Theory

This theory is taken from work of J. T. Staley and J. W. Evancho.

By considering kinetics of precipitation it is possible to predict more accurately the effects of precipitation during the quench on properties, regardless of the shape of the cooling curve. Isothermal precipitation kinetics for aluminum alloys are defined by the equation:

$$\zeta = 1 - \exp(-t/k), \quad (3)$$

where

ζ = fraction transformed,

k = temperature dependent constant which is proportional to the time required to precipitate a constant amount of solute,

t = time.

The value of the constant k , and hence precipitation rate, depends principally on the degree of supersaturation and the rate of diffusion. It can be estimated using a reciprocal form of an equation describing nucleation rate that:

$$k = C_t/K_1 = K_2 \exp(K_3 K_4^2)/RT(K_4 - T)^2 \exp K_5/RT, \quad (4)$$

where

C_t = critical time required to precipitate a constant amount (the locus of the critical times is the C-curve),

K_1 = constant which equals the natural logarithm of the fraction untransformed ($1 - \text{fraction defined by the C-curve}$),

K_2 = constant related to the reciprocal of the number of nucleation sites,

K_3 = constant related to the energy required to form a nucleus,

K_4 = constant related to the solvus temperature,

K_5 = constant related to the activation energy for diffusion,

R = gas constant, $8.3143 \text{ J} \cdot \text{K}^{-1} \cdot \text{mol}^{-1}$,

T = temperature degrees K.

See J. W. Cahn, *Acta. Met.*, 1956, V. 4, pp. 449-457.

Consequently, equation (3) can be rewritten as:

$$\zeta = 1 - \exp(K_1 t/C_t) \quad (5)$$

Using this model for isothermal precipitation, fraction of solute precipitated during the quench can be calculated. Cahn has shown, for transformations where reaction rate is a function only of the amount transformed and temperature, that a measure of the amount transformed during continuous cooling is given by the integral:

$$\int_{t_0}^{t_f} \frac{dt}{C_t(T)} = \tau, \quad (6)$$

where

τ = quench factor,

t = time from the cooling curve,

t_0 = time at the start of the quench,

t_f = time at the end of the quench,

$C_t(T)$ = critical time from the C-curve.

See J. W. Cahn, *Acta. Met.*, 1956, V. 4, pp. 572-575.

Precipitation kinetics on continuous cooling, therefore, can be expressed by the equation:

$$\zeta = 1 - \exp(K_1 \tau), \quad (7)$$

where τ substitutes for t/C_t in equation (5). When $\tau = 1$, the fraction transformed, ζ , equals the fraction transformed designated by the C-curve.

To predict yield strength, some knowledge of the relationship between extent of precipitation and loss in ability to develop property is required. Because attainable strength of precipitation-hardenable aluminum alloys is a function of the amount of solute remaining in solid solution after the quench, equation (3) can be expressed

$$\sigma - \sigma_{min} / \sigma_{max} - \sigma_{min} = \exp(-t/k) \quad (8)$$

where

σ = yield strength attained,

σ_{min} = annealed yield strength,

σ_{max} = maximum yield strength.

For high strength alloys, $\sigma_{min} \ll \sigma_{max}$, so equation (8) can be approximated by:

$$\sigma/\sigma_{max} = \exp(-t/k) \quad 9.$$

By substituting the term σ/σ_{max} for $(1-\zeta)$ in equation (7), relationships between the yield strength attainable after continuous cooling, σ , and quench factor, τ , can be expressed as follows:

$$\sigma = \sigma_{max} \exp(K_1 \tau) \quad 10.$$

where

σ_{max} = yield strength attainable with infinite quench rate,

$$K_1 = \ln \sigma_x / \sigma_{max},$$

σ_x = yield strength represented by the C-curve, and

$$\tau = \int_{t_0}^{t_f} \frac{dt}{C_{\sigma_x}(T)}, \quad (11)$$

where

t = time

$C_{\sigma_x}(T)$ = the C-curve for σ_x , i.e., critical time as a function of temperature in °Kelvin to reduce attainable strength to σ_x ,

t_0 = time at the start of the quench.

t_f = time at the end of the quench.

