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Formability analysis of aluminum double-layer sheets using a magnetorheological fluid

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ABSTRACT

Bulging with overlapping metal sheet is one of the important ways to improve the forming performance of light alloy sheet. In order to investigate the bulging performance of aluminium double-layer sheets, this paper uses intelligent materials magnetorheological fluid (MRF) as a force medium for the first time, and also develops a exclusive device structure for it. The results show that: With the increase of magnetic field strength or mass fraction of MRF, the bulging limit of the inner layer aluminium sheets is significantly increased when the double-layer sheets reach the bulging limit, and the size of the location where the cracking length occurs produces an inverse trend change. As the mass fraction of the magnetron fluid increases from 56% to 80% with 3A field coil current, the ultimate wall thickness variation rate of the inner layer aluminium sheet decreases by 15.75%, and bulging limit height increases by 8.74%. It can be seen that with stronger magnetic field or higher mass fraction of the MRF, it improves the uniformity of deformation coordination at various parts of the sheet. This study provides a scientific basis for improving the forming performance and comprehensive quality of low-plastic lightweight sheet.

Introduction

Lightweight alloy sheets including aluminum and magnesium are ideal materials to achieve lightweight in aerospace and automotive [1,2], but some problems, such as poor performance of plastic forming in the room temperature, result in the difficulty to form a complex structure or large deformation of the sheet with the traditional stamping process. Improving the plastic forming ability of light alloy sheets has become the key to solve such problems [3–6].

The results of the related studies show that if the experiment changes the pressure on both sides of the sheet which puts load pressure on them [7], it can improve the hydrostatic pressure of deformation area but simultaneously inhibit the generation and expansion of internal cracks in the material, thereby it is necessary to enhance the plasticity of the material. Tiejun Gao et al. [8] selects different thickness and performances of the sheets to make the experiment on pressure bulging of the aluminum alloy LF21 in viscous media and the result shows that, the sheet with higher strength coefficient K, larger work hardening index n and appropriate thickness is helpful to improve the forming performance of the sheet. The study of 5A06 aluminum alloy sheet under different conditions of hydraulic forming by Xu et al. [9] indicates that the thinning rate of thinnest wall is 13.6% while the single layer sheet is hydroforming with an internal pressure of 30 MPa, and the sheet thinning rate is only 8.7% when the double sheets are hydroforming with an internal pressure of only 15 MPa, it can be seen that the double-layer sheet makes the distribution of wall thickness more evenly and a reasonable upper layer auxiliary sheet can also inhibit wrinkling and excessive thinning of the lower sheet. The liquid-filled bending experiments of double tubes of low carbon steel/aluminum alloy show that the application of the cladding tube changes the thickness ratio and the stress state [10], and the outer maximum thinning point is not located at the center but at a certain angle with the central section. Thus it provides the theoretical basis for forming and processing of the large slender pipe.

Then the intelligent materials MRF has been introduced as a medium to the sheet metal forming field [11], and its rheological properties under the action of the magnetic field can be changed to achieve the effect of quantitative control to required parts of the sheet. It makes initial attempts by simultaneously applying magnetic media pressure on both sides of the sheet, the distribution of wall thickness and the uniformity of deformation have been improved [12].

It is a meaningful attempt to study the bulging behavior of aluminum double-layer sheets by using MRF as force-transmitting medium. As the magnetic fluid force and the mode of action of the

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hydraulic force medium are different from the conventional mediums, the deformation behavior and coordination order are very different. At the same time, the magnetic field and the rheological properties of magnetic particles change with different magnetic field strength and MRF component coupling, which affects the of wall thickness distribution and the of the forming quality control in the process of sheet bulging [13]. Therefore a systematically study of them will be introduced in this article.

Research and scheme

Process principle

Double layer bulging of MRF is a process that using MRF instead of the original rigid punch on the double sheets compression molding. According to requirements of the study, the inner sheet closes to the magnetic medium is the main research object, and a layer sheet is added on the outside. When the punch loads downward, the MRF plays up a different force effect until the bulging is complete. Throughout the forming process, the end of the rigid punch is not contact with the sheet, but through the magnetic medium. The process principle is shown in Fig. 1.

