Space-Time-Controlled Multi-Stage Pulsed Magnetic Field Forming and Manufacturing Technology[*]

Liang Li[1, 2,*], Xiaotao Han[1,2], Tao Peng[1,2], Hongfa Ding[1,2], Tonghai Ding[1,2], Li Qiu[1,2], Zhongyu Zhou[1,2], Qi Xiong[1,2]

[1] Wuhan National High Magnetic Field Center, Huazhong University of Science and Technology, Wuhan, China
[2] State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan, China

Abstract

Electromagnetic forming (EMF) is a high strain-rate forming method where a pulsed electromagnetic force is applied to a conductive metallic workpiece. To improve the performance of the EMF system, the current problems which restrict its extensive application have been analyzed. To this end, a space-time-controlled EMF technology with multi-stage and multi-direction coils system has been developed. In our new EMF system, the magnetic field generated by driving coils is much higher than in conventional EMF due to introducing design methods developed for non-destructive pulsed high field magnets. This technology enables the forming of complex, large-scale sheets and tubes that may be difficult to deform by conventional methods, as well as controlling particular properties of the work pieces.

Keywords

Electromagnetic forming, space-time-controlled, multi-stage, multi-direction, driving coil

1 Introduction

In the EMF process, the work piece is accelerated by the electromagnetic force between the driving current and the eddy current [1]. Compared with traditional quasi-static forming methods, EMF technology is quite beneficial due to high-speed deformation and non-

[*] *The authors would like to thank National Basic Research Program of China (973 Program): 2011CB012800 (2011CB012801) for its financial support*

contact processes; this can provide a substantial increase in the forming limit for high-strength materials, improved formability, improved strain distribution, reduction in wrinkling, active control of spring-back and the possibility of local coining and embossing [2].

The EMF technology is well known with a lot of published research dating back to the 1960's, but the application of the technology is still quite limited in industry. This was primarily focused on the study of macro-deformation behavior and the dynamic numerical simulation of the EMF process [3]. However, two problems which restricted its extensive application have not yet been solved: 1) How to generate stronger pulsed electromagnetic force (i.e., the design of high-field drive coils). The performance of the conventional electromagnetic forming is limited by the strength of the pulsed driving coil and by its power supply. The maximum magnetic field strength generated by conventional driving coils is normally relatively low, and the energy of the capacitor bank used for this purpose is mostly less than 100 kJ due to the strength of the coil in the conventional EMF system. Therefore it is difficult to further improve the forming speed, range and depth which has restricted its extensive application in the high speed forming process. 2) How to generate the space-time-controlled multi-stage electromagnetic force in the EMF process. For a single coil system, the Lorenz force on the work piece decreases rapidly with increasing distance from the driving coil. Thus the conventional single coil system can only be applied to form small or thin-walled workpieces. In order to meet the requirements for larger size and more complex structures of the forming materials, multi-coil systems should be proposed and designed. Thus in future research more attention should be paid to space-time-controlled methods of generating the electromagnetic forceby multi-stage pulsed magnets.

With the ongoing development of non-destructive pulsed high field magnet technology, magnetic fields in excess of 80 T have been achieved by using new materials, inserting internal reinforcement between the conductor layers, increasing the energy of the power supply, and new schemes of coil design [4]-[7]. The improved pulsed magnetic field associated with the multi-stage magnet, modular power supplies, timing control and a series of new technologies has introduced a new work pattern and design method for the development of EMF systems, which may greatly improve the efficiency of EMF technology in forming large-scale and deep-drawn components, large panels, and shaped tubes.

In this paper, we propose a Space-Time-Controlled Multi-Stage Pulsed Magnetic Field (Stic-Must-PMF) forming and manufacturing technology to improve the performance of the EMF system by applying the design methods of a high-field pulsed magnet system, which is based on strategically placed multiple coils where each coil can be addressed individually by its associated power supply with precise timing control. The magnetic flux density of these coils can be in the range 40-80 T.

2 Concept and Design of the Stic-Must-Pmf Forming System

The Stic-Must-PMF system contains multiple pulsed electromagnetic coils and several sets of pulsed power systems. Each coil is energized by a pulsed power system that can be controlled independently according to the required magnetic field direction and special functions. The magnetic flux density of these coils can be in the range 40-80 T by using high-strength materials and internal reinforcement between the conductor layers. The power supplies are based on self-healing metallized film capacitors, which provide high reliability, high energy density and compact structures.