C-curves for yield strength can be determined from interrupted quench data using graphical analyses, but graphical methods suffer from the disadvantage that effects of precipitation during the quench to the intermediate temperature and from the holding temperature to room temperature are ignored. To eliminate this deficiency, a new method of determining C-curves from data obtained by either isothermal or nonisothermal precipitation was developed by Staley and Evancho. Using an iterative procedure, constants in the C-curve equation are determined to provide the best fit of the data to equation (10).

Thus, after Cahn, Acta. Met., 1956, Vol. 4, pp. 449-457, the C-curve is expressed as a form of Becker's nucleation equation:

$$C_{\sigma_x} = K_1 K_2 \exp(K_3 K_4^2) / RT (K_4 - T)^2 \exp K_5 / RT \quad (12)$$

where

$$K_1 = \ln(\sigma_x / \sigma_{max})$$

K_2, K_3, K_4 , and K_5 = constants

R = gas constant, 1.9872 cal/mole/°K

T = temperature in degrees Kelvin.

The values of the constants K_2 through K_5 may be determined empirically using the following steps:

1. Quench samples from the solution heat treatment temperature using techniques which provide a wide range in strength and apply appropriate precipitation heat treatment.

2. Determine either strength or hardness.

3. Select an arbitrary value for σ_x / σ_{max} .

4. Hypothesize values for K_2 through K_5 .

5. Calculate quench factor τ for each sample making use of the quench curves, i.e., sample temperature as a function of time, occurring in step 1.

6. Fit data to $\sigma = \sigma_{max} \exp[\ln(\sigma_x / \sigma_{max}) \tau]$ and determine residual errors.

7. Square the errors and sum.

8. Repeat steps 3-7 until the sum of the squared errors is minimized.

The C-curve calculated is for the property level selected in step 3.

A computer program may be written to do the calculations. The ratio σ_x / σ_{max} , time-temperature data and property for each sample, and candidate values for $K_2 \dots K_5$ are input. A quench factor τ for each sample is calculated, and regression and error analyses are made. Using the technique of pattern search, new constants are selected until the sum of the squared residuals is minimized. See D. J. Wilde, *Optimum Seeking Methods*, p. 145, Prentice-Hall Inc., Englewood Cliffs, New Jersey, 1964. Constants $K_2 \dots K_5$ and σ_{max} are output.

Staley and Evancho have applied the interrupted quenching data of Fink and Willey, *Trans. AIME*, 1948, Vol. 175, pp. 414-427, to determine C-curves for the strength of 7075-T6 sheet. The obtained C-curve for yield strength is given by the equation:

$$C_{\sigma_x} = -\ln(\sigma_x / \sigma_{max}) \frac{4.055 \times 10^{-13} \exp 251.2(782.7)^2 / RT_K (782.7 - T_K)^2 \exp 33,760 / RT_K}{1.9872 \text{ cal/mole/°K}} \quad (13)$$

where T_K is expressed in °K, C_{σ_x} in seconds, and $R = 1.9872$ cal/mole/°K. The quench factor τ for each sample was calculated using times C_{σ_x} given by Equation (13) when $\sigma_x / \sigma_{max} = 0.995$. Standard error of these data fitted to the equation:

$$\sigma = 72.42 \exp[0.005013 \tau]$$

was 1.2 percent, where σ is here calculated in kilopounds per square inch or ksi.

Where the material is 7075 alloy but the heat treatment conditions are not for the case of T6 sheet, but rather, for example, for the case of T73 forgings, only Equation (14) need be adjusted. The constants K_1 to K_5 remain the same. In the case of 7075-T73 aluminum forgings, σ_{max} is about 63,600 psi, so that equation (14) is altered only by having 63.6 ksi in place of 72.42 ksi.

