

板坯电磁成形载荷计算方法及分布特性^①

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摘 要 用平面螺旋和多叠式线圈加工平板毛坯是电磁成形的一种基本方式, 其理论研究包括电路分析和动态变形分析两个方面, 其中电路分析的目的是确定作用在工件上的脉冲电磁力, 并用于变形分析。通过分析板坯电磁成形中工作线圈在强脉冲电流激励下的动态响应过程, 建立了线圈磁场、工件表面感应涡流及磁场的计算公式, 给出了成形载荷的计算方法。通过数值分析讨论了载荷的分布特性, 数值求解结果与相关实验研究结论一致。将成形载荷数值求解结果用于变形分析时, 成功地预测了铝板毛坯的自由胀形过程。

关键词 板坯 电磁成形 载荷

中图法分类号 TG391

电磁成形是将强脉冲电磁力作用于金属毛坯使其产生塑性变形的一种高能率成形新工艺, 具有生产率高、工艺重复性好、工装简单等一系列优点, 因而倍受塑性加工界重视。脉冲电磁力的计算是变形分析和数值模拟、优化力能及工艺参数的基础。对管状毛坯电磁成形的载荷, 国内外已有较深入的研究^[1-5], 人们能够用塑性动力有限元方法对其成形过程进行数值模拟^[6-8], 目前管坯电磁成形已从定性分析发展到定量研究阶段。

相比之下, 有关板状毛坯电磁成形载荷的研究尚少, 仅日本的 Negishi^[9] 和前苏联 Скрипниченко 等人^[10] 对其磁场分布作过一些实验研究。人们对板状毛坯电磁成形载荷分布规律的认识仍处于实验研究和定性分析阶段, 尚不能对板坯电磁成形进行客观的理论分析和实用的工艺计算。为此, 本文对工作线圈在强脉冲电流激励下的磁场、平板毛坯表面感应涡流及磁场的分布规律进行了研究, 建立了成形载荷的计算公式。

1 工作线圈磁场计算

板坯电磁成形时, 常用线圈结构如图 1(a) 和(b) 所示, 其中多叠式线圈由多个平面螺旋线圈组成。为简化计算, 将图 1(a) 所示螺旋线圈按周长相等原则近似处理为图 1(c) 所示同心圆形式。简化前后线圈中心线的方程为

$$\begin{cases} \rho = \rho_0 + \frac{a+b}{2\pi} \theta & (\theta \in [0, 2n\pi]) \\ R_j = \rho_0 + (a+b)(j-0.5) & (j = 1, 2, \dots, n) \end{cases} \quad e i$$

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式中 ρ_0 为简化前第一匝(从内向外)线圈中心线起点至圆心距离。

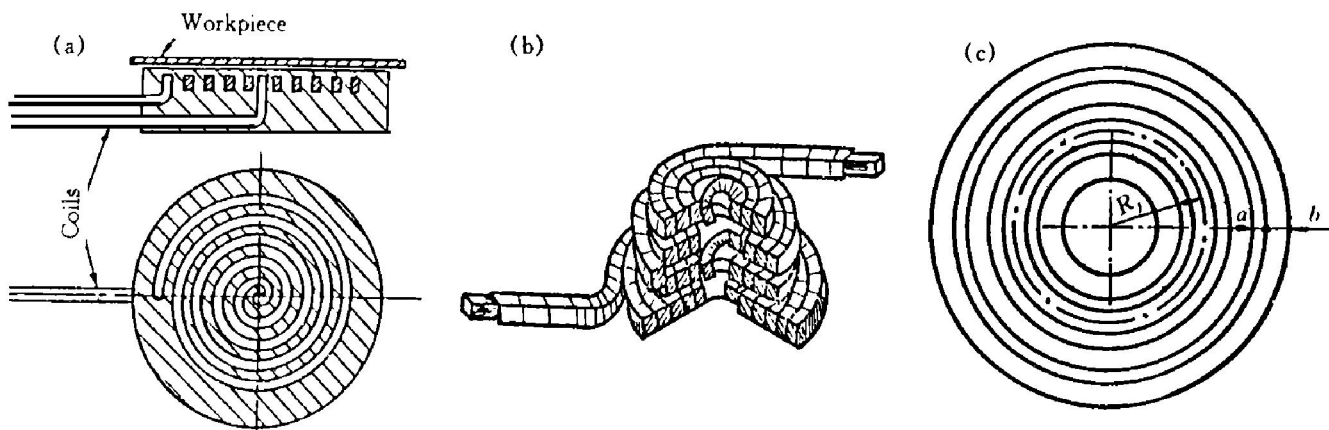


图1 板坯电磁成形常用线圈结构及简化处理

Fig. 1 Types of coils used in sheet metal electromagnetic forming and their simplifications