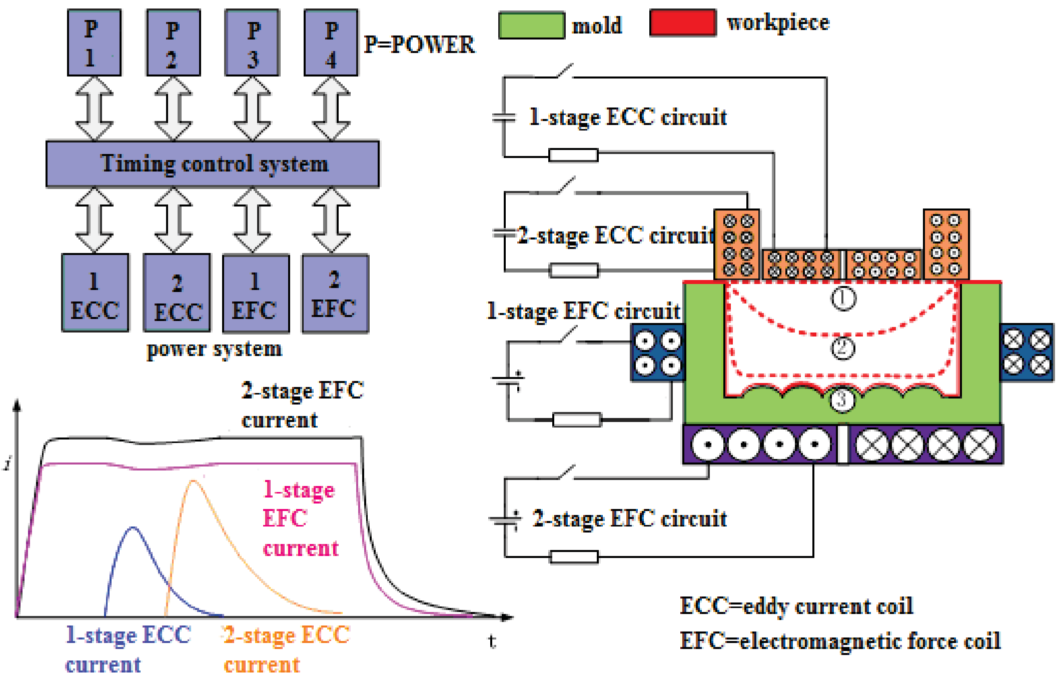

Figure 1*: Schematic illustration of the two-stage and two-direction high pulsed magnetic field forming system.*

Next we will introduce the basic structure and working principle of the multi-stage and multi-direction pulsed high magnetic field forming system by the example of a two-stage and two-direction forming system. It works as follows: the stage-1 and stage-2 " eddy current" coils generate short-duration pulsed magnetic fields perpendicular to the work piece and thus can generate eddy currents in the work piece. The stage-1 and stage-2 "electromagnetic force" coils generate long-pulse magnetic fields parallel to the work piece and can interact with the eddy current in the work piece to produce an electromagnetic force for moving the mold. Initially, the work piece deforms from the starting position 1 to position 2 under the action of the electromagnetic force by triggering the stage-1 "eddy current" coil and the two "electromagnetic force" coils, as shown in Fig. 1. Since the eddy current in the work piece decreases rapidly with increasing distance away from the stage-1 "eddy current" coil, the stage-2 "eddy current" coil needs to be triggered when the work piece is in position 2 in order to increase the eddy current. Since the stage-2 "eddy current" coil is located near to the position 2, it can provide a sufficient magnetic force on the work piece.Then the work piece can be further deformed to position 3 and make contact with the mold to achieve the final shape. In the system, the space structures of the first and second coils are static. The parallel and vertical magnetic fields are generated by different coils that can be designed and controlled independently according to the different functions of the eddy current and electromagnetic force. The two "eddy current" coils are relatively small which not only reduces the time constant of the circuit that can easily generate the short-pulse field and strong eddy current in the work piece, but also the coils located in the different positions can be timingly and independently controlled .The "electromagnetic force" coils are arranged according to the work piece forming requirements to ensure a continuous electromagnetic force on the work piece.

3 Key Issues to be Solved

The electromagnetic forming technology based on the pulsed high magnetic field involves a combination of electromagnetism, materials science and manufacturing technology. As it is a novel technology system, there are still many critical issues that must be attended to:

(1) The effects of the pulsed magnetic field and pulsed electromagnetic force on the flow behavior and forming mechanisms of the metals have not yet been fully clarified. Since the foundational theories of the technology are still imperfect at present, there are few theoretical guidance on 1) how to apply the pulsed electromagnetic force efficiently on the metal workpiece, 2) how to ensure that the pulsed electromagnetic force has beneficial effects on the workpiece for the metal flow, material evolution and service performance.

(2) The experimental platform of the multi-stage and multi-direction pulsed high magnetic field system is not yet perfect and few experimental data are available. Meanwhile, the conventional unipolar pulsed magnetic field forming technology for single-process can only give a reference on the trend for test data and criteria, but cannot provide technical support for work pieces with complex shape. These will cause the lack of evaluation criteria for the forming limit and forming structure.