After the constants in the C-curve are determined, predicting properties that would be developed in samples quenched in a hypothetical manner is straightforward. The quench factor τ is calculated using data taken from the postulated time-temperature curve to express equation (13) in terms of t for the evaluation of equation (2). The calculated τ is then substituted in equation (1). Conversely, given a desired yield strength for a web section, a quench factor τ appropriate to achieve the desired yield strength may be obtained from equation (14). Then, a quench required to give the appropriate quench factor τ may be selected by experiment and equation (2). In the experimentation, quench curves $T=f(t)$ are determined. For each quench curve, $C_{\sigma_x} = 0.995 \sigma_{max}(T)$ is expressed as $C(t)$. Then the integration of equation (2) is performed to see if the desired quench factor τ results.

C.2. Surface Heat Transfer Coefficient

To further facilitate determining how to achieve a desired yield strength in a web section of a forging, one may work from the Biot Modulus. The classical theory for analyzing transient heat flow in plates (one-dimensional flow) allows one to estimate the transient conditions in the webs of aluminum forgings. The pertinent equations as developed by Kruth, "Principles of Heat Transfer," Chapter IV, pp. 127-150, are:

$$\frac{T(X, t) - T_F}{T_S - T_F} = 2 \sum_{n=1}^{\infty} \exp\left(\frac{-\delta_n^2 \alpha t}{L^2}\right) \times \left(\frac{\sin \delta_n \cos(\delta_n X/L)}{\delta_n + \sin \delta_n \cos \delta_n}\right) \quad (15)$$

and

$$\delta_n \tan \delta_n = HL/C' = BI$$

where

BI = Biot's Modulus = HL/C'

α = diffusivity of the metal = C'/DS

C' = thermal conductivity of the metal

D = density of the metal

H = surface heat transfer coefficient

L = $\frac{1}{2}$ the thickness of the section (for two-sided quench)

S = specific heat of the metal

T_F = final temperature

T_S = starting temperature

$T(X,t)$ = temperature at time, t , and location, X

X = location in the web measured out from the center

δ_n = the n -th root of equation (16)

t = time after beginning of quench

If T_S is the temperature of the part at the beginning of the quench and T_F its temperature at completion of the quench, then a plot of $T(X,t)$ versus t is the quench curve of the web at distance X from the center.

For the other variables, X and L are specified. The remaining two variables C' and H are determined by fitting the equations to experimentally determined quench curves.

A computer program may be written to generate tables of $T(X,t)$ versus t , as t increases from zero. For example, time t can be incremented in 0.01, 0.10, or 1.0-sec. steps depending on the anticipated rate of quench, among other things a function of L . For each trial set of quench conditions, a table of values can be generated and plotted on translucent graph paper. The experimental quench curve is plotted the same way to the same scale. The values of X , L , T_S , T_F , S , and D used in the computation of $T(X,t)$ versus t are the same as those used for the experimental quench. Trial values for H and C' are selected. The two quench curves, i.e., the computed one and the experimental, are compared visually by laying one curve over the other. H and C' are adjusted and a new table generated and plotted until the experimental curve is duplicated as closely as possible. Special attention is given to matching the slope of the experimental curves in the region where the critical time on the C -curve is the lowest for the particular alloy of interest.

It can be shown that for any given set of quench conditions with a high BI there is a distance X for which the quench curve changes very little over a wide range of C' values. If an experimental quench curve is plotted for this value of X and an approximate value C' is used, then it is necessary to adjust trial values of only H to fit the experimental curve.

It can also be shown that for any given set of quench conditions with a high BI and a large L that the quench curve at $X = 0$ is primarily a function of diffusivity, α . The product of density, D , and specific heat, S , change very little over a wide range of temperature; therefore, the variation of α or C'/DS with temperature, is largely dependent on C' . If an experimental quench curve of a thick web, say 3 in., is plotted for $X = 0$ and an approximate value of H is used, it is necessary to adjust only trial values of C' to fit the experimental curves. Using this trial and error procedure, a large number of experimental quench curves can be fitted.

It should be noted that equations (15) and (16) assume that H and C' are constant rather than temperature dependent. C' is known to vary at least 10 percent over the quench range in the case of aluminum alloy 7075. The value of H changes during the quench as the

water at the surface of the forging begins with stable film boiling, changes to nucleate boiling, then to convection cooling. An evaluation that assumes H and C' as constants represents an approximation; but for practical application, errors as high as ± 10 percent (usually the error is lower) in these values still give usable results. There is no known general analytical solution to the differential equations that allow H and C' to be functions of temperature.