It can be seen from Fig. 1, the experiment device includes punch, die, the blank holder with a guide structure, magnetic control unit and other major components. Before forming, a certain amount of MRF is injected into the theoretical closed cavity which is created by punch, blank holder and preformed sheet. The end of the punch is designed as an annular groove, meanwhile the inner space is wrapped around by enameled copper wire. Under the control of current, the distribution state and viscosity will be changed with different field strength. Then the inner sheet bulging deformation behavior and forming performance are also affected.

As we all known, MRF fluid has mass applications in the industrial field because of the special physical structure, and the orientation of magnetic particles which occurs under the magnetic field [14,15].Therefore, there is no sealing ring on the contacting flange part of the punch and die in the design of the device structure.

Magnetic control unit

It can be seen from the foregoing principle and structure of the device that magnetic field lines are generated below the end of punch after the coil is energized and penetrate through the MRF. In order to facilitate the research, the magnetic field lines can be approximately regarded as parallel to the axial direction. Coil current can adjust the magnetic induction strength, and magnetic particles in the magnetic fluid along the magnetic field direction is chain-like arrangement. With the distribution of the magnetic particle distribution and the changes of composition and the structure, the effect of MRF force is also changed. With the downward movement of the punch, the deformation behavior and the coordination order of the sheet are also changed accordingly. The key to the implementation of regulation is the magnetron unit structure, as shown in Fig. 2.

It can be seen from Fig. 2(a) and (b), the punch provides the motive force for magnetic force transmission medium to apply load, even though it does not directly contact the sheet during the bulging process. An enameled wire with diameter of 2.2 mm is wound in that end type groove, through optimization and calculation, the coil is 45 mm high and 18 mm thickness. The bottom of the punch is provided with an axial groove to facilitate the drawing of the wire without affecting the close cooperation between the punch and the blank holder guide part. At the same time, in order to enhance the effect of magnetic field, the punch material is DT4 pure iron. The real-time regulation of the rheological state of the magnetic medium is the key of this study, which is adjusted by excitation magnetic field generated by the punch and wound coils, and the coil current is supplied by the electronic control device, as shown in Fig. 2(c), including the range of 10A ammeter, slide-type rheostat, A-400W-24 V DC power supply and so on, it can be connected with each other through the copper enameled wire.

Materials and programs

This experiment is carried out on SPV hydraulic working machine with 500 KN maximum load and the forming speed is 1 mm/s. The forming object which is the inner layer sheet, is made of Al1060 sheet with a diameter of 150 mm and a thickness of 1 mm into a circular blank, while the outer cover is made of the same material and size, but the thickness is 0.5 mm. The chemical composition and performance parameters of samples are shown in Table 1.

The selection of force-transmitting medium is one of the key issues in this study. In order to facilitate the comparative study, the experiment chooses three different components (mass fraction), in the case of current 5A, the physical state is shown in Fig. 3. Taking into account the loss of media consumption during the experiment, it should be ensured that the medium capacity is the same and the concentration changes in reasonable range of error before each experiment.

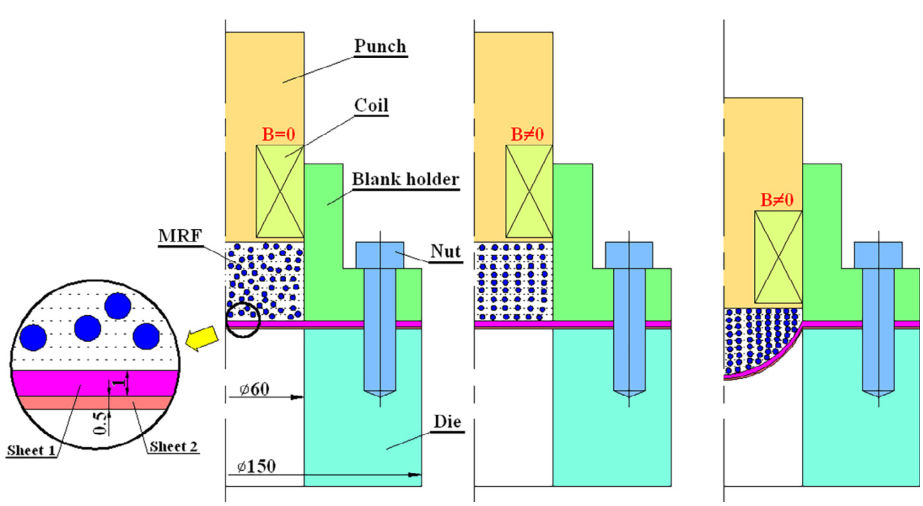


Fig. 1. The schematic diagram of press forming of double-layer sheets with magnetic.

