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Research Progress of Metal Semi-solid Forming Technology

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Abstract

This article summarizes the application of semi -solid forming technology in non -ferrous metal materials and steel.This paper is to expound the historical evolution of metal semi-solid forming technology, the classification of semi-solid forming technology, and the preparation process of semi-solid metal billet slurry. It is to summarize the domestic and foreign research progress of metal semi-solid forming, discussing the existing problems in the development of metal semi-solid forming likewise the future challenges and opportunities.

Keywords

Semi-solid; Forming Technology; Research Development.

1. Introduction

In the 1970s, Flemimgs et al. put forward the metal semi-solid forming technology (Semi-Solid Mental Forming Processes, SSM) [1, 2]. Compared with conventional metal forming processes, there are many advantages for metal semi-solid forming [3, 4]. It can form complex metal parts with good internal microstructure and high dimensional accuracy at a relatively high speed, which is regarded by experts as one of the key emerging metal manufacturing technologies in the 21st century.

In this paper, the research and progress of the application of semi-solid forming technology in non-ferrous metal materials and iron and steel are reviewed, analyzing the main problems existing in the semi-solid forming technology of metal alloys with high melting point, and the development trend of metal semi-solid forming technology is prospected.

2. Classification of Metal Semi-solid Forming Technologies

There are two main processes of metal semi-solid forming: semi-solid rheology and semi-solid thixoforming, and the former is difficult to achieve in actual production because the storage and transportation of semi-solid slurry is very inconvenient. At present, the commonly used methods for preparing semi-solid blanks [5] are: stirring method (mechanical stirring method, electromagnetic stirring method, etc.), non-stirring method (rotary cooling needle method, SSIT method, etc.) and solid phase method (SIMA method, deformation heat treatment method, powder metallurgy method, etc.).

Among them, Strain Induced Melt Activation (SIMA) is a large plastic deformation of the solid blank to obtain a SIMA raw material with fine grains, and then it is heated to the solid-liquid two-phase zone for a period of time. This method is suitable for the preparation of semi-solid blanks for both low-melting alloys and high-melting metal materials. The direct heating-isothermal treatment method is to directly heat and isothermal treatment of industrial bars that have been plastically deformed grain refinement to obtain an ideal semi-solid structure. However, these methods are now mostly used for semi-solid billets with low melting point alloys.

3. Research Progress in Metal Semi-solid Forming Technology

3.1. Semi-solid Forming of Non-ferrous Metals

In recent years, a mature semi-solid thixoforming process has been obtained in the fields of extrusion, rolling, forging and casting of aluminum-magnesium alloys with low melting point. In China, Liu Guojun et al. [6] studied the preparation of semi-solid blanks and semi-solid die-casting forming processes of A357, ZL108 and other low-melting aluminum alloys in 2001. Mao et al. [7] successfully prepared a high-quality 7075 aluminum alloy semi-solid slurry by serpentine channel pouring method. Wang Weiwei et al. [8] used industrial extruded bar stock as raw material, and used the principle of SIMA method to successfully prepare large-diameter 7A09 aluminum alloy semi-solid blanks by direct heating-isothermal treatment. Luo Shoujing et al. [9] successfully prepared AZ91D magnesium alloy semi-solid blanks with fine grains and good spheroidization by Equal Channel Angular Extrusion (ECAE) + isothermal treatment. Semi-solid processing can theoretically be achieved for alloys with solid-liquid two-phase zones. The semi-solid thixoforming of alloys is easy to realize industrial and automated production, and has become the main processing method of semi-solid forming today, among which semi-solid alloy thixotropic die casting and thixotropic forging are the two main forming processes that have received extensive attention and research.The semi-solid thixoforming process of low-melting alloys such as aluminum and magnesium has been successfully applied to industrial production: Xu Jun [10] and other semi-solid extrusions have formed A356 aluminum alloy automobile wheels. Luo Shoujing, Wang Weiwei et al. [7] successfully forged the complex 7A09 aluminum alloy impeller and AZ91D connecting rod by semi-solid precision forging process, and analyzed the influence of die structure, lubrication conditions, equipment speed, initial mold temperature and other parameters on the semi-solid forging quality of the impeller by combining finite element simulation. Jiang Jufu et al. [9] carried out semi-solid isothermal compression experiments on the Gleeble-1500 thermal simulator, and obtained the true stress-true strain curves of the deformation of the semi-solid AZ91D magnesium alloy at different temperatures and different strain rates. The influence of process parameters such as billet temperature, mold temperature and loading speed on the thixotropic die forging process of semi-solid AZ91D alloy was obtained by finite element simulation on the Deform-3D software platform. By using the semi-solid thixotropic die forging process, the AZ91D magnesium alloy elastic plate with the thinnest wall thickness of 2mm was successfully manufactured on a lower tonnage press.