By the above-described curve comparison, it is possible to obtain values of the surface heat transfer coefficient H for the various insulating materials which are available for reducing oil canning. An exemplary table of values for H is Table I. The values of Table I were determined using 7075 aluminum alloy and a constant $C' = 92.5$ Btu/hr.ft. $^{\circ}$ F. Now, if it is desired to obtain a certain yield strength σ in a web section, equation (1) is used to determine an appropriate quench factor τ to give such a σ . Then, assuming fixed L and C' , trial values of H are selected from Table I, and equations (16), (15), (12) and (11) or (2) are used to calculate τ for the chosen H values. In going from equation (15) to equation (12) it is customary to use $T_K = 5/9[T(X,t) + 460]$, since equation (15) will ordinarily be evaluated in $^{\circ}$ Fahrenheit while equation (12) is in $^{\circ}$ Kelvin. In this manner, one can determine an appropriate H for giving the desired value of σ . Then the insulation corresponding to the determined H value is applied to the web section and the forging is solution heat treated and quenched.

Besides having the possibility of varying the surface heat transfer coefficient H , a web section can be machined to vary the web thickness and thus the value of L in Biot's Modulus.

TABLE I

APPROXIMATE AVERAGE SURFACE HEAT TRANSFER COEFFICIENT FOR QUENCH INSULATING MATERIALS

Material Description	H,	Btu
		$Ft^2 \cdot Hr \cdot F$
Johns-Manville Fireite Cement		
light coat (approx. 10 to 15 mils)	1000	
heavy coat (approx. 30 to 40 mils)	920	
Johns-Manville Fibrous Adhesive		
light coat (approx. 10 to 15 mils)	640	
heavy coat (approx. 30 to 40 mils)	220	
Burlington Industries Glass Cloth		
No. 7500, weave 16 $\times$ 14,		
.0138 in. thick, 9.55 oz. per sq yd	340	
No. 1528, weave 42 $\times$ 32,		
.0070 in. thick, 5.95 oz. per sq yd	240	
No. 1510, weave 32 $\times$ 29,		
.0060 in. thick, 4.90 oz. per sq yd	300	

C.3. Computer Program

A computer program may be written to perform the integration in equation (2) for the quench curve of equation (15). The program may proceed as follows:

1. User loads the data for the alloy and quench conditions.
2. BI is calculated and a number of roots, δ_n , are solved in equation (16). Normally, only 8 roots are used; but more may be used, if so desired. In general, more roots are required as BI increases.
3. Upper and lower temperatures are found that correspond approximately to critical times of $C_{\sigma_x} = 0.995\sigma_{max} = 10,000$ seconds.

4. The times from the beginning of quench are found for each of these upper and lower temperatures. These times are used to replace $t = 0$ and $t = \infty$ as the limits of integration in equation (2).

5. Equation (2) is integrated numerically for any value of X to calculate the quench factor τ at the chosen X value. Commonly chosen values of X are $X = L$ (surface), $X = L/2$ (midpoint) and $X = 0$ (center-point). The average quench factor may be determined by integrating equation (15) with respect to X and dividing by L to calculate the average temperature, T , through the web. The result is

$$\frac{T_t - T_F}{T_s - T_F} = 2 \sum_{n=1}^{\infty} \exp\left(\frac{-\delta_n^2 \alpha t}{L^2}\right) \frac{\sin^2 \delta_n}{\delta_n^2 + \delta_n \sin \delta_n \cos \delta_n} \quad (17)$$

This "average" quench curve, equation (17), is used together with equation (16) in equation (12) and thence in equation (2) for the average quench factor from $X = 0$ to $X = L$. According to one preferred embodiment of the invention, insulation is applied to an oil-canning-susceptible web section to an extent such that the average quench factor in the web section is greater than the average quench factor in the surrounding rib sections, i.e., the ribs quench faster, in order to reduce overall warpage in the forging.