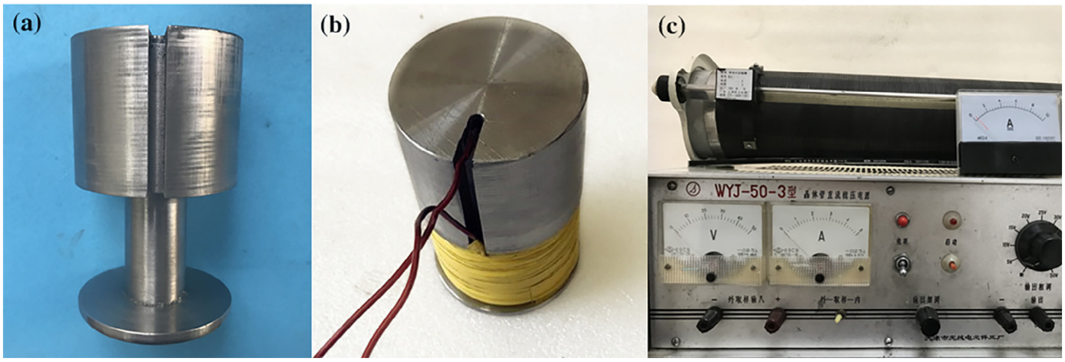
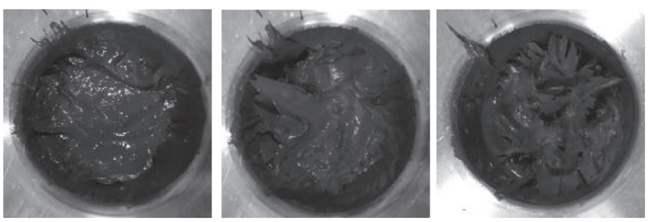


Fig. 2. Magnetic control unit and auxiliary structure (a) (b) punch structure (c) electronic control device.

Table 1
Al1060 sheet chemical composition.

Fe	Si	Mn	Cu	Mg	Zn	Ti +	$\sigma_b^{(MPa)}$	$\sigma_{0.2}^{(MPa)}$	δ (%)
≤0.350	≤0.250	≤0.030	≤0.050	≤0.030	≤0.050	≤0.030	≥110	≥40	≥12



(a) Component 56% (b)Component 70% (c)Component 80%

Fig. 3. States of the MRF under a magnetic field.

Discussion and analysis

Crack morphology

It can be seen from above that the magnetic medium plays the role of pressure transmission in load process, and the current can control the rheological properties of MRF through the magnetic field. Under the effect of the outer layer sheet, the bulging behavior of inner layer sheet is affected. In this paper, based on cracks inner layer sheet when it reaches the bulging limit. As shown in Fig. 4, morphological changes of the cracked form under different loading conditions are compared.

It can be seen from experimental results which are obtained in Fig. 4. Although the MRF components, magnetic field strength and other conditions are different, the cracked parts are mainly located in top center of hemisphere after sheets reach the bulging limit. This is consistent with the results of the uncovering effect. The results show that the deformation of the part is still the largest despite the outer sheet is covered and deformed together during the bulging process. At the same time, from the macroscopic morphology of the fracture site, under the same process conditions, the magnetic field strength increases with the increasing current, and results in a significant reduction in the length of the cracked portion. As the concentration of solid magnetic particles increases, the degree of fracture decreases significantly. The reason is that with the increment of the magnetic field strength, the magnetic particles in the medium are aggregated and arranged in a columnar structure, then the flexible loading plays a leading role on making the sheet more uniform and better coordination. Meanwhile, the solid phase ratio of three kinds of MRF is relatively high. With the increase of the magnetic field, the larger the composition, the more solid-like properties of the tend which is favorable for the deformation coordination of the sheet.