3.2. Semi-solid Forming of Steel Materials

Flemings et al. proposed the concept of semi-solid processing and further studied the rheological properties of stainless steels such as AlSi304 and 440C, and clarified the possibility of semi-solid processing of metals with high melting points such as steel [11]. Mao Weimin et al. [12] rolled 1Cr18Ni9Ti stainless steel plate in semi-solid form, Solek et al. [13] conducted a semi-solid die forging test of 100Cr6, and Khizhnyakova et al. [14] studied the metal flow and die wear in the semi-solid thixotropic forging process of X210CrW12 steel. In addition, some foreign enterprises have carried out the production of steel semi-solid thixomorphing, such as C70S6 steel thixotropic forming connecting rods, high-carbon steel C80 thixotropic forging parts, spherical cast iron semi-solid thixotropic die-casting connecting rods, etc.

However, due to the difficulty of continuous and stable preparation of semi-solid blanks of high-melting alloys such as steel, and the short service life of forming dies, the research and application of semi-solid thixoforming process are still slow. In China, it is still mainly in the laboratory research stage of semi-solid rheological rolling, semi-solid thixotropic forging and thixotropic die casting. However, scholars at home and abroad have still achieved certain research results: Song Renbo et al. [15,16,17] conducted uniaxial thermal compression

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experiments on the Gleeble-1500 testing machine and studied the rheological stress and microstructure properties of 60Si2Mn semi-solid blanks. The finite element simulation of the 60si2Mn semi-solid rolling deformation of spring steel was carried out on the MARC software platform, the variation law of stress field and velocity field under different deformation conditions was studied, and the direct rolling test of semi-solid slurry was carried out on the 60Si2Mn spring steel by using the self-designed semi-solid steel material direct rolling system. Bunck et al. [18] used the finite element simulation software MAGMAsoft to simulate the X39CrMo17 stainless steel semi-solid die-casting process, and fabricated the X39CrMo17 stainless steel wrench with good surface quality and mechanical properties on a mold sprayed with Al2O3 protective coating by PE-CVD method after surface nitriding.

Rogal et al. [19] die-cast 100Cr6 bearing steel gears from a semi-solid billet of 100Cr6 bearing steel prepared at 1390°C with a liquid phase volume fraction of 45% at a speed of 1 m/s. Solek et al. [13] carried out a semi-solid thixotropic forging test of 100Cr6 bearing steel, and studied the effects of microstructure and solid volume fraction on the semi-solid forging forming in the billet characteristics, and forged a part with good microstructure. Masek et al. [20] successfully die-cast small parts from X210Crl2 steel, which is difficult to form by conventional methods, using a semi-solid die-casting molding process. Khizhnyakova et al. [14] studied the metal flow law of X210CrW12 steel semi-solid thixotropic forging process and the wear of X38CrMoV5-1 die after surface modification by combining finite element numerical simulation and thixotropic forging experiments on a CNC hydraulic press.

Due to the small temperature range of solid-liquid line of high melting point alloy materials such as steel, which is greatly affected by the limitations of high-temperature performance of processing equipment, it is difficult to obtain non-dendrite structure, and the rheological behavior is not easy to determine, which brings great difficulties to the preparation of semi-solid blanks. Therefore, not all alloys with high melting points are suitable for semi-solid processing. Therefore, there are few studies on the preparation of semi-solid billets for high melting point metal materials such as steel at home and abroad, mainly focusing on a few steel grades such as 60Si2Mn spring steel, ZG25MnCrNiMo low alloy steel, 1Cr18Ni9Ti stainless steel, T12 tool steel, cast iron, and 100Cr6 bearing steel.

