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3,407,637

ELECTRODYNAMIC METHOD FOR FORMING METALLIC WORKPIECES

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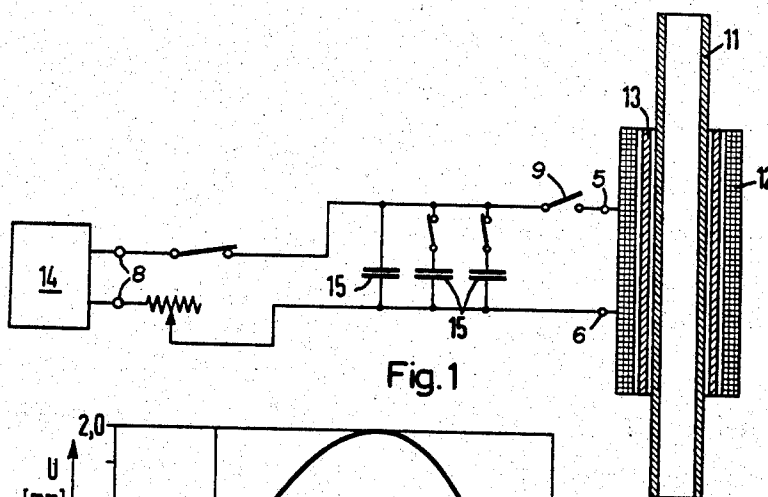


Fig. 1

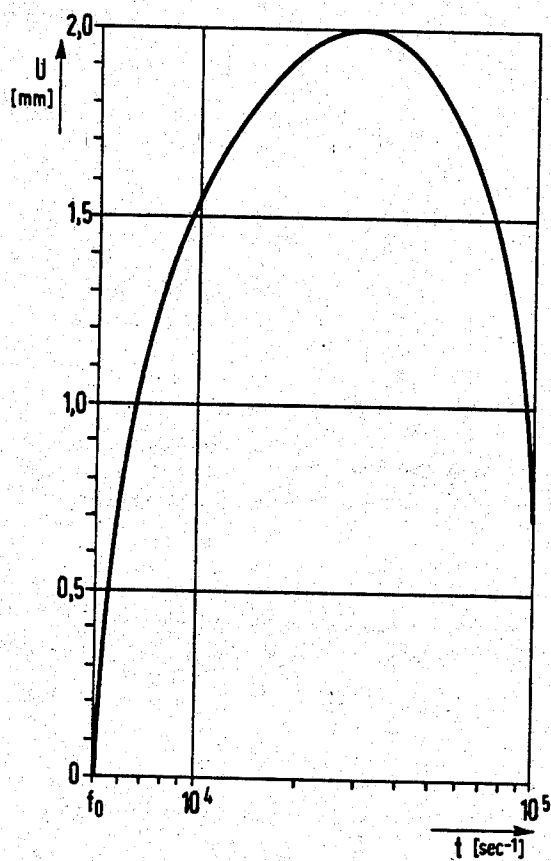


Fig. 2

1

3,407,637

ELECTRODYNAMIC METHOD FOR FORMING METALLIC WORKPIECES

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ABSTRACT OF THE DISCLOSURE

Improvement in method of electrodynamically forming solid metallic workpieces by magnetic field pulses produced by shock discharge of capacitance means in a discharge circuit containing a work coil which induces eddy currents in the workpiece includes measuring, for a given workpiece and a given total forming energy, the amount of forming travel in dependence upon the frequency of the discharge current; and setting the discharge-circuit parameters in accordance with the resulting optimal frequency, whereby the electrodynamic forming of corresponding workpieces is effected with optimal forming efficiency and minimal energy consumption.

Our invention relates to an electrodynamic method for forming metallic workpieces.

During the recent past there have been developed new methods of metal forming which afford a greatly higher forming speed than the conventional mechanical fabricating methods. In many cases these high-speed forming methods have also permitted simplifying and improving various manufacturing operations, and it has become possible to apply forming processes to materials which in the conventional manner can be worked only with difficulty. Among the high-speed forming methods are the explosive forming technique, the hydrospark method and the magnetic-pulse forming method.