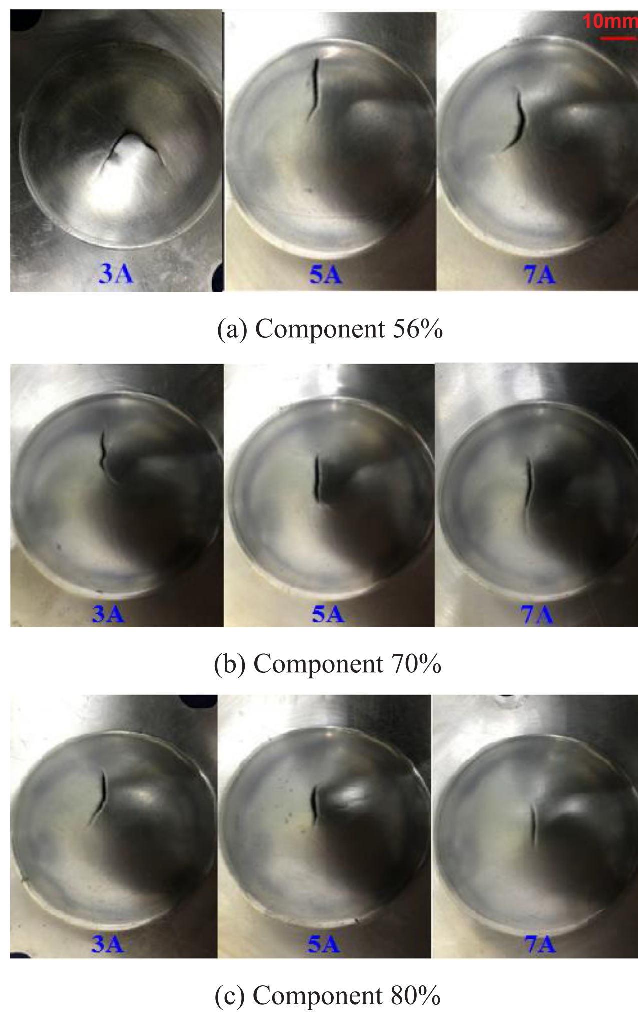
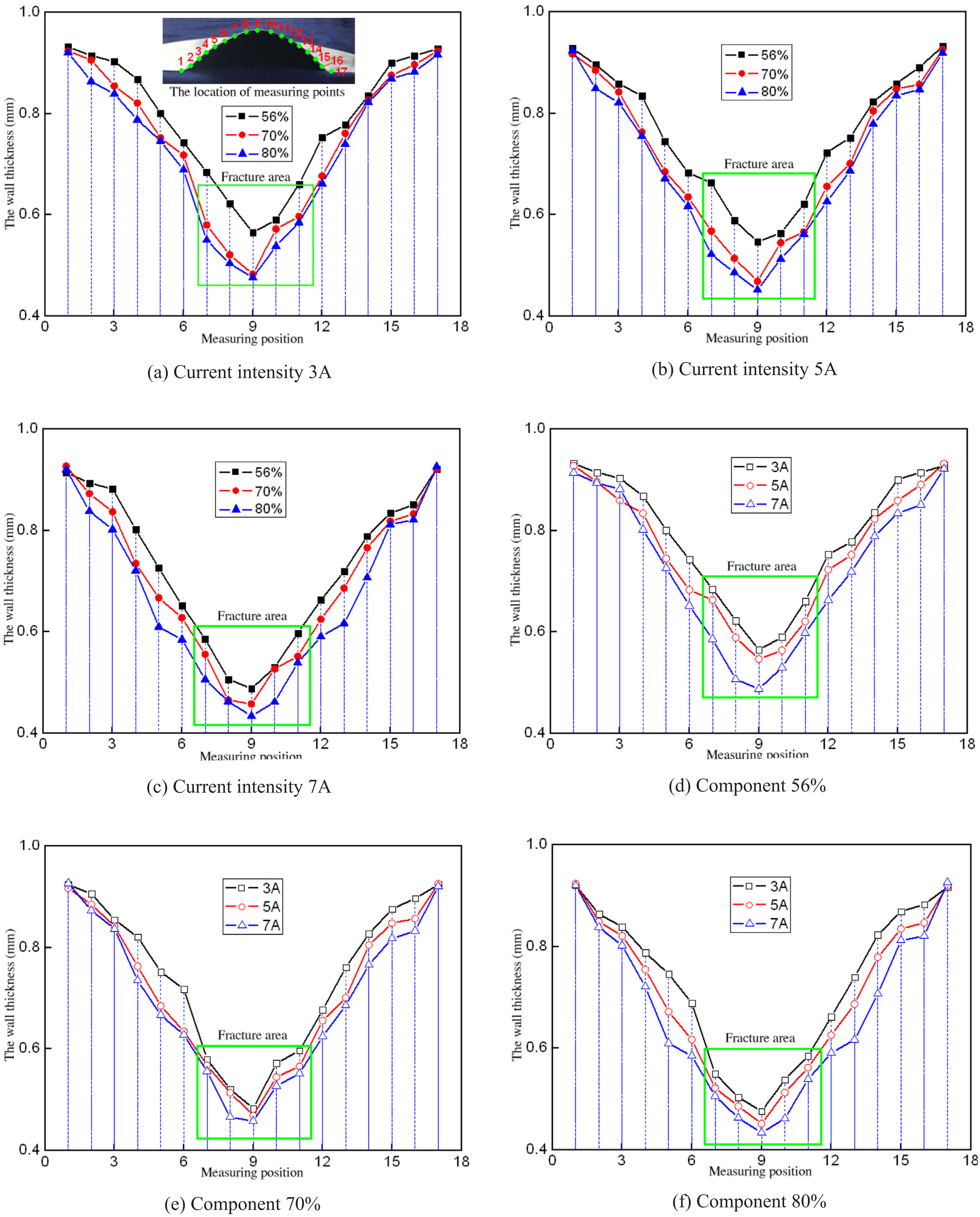