Among them, Flemings et al. [11] used mechanical stirring to prepare semi-solid blanks of stainless steels such as AISI440 and 440C. Mao et al. [21] prepared a 60Si2Mn steel semi-solid slurry by electromagnetic stirring device, and analyzed the effects of stirring process parameters, rare earth elements and cooling rate on the evolution of microstructure. Song et al. [15] conducted uniaxial thermal compression experiments on the Gleeble-1500 testing machine to study the rheological stress and microstructure properties of 60Si2Mn semi-solid blanks. Zhang Lizhong et al. [22] prepared a semi-solid slurry of low-alloy steel ZG25MnCrNiMo by near-liquidus method, and studied the effects of holding temperature and holding time on the water quenching structure of the slurry. Mao Weimin et al. used a continuous electromagnetic stirring pulping device, and Guan Renguo et al. [23] used a copper inclined plate to complete the preparation of 1Crl8Ni9Ti stainless steel slurry.

Li et al. [24] prepared T12 high-carbon tool steel semi-solid billets by electromagnetic stirring. Zhou Rongfeng et al. [25] prepared a semi-solid billet of supereutectic high-chromium cast iron by the inclined plate cooling method, and studied the effect of the length of the inclined plate on the semi-solid structure of the supereutectic high-chromium cast iron. Solek et al. [13] prepared 100Cr6 bearing steel semi-solid slurry by SIMA method and Łukasz et al. [26] by semi-solid isothermal treatment. However, the stirring method, inclined cooling plate method, and near-liquidphase insulation method used by the above-mentioned experts are generally only used for semi-solid rheological pulping.

4. Mold Surface Modification is a Necessary Means of Semi-solid Forming

Since the 90s of the 20th century, the research on semi-solid forming of low melting point alloys at home and abroad has matured and entered the stage of industrial production. The commonly used mold materials are mainly tungsten steel based on 3Cr2W8V (close to H21 in the United States) and chromium steel represented by Cr5MoSiV (H13) steel, two series of high-heat strength hot work die steel, and well meet the production requirements. However, the solid-liquid line temperature of high melting point alloys is very high, and the working conditions of their semi-solid forming molds are extremely harsh, requiring the molds to work normally and stably above 1200 °C [27], while the tempering temperature of commonly used martensitic hot work die steels is generally 550~650 °C. Therefore, when the actual working temperature exceeds 700°C, the mold life drops sharply, and a single high-heat strength hot work die steel can not meet the working requirements at all. Therefore, scholars at home and abroad have done a lot of research to improve the service life of semi-solid forming dies of high melting point alloys, mainly focusing on the surface modification of forming dies

At present, commonly used surface modification methods include surface thermal diffusion treatment, surface phase transformation strengthening, laser surface treatment, thermal spraying technology, and coating technology [28]. Feng Junjie et al. [29] used the carburizing and quenching and tempering heat treatment processes on the mold surface to increase the life of the 3Cr2W8V steel die-casting mold of die-casting low melting point alloy by 1.8~3.0 times. Kim.S.K et al. [30] used an alumina-based ceramic composite material as the cavity material of the mold during the thixoforming of steel materials, and achieved certain results. Lugscheider et al. [31] sprayed MgAl2O4 or ZrSiO4 on the surface of H11 hot work die steel as a semi-solid forming mold material for steel, and carried out a beneficial exploration. Borovik et al. [32] experimented with thermal protective coatings to reduce the thermal shock to the mold. Borovik et al. [32] experimented with thermal protective coatings to reduce the thermal shock of the mold; Lin et al. [33] used coatings to effectively improve the mold life of aluminum alloy pressure casting. Although the above research has made great achievements in improving the life of the mold through the surface modification of the mold, and some of the molds after surface modification have also been put into the actual production and application of semi-solid forming of low melting point alloys. However, in the semi-solid thixotropic forging of metals with high melting points, such as steel, the die must be able to withstand the thermal shock and sufficiently large mechanical loads caused by repeated contact with the blank at temperatures close to 1400°C.

Therefore, the mold material should have good high-temperature mechanical strength, wear resistance, fatigue resistance, creep resistance, thermal shock resistance, corrosion resistance, and high-temperature oxidation resistance [34]. It is difficult for a single high thermal strength hot work die steel to meet these requirements, and it is easy to have thermal deformation, mold sticking and other phenomena, so a new mold surface modification technology is urgently needed to solve this problem. Thermal barrier coatings (TBCs) have excellent resistance to high-temperature oxidation and very low thermal conductivity, which can effectively reduce the service temperature of the protected mold substrate and reduce its thermal shock load [34]. Only ceramic materials with high melting point, no phase change between service temperature and room temperature, low thermal conductivity, and high bonding strength with mold matrix can be used as TBCs materials. 7-8 wt.% Y2O3-ZrO2 (referred to as 7~8YSZ) is the most widely used thermal barrier coating.