The solution to these problems can provide technical support for the development of pulsed magnetic field technology in general and play an important role in promoting the development of electromagnetism, materials science and materials manufacturing technology.

4 Possible Solutions

According to the above key issues, we should establish a new theoretical framework of flexible forming with control of properties and performance using the space-time-controlled multi-stage pulsed magnetic field manufacturing technology. We can mainly look for a breakthrough in the Stic-Must-PMF forming system in the following areas:

(1) The effective regulation of the magnetic field and electromagnetic force for the multi-stage and multi-direction pulsed high magnetic field system.

To be specific, we mainly undertake research on the laws of the space-time distribution of the strong space-time-controlled multi-stage pulsed magnetic field, the influence of the vertical field, the parallel field and the equivalent frequency of a pulse on the eddy current and electromagnetic force, and the control of the force field in forming.

(2) The magnetic field penetration, eddy current distribution and the energy conversion law involved in the forming of complex structures.

It is important to establish the three-dimensional distribution model of magnetic field penetration and eddy current in the forming process. On basis of this, we can investigate the effects of the action time of magnetic field, materials and the structure of the work piece on the magnetic field penetration and eddy current distribution.The coupling mechanism of the magnetic field distribution, eddy current distribution and the motional electromagnetic force can be obtained as well.

(3) Modelling and design criteria for the multi-stage and multi-direction pulsed high magnetic field system.

In this section, we should develop the geometric models, physical models, mathematical models and virtual design technology of the whole system and subsystems of the multi-stage and multi-direction pulsed high magnetic field coils. Then an optimization design method of the coil structure under the electromagnetic-thermal-mechanical coupling action can be proposed. Furthermore, the optimization techniques for the combination of the power system and the coil system should be studied with a view to an accurate control for the repeatable pulse charge and the pulsed waveform control technology.

(4) To build the experimental platform of multi-stage and multi-direction high pulsed magnetic field system for large-scale and complex work pieces.

To verify the simulation result and provide data for optimization design, it is necessary to produce EMF prototypes and set up the experimental test platform based on the design principles and structural layout optimization of space-time-controlled multi-stage pulsed magnetic field facility. Then a number of experiments can be studied to achieve a more comprehensive understanding of plastic flow, diffusion bonding, microstructure evolution, and defect production and propagation in metal alloys upon deformation induced by the space-time-controlled multi-stage pulsed magnetic field.

5 Conclusion

The EMF technology has a long and significant history. However the technology has never quite taken its place among mainstream manufacturing methods. In this paper, we present the Stic-Must-PMF forming and manufacturing system to solve current problems of the EMF technology in forming large-scale deep drawing components, multilayered hollow plates, large panels, and shaped tubes in aerospace engineering. In the proposed system, the forming coils can generate higher pulsed magnetic fields and have a longer working life as compared to conventional forming coils due to introducing the internal reinforcement technology that is used widely in pulsed magnet design. Further, parallel and vertical magnetic fields can be generated and controlled independently which can improve the ability of manufacturing and control of electromagnetic forming of large-scale and complex work pieces by using the multi-stage and multi-directional coil system. This could transform the electromagnetic forming technology from its traditional role of aided forming to a direct integrated forming technology. It could lead to major advances in aerospace engineering in manufacturing large-scale and complex parts and components made from sheets and tubes.

References

[1] V.S. Balanethiram, G.S. Daehn. Hyperplasticity: increased forming limits at high work-piece velocity [J]. Scripta metallurgica. 1994, 30: 515-520.

[2] J.D. Thomas, M. Seth, G.S. Daehn, et al. Forming limits for electromagnetically expanded aluminum alloy tubes: Theory and experiment [J]. Acta Materialia. 2007, 55(8): 2863-2873.

[3] C.N. Okoye, J.H. Jiang, Z.D. Hu. Application of Electromagnetic-Assisted Stamping (EAMS) Technique in Incremental Sheet Metal Forming [J]. International Journal of Machine Tools & Manufacture, 2006, 46(11): 1248-1252.

[4] F. Herlach, L. Li, N. Harrison, et al. Approaching 100 T with wire wound coils [J]. IEEE Trans. Magn. 1996, 32(4): 2507-2510.

[5] L. Li, F. Herlach. Deformation analysis of pulsed magnets with internal and external reinforcement [J]. Meas. Sci. Technol. 1995, 6: 1035-1042.

[6] L. Li, B. Lesch, Y. Eyssa, et al. Insert Coil Design of the first 100 T Non-destructive magnet [J]. IEEE Transactions on Applied Superconductivity. 2000, 10(1): 518-521.

[7] L. Li, B. Lesch, V. Cochran, et al. High performance pulsed magnets with high strength and high modulus internal reinforcement [J]. IEEE Transactions on Applied Superconductivity. 2000, 10(1): 542-545.