Fig. 4. Comparison results of forming experiments.

Wall thickness distribution

It can be seen from the foregoing that the magnetic field is one of the decisive factors in the viscosity change of the MRF and the force effect, and the current intensity is an important method to control the



(a) Current intensity 3A

(b) Current intensity 5A

(c) Current intensity 7A

(d) Component 56%

(e) Component 70%

(f) Component 80%

Fig. 5. Comparison of wall thickness contrasts under different forming conditions.

magnetic field. For the sake of comparison, the center point of the sheet is divided in this study. The thickness of the 17 points is collected equidistantly from typical parts along the cross section of the bulging member. Taking into account the bulge specimen section is curved, it is necessary to ensure that measuring points are evenly distributed at various positions.

It can be seen from Fig. 5, the wall thickness of the deformation zone in the inner layer sheet has varying extent of reduction under

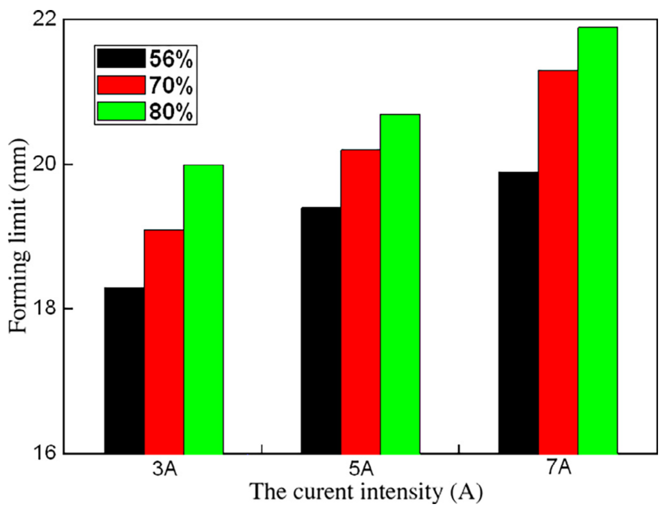


Fig. 6. Comparison of forming limit.

different process conditions, after the double layer sheets bulging of the magnetic medium pressure. Although there is a difference between the dielectric component and the current, the sheet reaches the bulge limit under different conditions. The wall thickness of the typical cross section is characterized by the wall thickness decreasing first and then increasing from one end through the bottom rupture region to the other end. The area of maximum wall thickness thinning is located around the fracture zone, the extreme points are at the central axis of the bulge, the wall thickness is the most serious in this part, and the closer two sides approach to the flange, the less the wall thickness decreases.