However, the maximum heat-resistant temperature of the surface of the YSZ thermal barrier coating is about 1200°C, and the coating structure is very unstable as the temperature increases further [35]. Rare earth zirconate has better thermophysical properties and mechanical properties than YSZ, and the double-layer La2O3-Y2O3-ZrO2/YSZ coating proposed by

Matsumoto et al. [36] improved the thermal insulation performance, anti-sintering performance and phase stability of the coating. Vassen et al. [37] found that La2Zr2O7 has a higher melting point (2573 K) and remains phase stable at 1400°C, so the La2Zr2O7/YSZ double ceramic layer structure was used to greatly improve the lifetime of the coating. At present, the coating preparation technology is mainly based on two methods: plasma spraying (PS) and electron beam physical vapor deposition (EB-PVD) [38], while plasma spray-physical vapor deposition (PS-PVD) [39] combines the technical advantages of PS and PVD, and has a wider range of applications. Because the thermophysical and mechanical properties of the thermal barrier coating, such as thermal conductivity, residual stress, and interface bonding strength with the substrate, affect its thermal insulation effect and service life, it is important to characterize these thermophysical and mechanical properties of the thermal barrier coating to evaluate its quality: Mu et al. [40] measured the thermal conductivity of thermal barrier coatings by laser flash emission.

5. Challenges and Opportunities

In recent years, metal semi-solid forming technology has also developed greatly. Although there is some basis for the research on semi-solid processing of high-melting ferrous materials, it has been found that the process parameters of semi-solid thixoforming directly determine the forming quality of the workpiece [6,7, 11,12]. However, the study has also found that the high melting point of metals such as steel, the narrow temperature range of the liquid-solid line, the difficulty of continuously and stably preparing high-temperature semi-solid blanks, the high forming temperature, the difficulty of effectively ensuring the high-temperature performance of the tool with the same melting point as the blank, the difficulty of filling complex thin-walled parts, and the low number of mold uses [11,12]. The very short service life of the mold has become a bottleneck for the continuous development of semi-solid forming of alloy materials with high melting point. It is believed that with the development of metal semi-solid material preparation technology and the in-depth research of metal semi-solid forming technology, the above problems will be gradually solved. In the near future, metal semi-solid forming technology will be better developed and applied.

6. Conclusion

1. Preparation of metal semi-solid slurries or blanks. In recent years, experts at home and abroad have developed more than 20 kinds of preparation technologies and processes for the preparation of metal semi-solid slurries or blanks, but the cost, stability, efficiency and many other aspects of these processes still need to be further connected with the actual industrial production.

2. The mechanical properties of the parts produced by metal semi-solid forming technology are good, and the cost is higher than that of casting, forging and other forming methods, which seriously restricts the wide application of metal semi-solid forming technology in industrial production.

3. The melting point of metals such as steel is high, the temperature range of the liquid solid line is narrow, it is difficult to prepare high-temperature semi-solid blanks continuously and stably, the forming temperature is high, and the high-temperature performance of the tool and die with the same melting point as the blank is difficult to be effectively guaranteed, and it is difficult to fill complex thin-walled parts. The development of related basic research and application technology is relatively lagging behind, and the preparation of slurry and blanks, the selection of tools and mold materials, the development of forming and heat treatment processes all require the majority of scientific research workers and practitioners to make persistent efforts.

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References

[1] D.B. Spencer, R. Mehrabian, M.C. Flemings. Rheological behavior of Sn-15 pct Pb in the crystallization range[J]. Metallurgical Transactions, 1972, 7:1925-1932.

[2] M.C. Flemings. Behavior of metal alloys in the semisolid state [J]. Metallurgical Transactions A, 1991, 22A:957-981.

[3] Luo Shoujing, Tian Wentong, Xie Shuisheng, Mao Weimin. Semi-solid processing technology and application[J]. Chinese colored genus Acta Sinica, 2000, 10(6): 765-773.

[4] XIE Shuisheng. Development and application of metal semi-solid processing technology[J]. Chinese Journal of Plasticity Engineering, 2002,9(2):1-11.

[5] JIANG Peng, HE Xiaomao. Process Overview of Semi-Solid Forming and Selection of Mold Materials[J]. Mould Technology, 1998,2: 54-60.

