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Laser welding of laminated electrical steels

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ABSTRACT

Weldability of the high-grade electrical steel B27ahv1500 has been researched. Weld bead characteristics, torsion strength and magnetic properties of the welded laminations were measured and analyzed. Torsion strength of the welded laminations was linearly related to the weld bead area. Iron loss of the laminations welded at the speed of 10 mm/s had a percentage of increase of 24 compared to that of the laminations without welding when the magnetic flux density was 1.0 T. Lower boundary of the welding speed can be determined by the magnetic properties requirement and upper boundary of the welding speed can be determined by the torsion strength requirement.

1. Introduction

As pure or hybrid electrical vehicles are more and more widely used in automotive industry, performance of the drive motor has drawn increasing attention. Stator, as a key part of the motor, has been widely researched in recent years to improve the performance. The high-grade non-oriented electrical steels have been increasingly used in these years. Centner and Schäfer (2010) optimized the structure of the stator to display the optimal performance of the electrical steel. Krings et al. (2014) compared the effects of welding process on the performance of the stator with SiFe and NiFe, respectively. To further improve the stator performance, effects of manufacturing process on the performance of the electrical steel laminations need to be focused on.

The electrical steel is designed to be thin (e.g., 0.2, 0.27 and 0.5 mm) to obtain high magnetic permeability and low iron loss. Philp (2002) introduced that many electrical steels are laminated to form the stator. Loose electrical steel laminations are joined together to ensure the strength. Fig. 1 shows three of the most widely used join methods, which include glue join, mechanical join and fusion welding. Fig. 1(a) shows the schematic of glue join. The glue is gelatinized on both sides of the steels and the laminated steels are bonded by glue. Fig. 1(b) shows the schematic of mechanical join, mechanical interlock is formed between the sheets through protuberances. Fig. 1(c) shows the schematic of fusion welding. The laminated sheets are welded at the external circumference with the heat from laser, plasma or arc. Schoppa et al. (2003) reported that glue bonded laminations have the best magnetic properties among these three methods, while this method has high cost because of the harsh requirement for glue and has not been widely used at present. Meanwhile, the glue bonded laminations have lower stacking factor because the adhesive coating is usually thicker than the traditional one. Lamprecht et al. (2012) reported that the mechanical join method can cause serious magnetism degradation, and fusion welded laminations are widely used in the situation with high quality requirement because of the high joint strength and relatively low magnetic properties deterioration. Vegelj et al. (2014) introduced an adaptive pulsed-laser welding method for thin electrical laminations with significant magnetic performance improvement. However, stability of this method needed to be further validated because of the high requirement for controlling the welding process. Yang et al. (2011) reported that continuous laser welding had high welding speed and stable quality, and this method had been widely used in welding high strength steel in automotive industry. Markovits and Takács (2010) reported that continuous laser welding might be one of the most potential fusion welding methods to obtain high quality laminations.

Several researches on weldability of the electrical steel have been reported. Vourna (2014) reported the influence of electron beam welding on the microstructure, hardness and magnetic Barkhausen noise values of butt joint of the non-oriented electrical steel. Schade et al. (2014) researched the effect of process, design and material on both the amount of pores and the lap shear strength of the laser welded electrical steel laminations. However,

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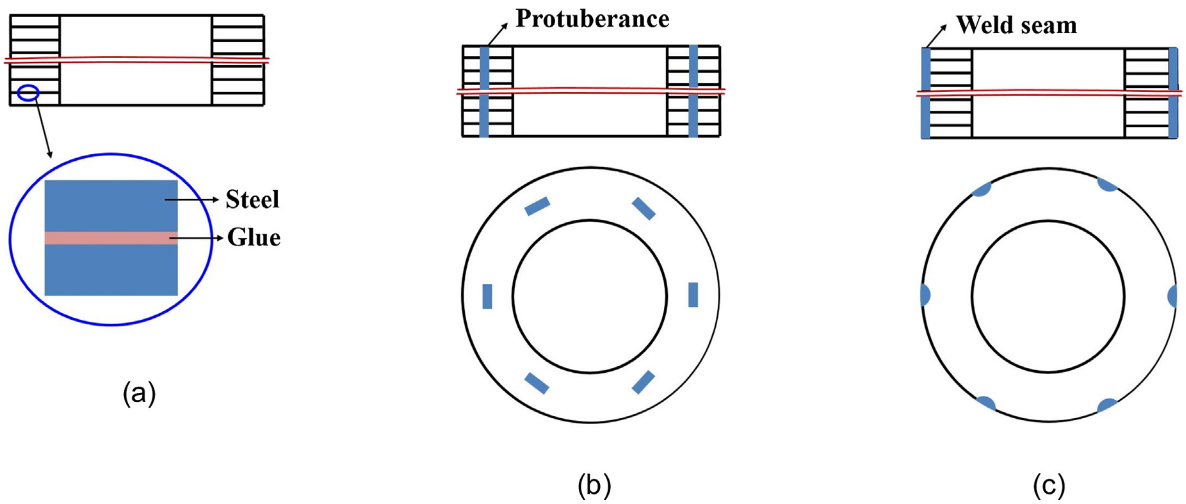