From Fig. 5(a)–(c), it can be seen that when the current intensity increases from 3A to 7A, with 56% mass fraction, the front wall thickness decreases from 0.565 mm to 0.488 mm when inner layer aluminum sheet begins to fracture, and the decline is 13.63%. While using MRF of 80% mass fraction as a medium, under the same condition, the decline is 8.82%. When the mass fraction of MRF increases from 56% to 80% under the current of 3A, the inner wall thickness of the inner layer decreases from 0.565 mm to 0.476 mm; When the current increases to 7A, the change rate of the wall thickness of the inner aluminum sheet reaches 11.07% from 15.75% under the same mass fraction of the MRF. Compared with the numerical change, it can be seen that under different conditions, with the increase of current intensity or mass fraction of MRF, the difference of the wall thickness of each part on the sheet reduces obviously and the uniformity of deformation is improved.

This is due to the special physical structure of magneto-rheological fluid under the control of magnetic field. When the current intensity or the mass fraction of MRF increases separately, the MRF is converted from a liquid state to a semi-solid state, the viscosity becomes larger, and the yield stress increases. The number and the closeness of the magnetic particles along the MRF lines improve significantly, transmission performance is also significantly enhanced. MRF as a smart force in the magnetic field under the control of rheological properties improves the interface contact conditions between the sheet and the traditional rigid punch load. When the magnetic induction intensity reaches a certain condition, the performance of the MRF will reach a certain optimization value which can effectively delay the occurrence of fracture. During the bulging of the coated panel, the tangential frictional force on the upper and lower surfaces of the sheet is directed towards the top of the bulge. When the interfacial friction coefficient of laminated sheets increases, the tangential adhesion of MRF on the upper and lower surfaces of sheets is reversed. Meanwhile, the plastic flow of the shear friction factor on the bulging member changes so that the overall deformation of the sheet is more uniform and the deformation coordination of various parts in the bulging process of the inner aluminum sheet is promoted. The effect of two conditions is bound to have a significant impact on the forming limit.

Forming limit

It can be seen from the foregoing analysis that the process conditions have a great influence on the bulging behavior and wall thickness distribution of the MRF. The forming limit is one of the important indexes to evaluate the sheet forming ability. As shown in Fig. 6, the contrast of the ultimate bulging height of the inner aluminum sheet measured by the height gauge under the coupling of different magnetic fields and component magnetic media.

As can be seen from the numerical comparison in Fig. 6, when the outer layer sheet is bulging, the limit bulge height change with the increase of current or mass fraction under the condition that other conditions are unchanged. Among them, the composition of 56% magnetic medium makes the ultimate bulging height increase from 18.3 mm to 19.1 mm, 20.0 mm when the current from 3A to 5A, 7A, the increment of corresponding is 4.37% and 9.29%. Maintaining other conditions unchanged, the forming limit increases by 7.04% and 10.05% respectively when the media composition is 80%. The ultimate bulging height changes with the state of the MRF component. When the coil current is 3A and 7A, respectively, the MRF component increases from 56% to 80%, the ultimate bulging of the inner aluminum sheet increases by 8.74% and 9.50% respectively. In the foregoing analysis, as the intensity of the magnetic field increases, the rheological properties of the magnetic medium are changed, and the number of directional arrangement of magnetic particles turns more stable. What is more the force effect is also significantly enhanced, improving the coordination of deformation and uniformity of the sheet, and raising the height of the bulge height of the upgrade. In the same way, the concentration of MRF components also increases, the proportion of its own magnetic particles is larger, under the condition of the same current, the number of magnetic particles involved in directional arrangement is larger.

Conclusions

1) In this paper, the use of MRF as a force medium on the double layer sheets bulging performance has been studied. The results show that although the conditions are different, the fracture sites are located around the top when the sheet reaches the bulging limit. By comparison we can see that the length of the cracked site is inversely proportional to the magnetic field strength and the mass fraction of the MRF.
2) Through comparing the results of the study, as the current intensity increases or the mass fraction of the MRF becomes larger, the wall thickness of the inner aluminum sheet decreases significantly when the bulging limit is reached.
3) Under the action of magnetic field regulation, the rheological state of MRF changes significantly, with a current of 3A and a mass fraction of 56%, the sheet bulging limit increases 9.29% when the current increases to 7A. When the current is 7A and the mass fraction increases to 80%, the bulge limit increases by 9.50%. By comparison we can see, as the magnetic field strength or the increase of mass fraction of MRF, the deformation uniformity and the bulging performance are obviously improved.