[6] LIU Guojun et al. Study on Semi-solid Forming Process of Several Automotive Aluminum Alloys[J]. Special Casting & Nonferrous Metals, 2001, S1:7-9.

[7] Wen-zhi ZHU, Wei-min MAO, Qin TU. Preparation of semi-solid 707 aluminum alloy slurry by serpentine pouring channel [J]. Trans. Nonferrous Met.Soc. China 2014,24: 954-960.

[8] Wang Weiwei, Han Fei, Song Liang, Luo Shoujing. Research on Semi-solid Forging Forming Technology of Aluminum Alloy Impeller[J]. Special Casting & Nonferrous Alloys, 2012, 32(5): 426-429.

[9] JIANG Jufu. Preparation of AZ91D semi-solid blanks by the new SIMA method and its thixotropic die forging[D]. Harbin: Ph.D. dissertation, Harbin Institute of Technology, 2005.

[10] Zhang Fan, Xu Jun, Zhang Zhifeng, et al. A356 Numerical simulation of aluminum alloy wheel Yi semi-solid extrusion casting[J].Special Casting & Nonferrous Metals, 2012, 32(5): 422-425.

[11] YOUNG.K.P, RIEK.R.G, FLEMINGS.M.C. Structure and properties of thixocast steels [J]. Metals Technology, 1979, 6: 130-137.

[12] Mao Weimin, Zhao Aimin et al. Preparation and Rolling of 1Cr18Ni9Ti Stainless Steel Semi-Solid Slurry[J]. Acta Metallurgica Sinica, 2003, 39(10): 1071-1075.

[13] K.P. SOLEK, A.RASSILI, J.C. PIERRET et al. Characterization of thixoforming process of 100Cr6 steel[C]. Proceedings of the 11th International Conference on Semi-Solid Processing of Alloys and Composites, Beijing: Elsevier Ltd, 2010： 1037-1041.

[14] L.KHIZHNYAKOVA, M.EWERING, G.HIRT et al. Metal flow and die wear in semi-solid forging of steel using coated dies[C]. Proceedings of the 11thInternational Conference on Semi-Solid Processing of Alloys and Composites. Beijing: Elsevier Ltd, 2010:954-960.

[15] Song Renbo, Wang Changsheng, Kang Yonglin, et al. Rheological stress and microstructure of semi-solid 60Si2Mn[J]. Journal of Beijing University of Science and Technology,2009,31(3): 335-340.

[16] Song Renbo, Kang Yonglin, Sun Jianlin, et al. Experimental test of rheological rolling of semi-solid iron and steel materials[J]. Journal of University of Science and Technology Beijing, 2001, 23 (5):439-441.

[17] Kang Yonglin,Song Renbo,Dong Hongbo,Ren Xueping. Finite element simulation of 60Si2Mn semi-solid rolling[J]. Journal of Mechanical Engineering,2002,38(6):83-87.

[18] M.BUNCK, E.SUBASIC, A.BUHRIG-POLACZEK et al. Thixo-casting combination spanners using stainless steel X39CrM017[C]. Proceedings of the 11th International Conference on Semi-Solid Processing of Alloys and Composites, Beijing: Elsevier Ltd, 2010:998-1 004.

[19] L.ROGAL, J.DUTKIEWICZ, T.CZEPPE et al. Characteristics of 100Cr6 bearing steel after thixo-forming process performed with prototype device[J]. Trans. Nonferrous Met. Soc. China, 2010, 20: 1033-1036.

[20] B.MASEK, D.AISMAN, M.BEHULOVA, et al. Structure of miniature components from steel produced by forming in semi-solid state [C]. Proceedings of the 11 th International Conference on Semi-Solid Processing of Alloys and Composites. Beijing: Elsevier Ltd, 2010:l037-1041.

[21] YANG Maosheng,LI Shiqi,ZHONG Xueyou,MAO Weimin. Experimental study on the preparation of semi-solid billets of 60Si2Mn spring steel[J]. Journal of Materials Science and Technology, 2005, 13(3): 268-271.

[22] ZHANG Lizhong, LI Haikai, HU Yuanmeng, et al. JOURNAL OF BEIJING JIAOTONG UNIVERSITY,2006, 30(4): 77-81.