6. The quench factor is used in equation 14 to estimate the yield strength. This program allows the mechanical properties to be calculated directly from the quench conditions.

EXAMPLES

Further illustrative of the present invention are the following examples:

EXAMPLE I

A forging, as illustrated in FIG. 2, of type 7075 aluminum alloy was subject to oil-canning when being machined to size. The forging had an overall length of 24½ inches, an overall width of 10 inches, a transverse rib 14 thickness of 1½ inches, a longitudinal rib 16 thickness of 1½ inches, and a web thickness of 0.622 inch. A yield strength of 60,000 psi in the web sections would be satisfactory. Using equation (14) adjusted for T73 heat treat conditions (i.e., $\sigma_{max} = 63.6$ ksi), it is determined that a quench factor τ of 10.55 would give a yield strength of 60,321 psi. This would be satisfactory for a web section of the forging. Next, equations (16), (15), (13), and (2) are used to determine which trial value of the Biot Modulus would give a quench factor of 10.55 at $X = 0$. Calculation using $X = 0$ is a conservative measure, because yield strength at $X = L/2$ and at $X = L$ should always be higher. With the Biot Modulus determined, suitable web thickness (2L) and average surface heat transfer coefficient (H) to give such modulus can be determined. Constants used in the various equations are: $T_s = 870^\circ\text{F}$; $T_F = 46^\circ\text{F}$; thermal conductivity $C' = 92.5$ BTU-ft/ft²-hr-°F; specific heat $S = 0.25$ BTU/lb-°F; density $D = 172.8$ lbs./cu.ft.; and diffusivity $\alpha = 2.141$ ft²/hr. It is determined that a Biot Modulus of 0.05743 would give a quench factor of 10.55 for $X = 0$; the first eight roots of δ are 0.23759, 3.15977, 6.29229, 9.43087, 12.57101, 15.71164, 18.85256, and 21.99377. Since the integration of equation (2) between $t_o = 0$ and $t_f = \text{infinity}$ would result in errors in the computer operation and is unnecessary, integration

is carried out only between the bounds $C_{log} = 11094$ seconds and 10508 seconds. The corresponding values of time t are, at a point halfway into the thickness of the web, i.e., $X = 0$, 0.579 seconds and 9.410 seconds. From Table I, an H value of 340 can be obtained by using Burlington Industries Glass Cloth No. 7500. Using this value in the formula for the Biot Modulus, it is determined that an appropriate half-thickness L would be 0.1875 inch, indicating that a web thickness of 0.375 or ¾ inch should be used. The 0.622-inch webs in this Example were therefore premachined to provide a reduced web thickness of ¾ inch. Following pre-machining, the forging was immersed in hot water to float away as much of the machining oil as possible and then dipped into a nitric acid bath to get rid of any remaining oil. For the purpose of promoting bonding between an insulating cement and the premachined webs, the forging is then roughened by immersing it in a caustic soda bath for approximately one minute. This is followed by a rinse in water and a dip into a nitric acid bath to remove smut resulting in the caustic soda bath. The caustic soda bath was a 5 percent aqueous sodium hydroxide solution at 140° to 180°F. A suitable nitric acid bath is an aqueous solution containing 60 to 70 percent by weight nitric acid; temperature is the ambient temperature. The glass cloth was cut into panels matching the dimensions of the webs. These panels were secured to both sides of each web using Fireite cement at each of the four corners of every panel. The resulting assembly is illustrated in FIG. 4, the dark patches at the corners of the glass cloth being Fireite cement which has impregnated the glass cloth. The heavier weight No. 7500 cloth used in this example has the advantage that attack on it by the sodium silicate in the cement is insignificant. The forging, insulated with glass cloth, was solution heat treated by leaving it in a furnace at 870°F overnight. The furnace heating first brought the forging to 870°F and then soaked the forging at this temperature. The quench was in a water bath at 46°F. Following this, the forging was age-hardened to the T73 condition by bringing it to 225°F in four hours and holding it at the 225°F temperature for six hours. Then the forging was brought to 350°F in four hours, followed by holding at 350°F for eight hours. The precipitation hardened forging was then machined, first to reduce the web thickness to 0.250 inch, the transverse rib 14 thickness to 0.250 inch, and the longitudinal rib thickness to 0.500 inch. Then, the web was machined incrementally first to 0.200 inch, then in steps of 40 thousandths of an inch to 0.120 inch, and finally in steps of 20 thousandths of an inch to 0.040 inch. Maximum oil-canning deflection of the webs was measured after each incremental reduction in web thickness. Results are plotted as Curves A and B in FIG. 5 for the two side webs and as Curve C in FIG. 6 for the central web. Mechanical properties also were determined using tensile specimens taken from the center of a side panel and having a tensile axis parallel to the side webs 14. The determined properties are given in Table II.