(a) —Flat spiral coil; (b) —Multiply coil; (c) —Simplified coil

简化后的线圈由 n 匝空心圆柱线圈组成, 根据毕-萨定理和叠加原理^[11] 可得:

$$B_k(r, z) = \sum_{j=1}^n \frac{\mu_0}{2\pi} \int_0^\pi d\alpha \int_{R_j - b/2}^{R_j + b/2} d\rho \int_{-\delta/2}^{\delta/2} J \cdot A_k d\tau \quad (k = r, z) \quad (1)$$

$$J = \begin{cases} \frac{i}{b\delta} & (|\tau| \leq \delta/2, |\rho - R_j| \leq b/2, \Delta = \min(b/2 - \delta_0, \delta/2 - \delta_0) \leq 0) \\ \frac{i}{2\delta_0(b + \delta - 2\delta_0)} & (\delta/2 \geq |\tau| \geq \delta/2 - \delta_0, b/2 \geq |\rho - R_j| \geq b/2 - \delta_0, \Delta > 0) \\ 0 & (|\tau| < \delta/2 - \delta_0, |\rho - R_j| < b/2 - \delta_0, \Delta > 0) \end{cases}$$

形式

$$A_r = \frac{\rho(z - \tau) \cos \alpha}{[(z - \tau)^2 + r^2 + \rho^2 - 2r\rho \cos \alpha]^{3/2}}$$

$$A_z = \frac{\rho(\rho - r \cos \alpha)}{[(z - \tau)^2 + r^2 + \rho^2 - 2r\rho \cos \alpha]^{3/2}}$$

$$\delta_0 = \sqrt{\frac{2}{\mu_0 \sigma \omega}}$$

将 J 的表达式代入式(1)得

$$B_k(r, z) = \frac{\mu_0 i}{2\pi} f_k(r, z) \quad (k = r, z) \quad (2)$$

式中

$$f_k(r, z) = \begin{cases} \frac{G_k(b/2, \delta/2) - G_k(b/2 - \delta_0, \delta/2 - \delta_0)}{2\delta_0(b + \delta - 2\delta_0)} & (\Delta > 0, k = r, z) \\ G_k(b/2, \delta/2)/(b\delta) & (\Delta \leq 0, k = r, z) \end{cases}$$

$$G_k(x, y) = \sum_{j=1}^n \int_0^\pi d\alpha \int_{R_j - x}^{R_j + x} d\rho \int_{-y}^y A_k d\tau \quad (k = r, z)$$

2 成形载荷、感应涡流及其磁场的计算

板坯电磁成形原理如图2所示。当高压开关闭合时, 储能电容对工作线圈放电并在其周围产生一脉冲磁场, 该磁场的轴向分量 B_z 因穿过工件平面而产生感应涡流, 感应涡流产生的磁感应强度为 B' 。放电瞬间, 在工件内部 B 与 B' 方向相反而相互削弱; 线圈与工件之间则方向相同而得到加强。密集的磁感应线具有扩张的特性, 因而工件表面各部分都受到背离线圈平面的冲击压力^[11]:

$$p = \frac{[B_r(r, d_0 + \delta/2) + B'_r(r, -\delta_0/2)]^2}{2\mu_0} \quad (3)$$

式中 $\delta_0 = \sqrt{\frac{2}{\mu' \sigma' \omega}}$

放电回路可等效为图3所示电路, 其微分方程为

$$L \frac{di}{dt} + Ri + \frac{1}{C} \int i dt + \varepsilon = 0 \quad (4)$$

根据麦克斯韦方程不难得到:

$$J' = - \frac{\sigma}{\rho} \int_0^{\rho} \frac{\partial B_z(r, d_0 + \delta/2)}{\partial t} r dr$$

$$\varepsilon = - \int_0^{2n\pi} d\theta \int_0^{\rho_0 + \frac{a+b}{2\pi}\theta} \frac{\partial B'_z(r, d_0 + \delta_0/2)}{\partial t} r dr \quad (5)$$