The magnetic-pulse forming method, known for example from U.S. Patent 2,976,907 and German Patent 1,122,188, operates with work coils acting as compression coils, expansion coils or flat (drawing) coils. According to this method, a capacitor is discharged through the work coil. The alternating current thus resulting in the oscillatory discharging circuit produces a variable magnetic coil field which induces eddy currents in a metallic workpiece mounted in the interior space of the coil. The force generated between the magnetic field and the eddy currents, this force being the so-called Maxwell pressure, is available for the desired deformation of the workpiece and may amount to several 1000 kp./cm.² at forming speeds up to several 100 m./sec.

During compression of cylindrical metal bodies with the aid of the magnetic-pulse forming method just described, a high-intensity magnetic field of several 100,000 gauss is being built up for short intervals of time in the space between the work coil and the workpiece. Due to the skin effect, resulting from the pulse character and high frequency of the magnetic field, the interior of the workpiece remains free of field effects. Consequently, there occurs a unilateral magnetic compressive force which causes a permanent deformation of the workpiece if the elastic limit of the workpiece material is exceeded. The difference between the magnetic pressure and the counter pressure of the material corresponding to the tension at the elastic limit, causes an acceleration of the workpiece. Assuming that the workpiece is tubular, the tubular wall thus being accelerated may be caused to hit upon a mandrel so that the desired formation is produced in this

2

manner. If no mandrel or other abutment is employed, the free deformation comes to a standstill when the kinetic energy is just consumed by the forming work done. The forming travel traversed during free forming of the latter type is a measure of the forming action.

The following method has so far been employed for forming thick-walled workpieces or workpieces having poor electric conductivity. While maintaining the discharging frequency of the shock-current capacitor unchanged, or while decreasing this discharging frequency, the energy of the discharge has been increased by correspondingly increasing the capacitance of the capacitor. This method requires using large capacitor batteries which must be connected through several cables with the work coil. Such equipment is difficult to handle in industrial manufacturing processes and also exhibits a very poor degree of efficiency. In order to afford forming poorly conducting workpieces although operating at low discharge frequencies, resort has heretofore been taken to the provision of so-called driver layers. These are envelope layers which surround the workpiece and consist of good conducting material so that eddy currents are induced in the driver layers and the resulting forces are transmitted to the workpiece. The equipment of this type as heretofore available is excessively expensive and difficult to apply.

It is an object of our invention to overcome or greatly minimize the above-described difficulties and disadvantages of the magnetic-pulse forming method and to further improve this method so that it will operate for various problems encountered, with optimal efficiency and minimal energy consumption for the particular forming process involved.

To this end, and in accordance with our invention, we take advantage of our discovery that for each given amount of forming energy there exists an optimal frequency at which the forming travel has a pronounced maximum. This can be explained by the observation that, although the magnetic pressure increases with increasing frequency, this pressure tends to approach a limit value, whereas the interval of time during which the pressure remains effective upon a workpiece decreases in inverse proportion with the frequency. It follows that there exists a singular frequency at which the forming process can be performed at optimal efficiency and minimal energy consumption. This, accordingly, constitutes the essence as well as the main advantage achieved by the present invention.

Our invention, therefore, resides in a method for the electrodynamic forming of solid metallic workpieces with the aid of magnetic pulse fields which are produced by capacitive shock discharge in a work coil and induce eddy currents in a fixedly mounted workpiece. According to the invention, the desired optimal efficiency and minimal energy consumption of the forming process is achieved by adapting, for a given total energy, the frequency of the magnetic field, by correspondingly rating the discharge-circuit parameters, to the particular forming problem to be solved, namely to the geometric relations and material properties of the workpiece. More specifically, we first measure for a given workpiece and a given total forming energy the amount of forming travel versus the frequency of the discharge current by testing of sample workpieces. In this manner we obtain from the resulting travel-to-frequency characteristic an optimal value of frequency. Thereafter we perform the forming operations on other workpieces of the series by setting the parameters of the discharge circuit in accordance with the optimal frequency previously determined, whereby, as explained above, the forming of the workpieces is effected with optimal forming efficiency and minimal energy consumption.