EXAMPLE II (A COMPARATIVE EXAMPLE)

For the purpose of providing a measure of the reduced oil-canning achieved according to the invention in Example I, a duplicate 7075 alloy forging was treated under exactly the same conditions as for Example I, except that (1) no insulation was used and (2) the web

thickness was 0.622 inch during quenching. The oil-canning for the side webs is illustrated by Curves D and E in FIG. 5 and for the central web by Curve F in FIG. 6. The reduced oil-canning exhibited by treatment according to Example I is clear from a comparison of Curves A, B, and C with Curves D, E, and F. The mechanical properties for this comparative example are presented in Table II. Note that the yield strength is close to the maximum of 63,600 psi.

EXAMPLE III (STANDARD MINIMUM PROPERTIES)

Standard minimum mechanical properties for forgings as in Examples I and II have been extracted from Table 15.1 in ALUMINUM STANDARDS & DATA, the Aluminum Association, 1972-1973, and are presented in Table II. It is to be noted that, despite the insulation provided in Example I, minimum mechanical properties were, nevertheless, met.

EXAMPLE IV

An aluminum alloy die forging as described in Example I was immersed in a caustic soda bath for about 5 minutes to remove the forging lubricant and to roughen the surface of the webs to promote bonding of insulation onto the webs. After rinsing, smut was removed by immersion in a nitric acid bath. The web thickness was 0.622 inch. In a potential use of the forging, a web yield strength of 58,500 psi would be acceptable. The same calculations as in Example I are gone through to give a quench factor of 16.12. This quench factor corresponds to a yield strength of 58,660 psi. Using parameters otherwise as in Example I, a Biot Modulus of 0.10506 is determined by calculation to give this quench factor of 16.12. The eight solutions of δ are: 0.31884, 3.174611, 6.29991, 9.43595, 12.57472, 15.71466, 18.85510, and 21.99592. The integration of equation (2) is carried out between $t = 0.779$ and

other areas the coating is dense enough to hide the underlying aluminum. This variation in coating thickness does not play a significant role, probably due to the high thermal conductivity of the aluminum. It will be apparent, however, that the glass cloth used in Example I has the advantage over any painted insulation coating that a uniform, reproducible insulation coating thickness is achievable. After the water forming the base of the Fibrous Adhesive was dried, the forging was solution heat treated, quenched, and age hardened to the T73 condition as explained in Example I. Machining was likewise carried out as in Example I. Maximum oil-canning deflection of the webs was measured and is presented as curves G and H in FIG. 8 for the two side webs and as curve I in FIG. 9 for the central web. Curves D, E, and F from Example II are provided in FIGS. 8 and 9 for the purpose of comparison. The reduced oil-canning obtained through insulation according to the present invention is again clear. Mechanical properties were also determined using specimens as explained in Example I. These properties are given in Table II. The yield strength σ is as desired and lies above the standard minimum properties of Example III.

Besides exhibiting reduced oil-canning, it was noted that the forging treated according to the present invention in this example exhibited a greatly reduced overall warpage as based on its total length. It is believed that this reduced large-scale warpage is promoted by the fact that the insulation on the thinner web sections allowed the thicker rib sections to quench more quickly than the web sections. Using half-thickness L equals 0.75 inch, an average heat transfer coefficient of 2,300 Btu/hr.ft².°F for bare aluminum in water, and other parameters as given in Example I yields an average (Equation 17) quench factor τ equal to 9.44 in the ribs, i.e., a value lower than the average quench factor, also 16.12, in the web of this example, indicating faster quenching.