由式(1)可得

$$B'_k(r, z) = \frac{\mu_0}{2\pi} \int_0^{\pi} d\alpha \int_0^{R'} d\rho \int_{-\delta_0/2}^{\delta_0/2} J' A_k d\tau \quad (k = r, z) \quad \varepsilon \text{—Electromagnetic potential induced by workpiece} \quad (6)$$

将式(2), 式(6)代入式(5)得

$$J' = - \frac{di}{dt} \frac{\mu_0 \sigma}{2\pi \rho} \int_0^{\rho} f_z(r, d_0 + \delta/2) r dr \quad (7)$$

$$\varepsilon = \frac{1}{K} \frac{d^2 i}{dt^2} \quad (8)$$

式中 $\frac{1}{K} = \left(\frac{\mu_0}{2\pi}\right)^2 \sigma \int_0^{2n\pi} d\theta \int_0^{\rho_0 + \frac{a+b}{2\pi}\theta} \left\{ \int_0^{\pi} d\alpha \int_0^{R'} d\rho \int_{-\delta_0/2}^{\delta_0/2} \left[\frac{1}{\rho} \int_0^{\rho} f_z(r, d_0 + \frac{\delta}{2}) r dr \right] A_z \right|_{z=d_0 + \delta_0/2} d\tau \} r dr$

将式(8)代入式(4)并利用边界条件 $i|_{t=0} = 0$, $\frac{1}{C} \int i dt|_{t=0} = V$ 得

$$i = A_0 e^{(2\beta - KL)t} + A e^{-\beta t} \cos(\omega t + \phi) \quad (9)$$

式中 $\phi = \arctan \left[\frac{(3\beta - KL)(\beta - KL)}{2\beta\omega} + \frac{\omega}{2\beta} \right];$

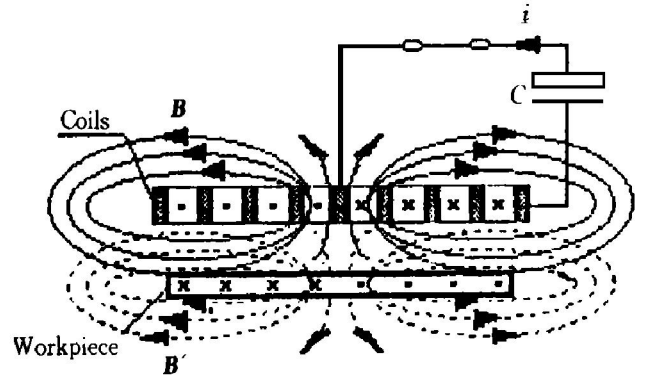


图2 板坯电磁成形原理

Fig. 2 Principle of sheet metal electromagnetic forming

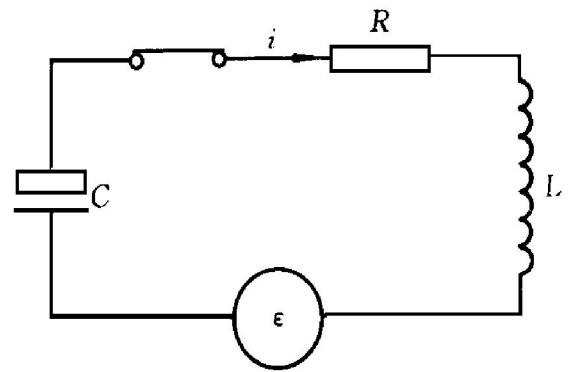


图3 放电回路等效电路

Fig. 3 Equivalent circuit of discharging loop

C—Capacitance; R—Loop resistance;

L—Loop inductance;

ε—Electromagnetic potential induced by workpiece

$$A_0 = \frac{2\beta(2\beta - KL)(\beta^2 + \omega^2)CV}{KL[(3\beta - KL)^2 + \omega^2]};$$

$$A = -\frac{(2\beta - KL)(\beta^2 + \omega^2)CV}{KL[(3\beta - KL)^2 + \omega^2]} \sqrt{4\beta^2 + [\omega + \frac{(3\beta - KL)(\beta - KL)}{\omega}]^2};$$

$$\beta = \frac{\lambda_1 + \lambda_2}{2} + \frac{KL}{3}; \quad \omega = \frac{\sqrt{3}(\lambda_1 - \lambda_2)}{2};$$

$$\lambda_{1,2} = \sqrt[3]{-\frac{K^3L^3}{27} + \frac{K^2LR}{6} - \frac{K}{2C} \pm \sqrt{(\frac{K^3L^3}{27} - \frac{K^2LR}{6} + \frac{K}{2C})^2 + (\frac{KR}{3} - \frac{K^2L^2}{9})^3}};$$