A particular advantage of the invention resides in the fact that the choice of the optimal frequency for a pre-

3

determined fabricating operation causes the total energy consumption to be lowered. This, in turn, affords either increasing the forming operations per unit time, or reducing the amount of cooling that must be applied to the work coil.

In further explanation of the term "optimal frequency," the following is stated.

The forming travel u depends upon the active pressure p_w and upon the duration T of the pressure effect. The duration T is inversely proportional to the frequency of the magnetic field, hence $T \sim 1/f$. The forming travel u increases with the active pressure p_w and also increases with the duration T of the force effect.

The pressure p_w comes about by the pressure of the magnetic field. The force effect of the magnetic field increases with a reduction in volumetric space over which the capacitor energy must be distributed. This volume is determined by the geometry of the arrangement, also by the width of the air gaps between work coil, field concentrators and workpiece, and also by the penetrating depth of the eddy currents in the workpiece, coil and concentrator. The penetrating depth of the eddy currents is in accordance with the following equation:

$$s = \frac{1}{\sqrt{\pi \cdot \mu_0 \cdot f \cdot \mathcal{H}}} \quad (1)$$

wherein:

s = penetrating depth of the eddy currents in the work-piece

$$f = \frac{1}{2\pi\sqrt{L \cdot C}} =$$

frequency of the magnetic field

$\mathcal{H}$ = specific electric conductivity of the workpiece material

μ_0 = magnetic permeability of vacuum

Furthermore, the active pressure p_w is determined in first approximation by:

$$p_w \sim \frac{W_g}{\delta_0 + s} \quad (2)$$

wherein:

$W_g = \frac{1}{2}CU^2$ = total energy

δ_0 = width of the air gap

s = penetrating depth of the eddy currents in the work-piece.

Equation 1 shows that the penetrating depth of the eddy currents decreases with increasing frequency f . This means, in view of Equation 2, that p_w increases with increasing f . However, it will be understood that at high frequencies, that is for very small values of s , the magnitude δ_0 becomes a determining criterion and hence that p_w increases only slowly. It follows therefrom that p_w increases greatly with f at low frequencies, but increases only slightly with f at high frequencies. The duration T decreases with the frequency f . Since the degree of formation depends upon the product of effective pressure times forming duration, the described frequency dependency of both magnitudes results in the existence of an optimal frequency at which the forming travel for a given geometry of the arrangement, a given material of the workpiece and a given total energy W_g , exhibits a maximum. This is tantamount to the fact that any change in frequency relative to the optimal frequency f_{opt} always results in a reduction in forming travel u , irrespective of whether the frequency is increased or reduced. For a predetermined total energy $W_g = \frac{1}{2}CU^2$, the values of U and C are to be so dimensioned that on the one hand the value W_g is satisfied and, on the other hand

$$f = \frac{1}{2\pi\sqrt{L \cdot C}} = f_{out}$$

The conditions or circuit parameters at which the optimal

4

frequency value f_{opt} will obtain, can be readily determined by a few sample tests.

The invention will be further elucidated with reference to an embodiment for forming equipment illustrated on the drawing and with reference to a specific example of performing the method. On the drawing:

FIG. 1 shows schematically a compression coil with a field concentrator for forming a workpiece; and

FIG. 2 shows a forming travel versus frequency characteristic prepared according to the invention and used for correspondingly rating the electrical parameters of equipment as shown in FIG. 1.