TABLE II

MECHANICAL PROPERTIES FOR FORGINGS OF EXAMPLES				
Example		Mechanical Properties		
		Tensile Strength (ksi)	Yield Strength (ksi)	Elong. (%)
I	(Present Invention)	72.7	60.3	9.5
II	(Comparison)	71.4	63.5	5.0
III	(Standard Minimum Properties)			
	Parallel to grain flow	66.0	56.0	7.0
	Transverse to grain flow	62.0	53.0	3.0
IV	(Present Invention)	68.0	58.6	8.0

EXAMPLE V

14.269 seconds at $X = 0$. The original 0.622-inch web thickness of the forging is used to determine L , the half-thickness, and the formula for the Biot Modulus is solved to yield an average surface heat transfer coefficient H of 375 as needed in the present instance to give a web yield strength of 58,660 psi. With reference to the data of Table I, it appears that a medium coat of Fibrous Adhesive could give the desired average surface heat transfer coefficient H . A coating of this adhesive was painted onto the web sections of the forging. The appearance of the coated web sections is shown in FIG. 7. It will be noted that there is a variation in the thickness of the coating over the web sections, it being possible to see the aluminum metal in some areas while in

A forging, i.e., an airplane wing rib, made up of rib and web (numerous sizes and shapes up to about 18-inches maximum dimension) sections and having overall dimensions of 8-feet in length, 28 inches at its widest point, and 3 to 4 inches rib breadth, was treated according to the present invention for the purpose of reducing oil-canning in the web sections. After quenching, the forging was laid on a flat surface and one end of the forging purposely held flat. The other end was raised by overall warpage only about 1/16th of an inch, as compared to up to 2 inches of overall warpage which has resulted when no insulation was placed on the web sections.

It will be understood that the above description of the present invention is susceptible to various modifications, changes, and adaptations, and the same are intended to be comprehended within the meaning and range of equivalents of the appended claims.

What is claimed is:

1. A method for making a heat treated aluminum alloy forging exhibiting reduced oil-canning in oil-canning-susceptible sections, comprising the steps of bonding insulation onto both sides of an oil-canning-susceptible section of an aluminum alloy forging with a bonding means for maintaining a bond during heating for solution heat treatment, solution heat treating the thus-insulated forging, and, with the insulation still on said section, subjecting the solution heat treated forging to a quench for maintaining precipitable components of the alloy in solution in the oil-canning-susceptible section, whereby, upon machining, said section will exhibit reduced oil-canning.

2. A method as claimed in claim 1, wherein the thickness of said section, $2L$, and the surface heat transfer coefficient H of the insulation are related to the desired yield strength σ of said section according to the following equations:

$$\delta_n \tan \delta_n = HL/C', \quad (16)$$

$$\frac{T(X, t) - T_F}{T_S - T_F} = 2 \sum_{n=1}^{\infty} \exp \left(\frac{-\delta_n^2 \alpha t}{L^2} \right) \times \left(\frac{\sin \delta_n \cos (\delta_n X/L)}{\delta_n + \sin \delta_n \cos \delta_n} \right), \quad (15)$$

$$\tau = \int_{t_0}^{t_f} \frac{dt}{C_{\sigma_x}(T)}, \quad (2)$$

$$\frac{C_{\sigma_x}}{\sigma} = K_1 K_2 \exp K_3 K_4 / RT_K (K_4 - T_K) \exp K_5 / RT_K \quad (12)$$

where

δ_n = the n -th root of equation (16)

H = surface heat transfer coefficient

L = $1/2$ the thickness of the section

C' = thermal conductivity of the alloy

$T(X, t)$ = temperature at time t and location X

X = location in the web measured out from the center

t = time

T_F = final temperature

T_S = starting temperature

α = diffusivity of the alloy = C'/DS

D = density of the alloy

S = specific heat of the alloy

$C_{\sigma_x}(T)$ = the C-curve for σ_x , i.e., critical time as a function of temperature to reduce obtainable strength to σ_x

τ = quench factor

K_1, K_2, K_3, K_4 , and K_5 = constants

R = gas constant

T_K = temperature in degrees Kelvin

σ_{max} = maximum yield strength

σ_x = yield strength represented by equation (12).