V —储能电容充电电压

3 载荷分布特性及讨论

利用式(2), (3), (6), (7), (9)即可对工件所受电磁冲击压力进行数值分析, 图4(a)是某一密绕平面螺旋线圈成形铝板时载荷沿径向的分布规律, 可见, 成形载荷在工件中心的值最小, 随半径增大, 载荷迅速增大, 在二分之一半径附近达到最大值, 此后随半径增大, 载荷单调减小。这与薄板电磁拉深试验结果是一致的, 工件中心部分往往因压力较小而贴模不良。

用ADINA软件对铝板受图4所示载荷时的自由胀形过程进行数值模拟, 结果如图5所示, 可见, 模拟结果与成形工件实测值具有较好的一致性, 模拟值比实测值略小是由于将螺旋线圈简化成轴对称结构所造成的。事实上, 因线圈存在螺旋升角, 工件中心磁感强度的水平分量(由径向和周向分量组成)不为零, 因此工件中心所受压力亦不为零, Скрипниченко等人^[10]的实验研究结果也证明了这一点。工件在变形过程中各时刻的形状与文献[12]的测试结果是一致的。在加载期间, 工件的变形很小, 因此, 载荷计算时可以忽略工件变形对放电过程的影响, 这与管坯电磁成形是不同的。

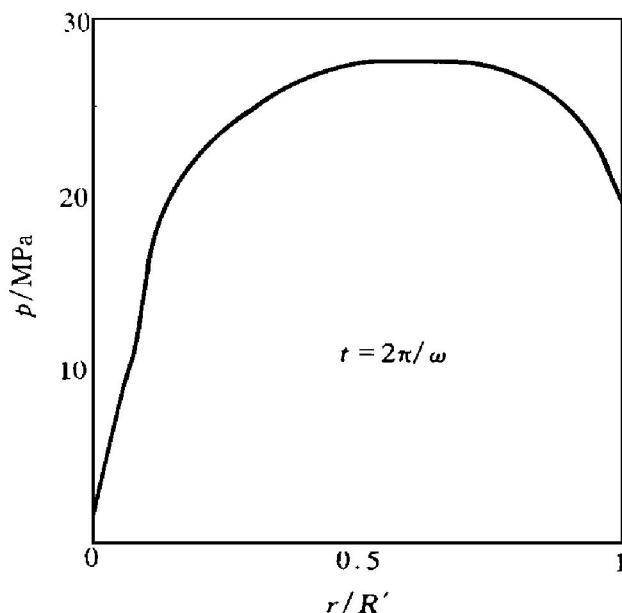


图4 磁压力径向分布

Fig. 4 Radial distribution of magnetic pressure

($d_0 = 1 \text{ mm}$, $V = 3 \text{ kV}$, $C = 390 \text{ }\mu\text{F}$,
 $L = 8.4 \text{ }\mu\text{H}$, $R' = 27 \text{ mm}$)

4 结论

- (1) 用平面螺旋线圈加工板坯时, 工件中心磁压力最小, 二分之一半径附近磁压力最大。
- (2) 载荷计算时可以不考虑工件变形对放电过程的影响, 将螺旋线圈简化为同心圆结构是可行的。
- (3) 利用本文给出的载荷计算方法, 可通过数值模拟来研究各力能参数和工艺参数对成形的影响, 为工艺设计和参数优化提供理论依据。