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References

[1] Qiang Chen, Bao-guo Yuan, Gao-zhan Zhao, Da-yu Shu, Chuan-kai Hu, Zu-de Zhao, Zhi-xiang Zhao. Microstructural evolution during reheating and tensile mechanical properties of thixoforged AZ91D-RE magnesium alloy prepared by squeeze casting-solid extrusion. Mater Sci Eng A 2012;537:25–38.

[2] Zhong-jin Wang, Yi Li, Jian-guang Liu, Yi-he Zhang. Evaluation of forming limit in viscous pressure forming of automotive aluminum Alloy 6k21-T4 sheet. Trans Nonferrous Metals Soc China 2007;17:1169–74.

[3] Feng Li, Xin-long Zhang, Wei Shi. Deformation behavior in the uniaxial tension process of aluminum and aluminum alloy sheets under fluid pressure. JOM J Miner Metals Mater Soc 2013;65:604–12.

[4] Zhi-chao Zhang, Yong-chao Xu, Shi-jian Yuan. Analysis of thickness variation of reverse deep drawing of preformed 5A06 aluminum alloy cup under different temperatures. Int J Adv Manuf Technol 2016;86:521–9.

[5] Xiao-bo Fan, Zhu-bin He, Wen-xuan Zhou, Shi-jian Yuan. Formability and strengthening mechanism of solution treated Al-Mg-Si alloy sheet under hot stamping conditions. J Mater Process Technol 2016;228:179–85.

[6] Li-hui Lang, Yong-ming Wang, Ya-su Xie, Xi-ying Yang, Ying-qiang Xu. Pre-bulging effect during sheet hydroforming process of aluminum alloy box with unequal height and flat bottom. Trans Nonferrous Metals Soc China 2012;22:302–8.

[7] Zhe Wang, Zhong-jin Wang, Min-xing Li. Microstructure evolution of Al 1060 under double-sided pressure deformation condition during viscous pressure bulging (VPB) test. Arab J Sci Eng 2009;34:3–10.

[8] Tie-jun Gao, Yang Liu, Peng Chen, Zhong-jin Wang. Analysis of bulging process of aluminum alloy by overlapping sheet metal and its formability. Trans Nonferrous Metals Soc China 2015;25:1050–5.

[9] Zhou Bin-Jun, Yong-Chao Xu. Wrinkle behavior of hydroforming of aluminum alloy double-layer sheets. JOM J Miner Metals Mater Soc 2016;68:3201–7.

[10] Teng Bu-gang Hu, Lan Liu Gang, Shi-jian Yuan. Wrinkling behavior of hydro bending of carbon steel/Al-alloy bi-layered tubes. Trans Nonferrous Metals Soc China 2012;22:560–5.

[11] Feng Li, Fu-jian Zhou, Mo-nan Wang, Peng Xu, Cheng-chuang Jin. Experimental studies on flexible forming of sheet metals assisted by magnetic force transfer medium. JOM J Miner Metals Mater Soc 2016;68:2261–7.

[12] Feng Li, Fu-jian Zhou, Mo-nan Wang, Shu-yue Zhu, Cheng-chuang Jin. New processing research on sheet metal bidirectional pressure forming using a magnetorheological fluid. Int J Adv Manuf Technol 2017;88:923–9.

[13] Feng Li, Peng Xu, Xiao-chong Sui, Fu-jian Zhou. Investigation of a new method for sheet deep drawing based on the pressure of magnetic medium. Mater Trans 2015;56:781–4.

[14] Merklein M, Rösel S. Characterization of a magnetorheological fluid with respect to its suitability for hydroforming. Int J Mater Form 2010;3:283–328.

[15] Rösel S, Merklein M. Improving formability due to an enhancement of sealing limits caused by using a smart fluid as active fluid medium for hydroforming. Prod Eng Res Devel 2014;8:7–15.