Referring to FIG. 1, there is schematically shown a magnetic-pulse forming apparatus of the type known from the above-mentioned patents. A compression coil 12 serves for producing a constriction in a tubular workpiece 11. The axial length of the workpiece portion to be formed is determined by the adjacent area of an annular field concentrator 13 seated in the central opening of the coil and surrounding the workpiece 11 with a narrow air gap. The terminals 5 and 6 of the work coil are connected to a capacitor, such as a battery of shock-current capacitors 15 which are charged at terminals 8 from a source 14 of high direct voltage. The charged capacitor is discharged upon closing of an electronic switch here schematically represented at 9. The shock current then flowing through the discharge circuit has the character of a high-frequency alternating current due to the oscillatory character of the circuit.

The following specific example is intended to show how in practice the components or parameters of the forming equipment are to be dimensioned in order to perform the process with optimal efficiency in accordance with the present invention.

A tubular workpiece of steel having an elastic limit $\sigma_d = 70$ kp./mm.², a length $L = 7$ cm., a diameter $D = 3$ cm. and a wall thickness $\delta = 0.1$ cm. is to be compressed in a compression coil having an inductivity $L' = 0.68$ μ h. and having $n = 8$ turns. The forming travel or amount of compression is to be approximately 2 mm. The specific electrical conductivity $\mathcal{H}$ of the steel is $\frac{1}{16}$ of that of copper ($\mathcal{H}_{Cu} = 5.56 \cdot 10^8$ a./v. cm.). Used as field concentrator is a copper-beryllium tube having a radial thickness of 1.5 cm. The median radial air gap δ_R between compression coil, field concentrator and steel tube is 0.1 cm. The total energy W_g to be converted into forming work is to be 25 kws. Available for charging the capacitor is a voltage source furnishing 40 kv. maximal voltage.

Using a test specimen of the workpieces to be formed, capacitors (15 in FIG. 1) of respectively different capacitance are employed for performing a number of tests, in each case observing the condition $W_g = \frac{1}{2}CU^2 = 25$ kws.

FIG. 2 graphically represents the result of the tests made for the forming problem stated in the foregoing. Indicated along the abscissa is the discharging frequency f in c.p.s., and on the ordinate the forming travel u in mm. The curve shows that the maximal forming travel of slightly more than 2 mm. is obtained at a frequency of $3 \cdot 10^4$ c.p.s. The optimal discharging frequency f_{opt} in the present example, therefore, is equal to $3 \cdot 10^4$ c.p.s. This frequency corresponds to a charging capacitor or battery having a total capacitance $C = 40$ μ f. and a charging voltage of 35 kv.

Exchangeable capacitors of respectively different capacitance, or a capacitor battery with tap contacts and a selector switch for changing the effective total capacitance in the discharge circuit may be used for performing the sample tests. Once the optimal frequency is determined, the equipment can be readily set, with the aid of a suitable rated total capacitance or other frequency-depending circuit components, to achieve the desired maximal efficiency when performing the forming operations with a series of other workpieces corresponding to the one initially tested.

Upon a study of this disclosure it will be obvious to those skilled in the art that the invention is not limited to any details of the particular magnetic-pulse forming

5

equipment being used and hence can be reduced to practice with embodiments of equipment other than particularly illustrated and described herein, without departing from the essential features of the invention and within the scope of the claims annexed hereto.

We claim:

1. In the method of electrodynamically forming solid metallic workpieces by magnetic field pulses produced by shock discharge of capacitance means in a discharge circuit containing a work coil which induces eddy currents in the workpiece, the improvement which comprises measuring, for a given workpiece and a given total forming energy, the amount of forming travel in dependence upon the frequency of the discharge current; and setting the discharge-circuit parameters in accordance with the resulting optimal frequency, whereby the electrodynamic forming of corresponding workpieces is effected with optimal forming efficiency and minimal energy consumption.

2. The forming method according to claim 1, wherein

6

said measuring of forming travel in dependence upon frequency is effected by repeatedly subjecting test specimens to said given amount of forming energy, and changing only the capacitance of the capacitance means in the discharge circuit to thereby vary the frequency of the discharge current, whereafter other workpieces corresponding to the test specimens are subjected to forming by the same amount of energy and at the optimal frequency resulting from the specimen tests.

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