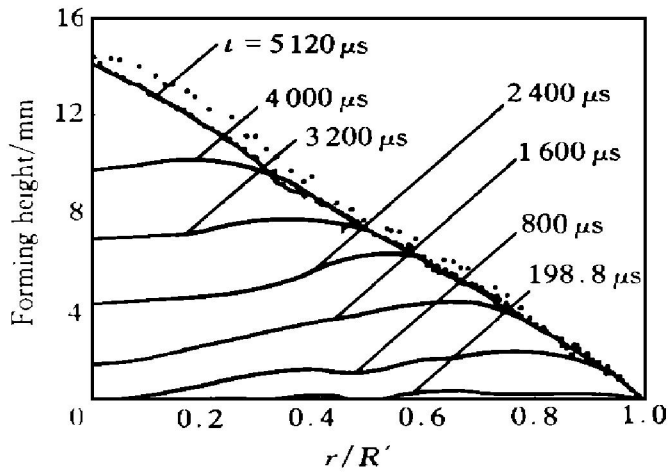


图5 铝板自由胀形过程的数值模拟

Fig. 5 Numerical simulation on free magnetic bulging process of sheet aluminium

Solid line—Calculated data;

Dotted line—Measured data

符号表

a, b —线圈匝隙距及导线径向宽度;

δ, n —线圈厚度及匝数;

i, ω —放电电流及角频率;

d_0, R' —线圈工件轴向间隙及板坯半径;

J, J' —线圈、工件电流密度;

δ_0, δ'_0 —线圈、工件电流趋肤深度;

σ, σ' —线圈、工件材料电导率;

μ_0, μ, μ' —真空、线圈及工件磁导率;

B_r, B_z, B'_r, B'_z —线圈、工件产生磁感强度的径向及轴向分量;

p —磁压力。

REFERENCES

- 1 Negishi H, Murata M, Suzuki H *et al.* Journal of JSTP, 1980, 21(234): 642– 648.
- 2 Murata M, Negishi H and Suzuki H. Journal of JSTP, 1982, 23(255): 328– 334.
- 3 Suzuki H, Negishi H, Yokouchi Y *et al.* Journal of JSTP, 1986, 27(310): 1254– 1260.
- 4 Zhang Shoubin(张守彬). PhD Dissertation, (in Chinese). Harbin Institute of Technology, 1990: 26– 29.
- 5 Song Fuming(宋福明), Wang Zhongren(王仲仁), Zhang Xu(张旭) *et al.* Journal of Plasticity Engineering(塑性工程学报), 1995, 2(3): 31– 36.
- 6 Suzuki H, Yokouchi Y, Murata M *et al.* In: The Organizing Committee of the First International Conference on Technology of Plasticity eds, Advanced Technology of Plasticity: Vol I. Tokyo: The Japanese Society for Technology of Plasticity and the Japan Society of Precision Engineering, 1984: 367– 372.
- 7 Murata M, Zhang Hai, Yokouchi Y *et al.* In: Wang Yungan, Zou Shineng and Li Congxin eds, Proc of Int Conf on Advanced Technology and Machinery in Metal Forming. Wuhan: Huazhong University of Science and Technology Press, 1992: 216– 229.
- 8 Min D-K and Kim D-W. Journal of Materials Processing Technology, 1993, 38: 29– 40.
- 9 Negishi H, Suzuki H and Maeda T. Journal of JSTP, 1977, 18(192): 16– 21.
- 10 Selipnichenco A L and Yascovich A G. Impulse Methods of Metal Forming. Moscow: Science and Technology Press, 1979: 61– 65.
- 11 Lei Yinzhao(雷银照). Calculation of Magnetic Fields of Axial Symmetry Coils(轴对称线圈磁场计算). Beijing: China Measurement Press, 1991: 106– 109.
- 12 Negishi H, Suzuki H and Maeda T. Journal of JSTP, 1977, 18(194): 197– 203.

CALCULATION AND DISTRIBUTION OF FORMING LOAD FOR SHEET METAL MAGNETIC FORMING

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ABSTRACT To form flat workpiece by the flat spiral coil or conical coil is a typical method of magnetic forming. The analysis of the forming processes consists of the analysis of the electric circuit and the dynamic deformation of the workpiece. The purpose of the electric circuit analysis is to calculate the impulsive magnetic pressure and to apply it to the deformation analysis. By analysing the dynamic response of the coil-workpiece system while the working coil being stimulated by intensive impulsive current, the formulas calculating magnetic intensity induced by coil, whirling current on workpiece and its magnetic intensity have been established. And the method for determination of forming load has been given. Then, some characteristic curves of forming load have been obtained to describe its distribution. The computation results are consistent with the conclusion obtained from some relative experiments. Finally, by applying the calculating results of forming load to the deformation analysis, the free magnetic bulging process of sheet aluminium have been predicted successfully.

Key words flat workpiece magnetic forming forming load

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