[23] Guan Renguo, Li Gang, Li Junpeng, et al. Preparation of 1Crl8Ni9Ti stainless steel semi-solid materials by inclined shear cooling[J].Journal of Northeastern University:Natural Science, 2005, 26 (9): 867-870.

[24] LI Jiguan, KANG Yonglin, SONG Renbo, et al. Evolution of partial remelted microstructure of semi-solid T12 steel[J].Metal Heat Treatment,2010,35(3) :47-50.

[25] ZHOU Rongfeng,YANG Chengdong,JIANG Yehua,ZHOU Rong. Effect of inclined plate length on semi-solid microstructure of supereutectic high chromium cast iron[J].Special Casting & Nonferrous Alloys,2008,28(2):125-127.

[26] Łukasz Rogal, Grzegorz Korpala , Jan Dutkiewicz. Evolution of microstructure in 100Cr6 steel after cooling from a thixoforming temperature to bainitic transformation ranges[J]. Materials Science& Engineering A, 2015,624:291–299.

[27] HE Shuhua,ZHANG Lizhong,JIAO Zhongsheng,LIU Jinxiang,CHEN Yu,LIU Wen,XING Shuming. Failure and material selection of semi-solid metal rheological forming mold[J].Special Casting & Nonferrous Alloys,2004(2): 33-35.

[28] YAO Shuqing. Research on special coatings for extrusion casting of iron and steel materials[D]. Beijing:Ph.D. dissertation, Beijing Jiaotong University, 2010.

[29] Feng Junjie,Li Yaojun. Research on Improving the Life of 3Cr2W8V Steel Hot Mold[J]. Mechanical Technology, 2005(3):43-45.

[30] Kim.S.K, Kim.K.D, Kim.Y.J. Development of SRT Technology[C]. Proceeding of the 7th S2P,Tsukuba, JAPAN, National Institute of Advanced Industrial Science and Technology, Japan Society for Technology of Plasticity, Sept.23 -29,2002:391-396.

[31] Lugscheider. E, Bobzin. K. Development, Investigation and Characterization of New Surface Technologies for the Use of Semisolid Metal Forming of Steel[C]. Proceeding of the 7thS2P, Tsukuba, JAPAN, National Institute of Advanced Industrial Science and Technology, Japan Society for Technology of Plasticity, Sept.23 -29,2002:385-390.

[32] S.I. Borovik, T.N. Ivanova, N.L. Mironenko et al. Protective coating as a means of improving heat resistance of the refractory lining for extra-furnace steelmaking facilities[J]. Refractories and Industrial Ceramies,2005,46(1):24-26.

[33] J. Lin, S. Carrera, A.O. Kunrath, D. Zhong et al. Design Methodology for Optimized Die Coatings: The case for aluminum Pressure die-casting[J]. Surface and Coatings Technology, 2006,201(6,4):2930-2941.

[34] Xu Binshi, Zhu Shaohua, et al. Theory and technology of surface engineering[M].Beijing:National Defense Industry Press,1999.

[35] Zhou Yichun, Liu Qixing, Yang Li et al. Failure Mechanism and Life Prediction of Thermal Barrier Coatings[J]. Solid Mechanics Newspaper, 2010, 31(5):504-531.

[36] M.Matsumoto, N.Yamaguchi, H.Matsubara. Low Thermal Conductivity and High Temperature Stability of ZrO2-Y2O3-La2O3 Coatings Produced by Electron Beam PVD [J] . Scripta Materialia, 2004, 50: 867-871.

ISSN: 2688-8645

[37] R.Vassen, F.Traeger, D.Stover. New Thermal Barrier Coatings Based on Pyrochlore/YSZ Double-Layer Systems [J]. International Journal of Applied Ceramic Technology, 2004, 1: 351-361.

[38] R.A.MILLER. Thermal barrier coatings for aircraft engines: History and directions [J]. Journal of Thermal Spray Technology, 1997, 6(1):35-42.

[39] Guo Hongbo,Gong Shengkai,Xu Huibin. Research progress on new high-temperature/ultra-high-temperature thermal barrier coating and preparation technology[J].Acta Aeronautical Sinica, 2014, 35: 1-10.

[40] MU Rende,SONG Xiwen,TAO Chunhu,HE Limin. Test Method of Thermal Diffusivity of EB-PVD Thermal Barrier Coatings and Its Influencing Factors[J]. Journal of Central South University(Natural Science Edition), 2009, 39(2): 256-261.