3. A method as claimed in claim 2, wherein the average quench factor of sections surrounding said oil-canning-susceptible section are less than the average quench factor for said oil-canning-susceptible section, average quench factors being determined by the

following equations:

$$\delta_n \tan \delta_n = HL/C' \quad (16)$$

$$\frac{T_t - T_F}{T_S - T_F} = 2 \sum_{n=1}^{\infty} \exp \left(\frac{-\delta_n^2 \alpha t}{L^2} \right) \frac{\sin^2 \delta_n}{\delta_n^2 + \delta_n \sin \delta_n \cos \delta_n}, \quad (17)$$

$$\tau = \int_{t_0}^{t_f} \frac{dt}{C_{\sigma_x}(T)}, \quad (2)$$

$$C_{\sigma_x} = K_1 K_2 \exp K_3 K_4 / RT_K (K_4 - T_K) \exp K_5 / RT_K \quad (12)$$

where

δ_n = the n -th root of equation (16)

H = surface heat transfer coefficient

L = $1/2$ the thickness of the particular section being considered

C' = thermal conductivity of the alloy

T_t = temperature at time t

t = time

T_F = final temperature

T_S = starting temperature

α = diffusivity of the alloy = C'/DS

D = density of the alloy

S = specific heat of the alloy

$C_{\sigma_x}(T)$ = the C-curve for σ_x , i.e., critical time as a function of temperature to reduce obtainable strength to σ_x

τ = quench factor

K_1, K_2, K_3, K_4 , and K_5 = constants

R = gas constant

T_K = temperature in degrees Kelvin.

4. A method as claimed in claim 1 wherein said insulation results, during the quench, in the cooling of sections surrounding said oil-canning-susceptible section faster than said oil-canning-susceptible section.

5. A method as claimed in claim 1, further comprising a preliminary step of machining said oil-canning-susceptible section, the preliminary step of machining being performed before the step of bonding.

6. A method as claimed in claim 1, further comprising roughening the surface of said oil-canning-susceptible section before the step of bonding.

7. A method as claimed in claim 1, wherein said insulation and bonding means is, on a dry weight basis, 80 percent sodium silicate and 20 percent asbestos fiber shorts.

8. A method as claimed in claim 1, wherein said insulation is glass cloth.

9. A method as claimed in claim 1, further comprising, subsequent to quenching, machining said oil-canning-susceptible section.

10. A method as claimed in claim 9, further comprising, following the step of quenching, age-hardening the forging.

11. A method as claimed in claim 10, wherein the step of age-hardening is carried out before the step of machining subsequent to quenching.

12. A method as claimed in claim 10, wherein the forging has in said oil-canning-susceptible section, following the step of age-hardening, a yield strength equal to or greater than 56,000 psi.

* * * * *

UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,850,705 Dated November 26, 1974

Inventor(s) Charles P. Furney, Jr. et al

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Col. 3, line 32 After "cloth" change "off"
to --of--.

Col. 4, line 20 Change "K₂" to --K₃--.

Col. 6, line 23 After the equation insert
--(14)--.

Claim 2,
Col. 13, line 35 Change

$$"C_{\sigma_x} = K_1 K_2 \exp K_3 K_4 / RT_K (K_4 - T_K) \exp K_5 / RT_K \quad 12."$$

to

$$--C_{\sigma_x} = K_1 K_2 \exp \frac{K_3 K_4^2}{RT_K (K_4 - T_K)} \exp \frac{K_5}{RT_K} , \quad (12)--.$$

Claim 3,
Col. 14, line 26 Change " δ_x " to -- σ_x --.

Claim 3,
Col. 14, line 28 Change " δ_x " to -- σ_x --.

Signed and sealed this 8th day of April 1975.

(SEAL)
Attest:

RUTH C. MASON
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents
and Trademarks