Fig. 1. Schematic of the join methods for laminated electrical steels: (a) glue join; (b) mechanical join; (c) welding.

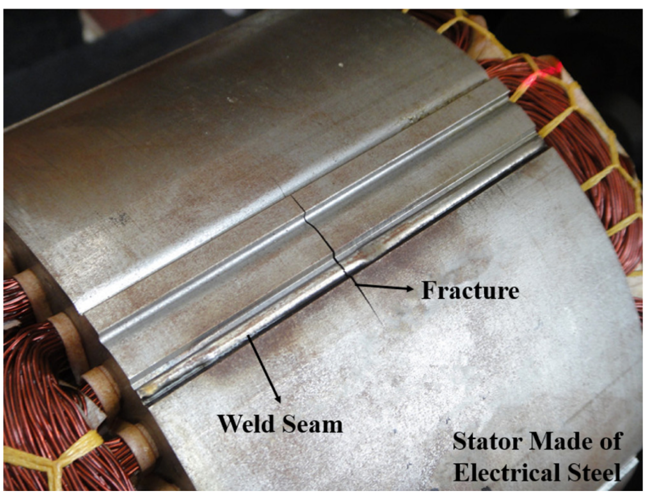

Fig. 2. Fracture in the weld seam zone of the welded stator.

weldability of the electrical steel laminations for laser considering both the mechanical properties and the magnetic properties had rarely been researched.

Nakayama and Kojima (2007) reported that joint strength and magnetic properties are two of the most important performance indicators of the stator. As the stator needs to bear the anti-torque equal to the motor output torque when motor works, torsion strength of the welded stator needs to be focused on. Fig. 2 shows the failed stator with the fracture at the weld seam zone, the stator with low torsion strength may fail under the function of torque. Kurosaki et al. (2008) developed a J-shaped hook to measure the joint strength of mechanical interlock and the critical factors that affecting the strength of the joined electrical steels were researched. Lee et al. (2014b) researched the effect of welding parameters on the strength of the welded lapped aluminum and copper specimen, and found that both the size and the microstructure of the joint significantly affected the strength of the lapped joint. However, parameters affecting strength of the welded stator had rarely been researched. As the stator works in the environment with alternating magnetic fields applied, both magnetic hysteresis loss and eddy current loss occur in the stator, which are totally called iron loss. Takashima et al. (1999) reported that high iron loss in the stator may reduce the energy conversation efficiency of the motor. Meanwhile, temperature of the stator increased as magnetic energy converted to thermal energy, and the insulation layer of the winding might be melt when the temperature was high enough. Clerc and Muetze (2012) reported that welding process could lead to magnetic properties deterioration. However, the quantitative effects of welding parameters on the magnetic properties had rarely been reported. As performance of the stator welded at various parameters has marked differences, it is meaningful to research the effects of laser welding parameters on this performance and obtain the range of the appropriate welding parameters.

In this paper, weld bead characteristics, torsion strength and magnetic properties of the laser welded laminations were measured and compared. Relationship between weld bead area and torsion strength was analyzed and magnetic properties deterioration mechanism was discussed. This work provides a guide to choose the appropriate laser welding parameters for laminated electrical steels.

Table 1
Chemical composition of electrical steel B27ahv1500.

Element	Si	Al	Mn	Fe
Mass fraction (%)	1.95	0.57	0.54	96.94

2. Experiment procedure

2.1. Welding experiment

Non-oriented 0.27 mm thick electrical steel B27ahv1500 (Baosteel Co., Ltd., Shanghai, China) was selected in this study. The composition and mechanical properties measured by us are shown in Tables 1 and 2, respectively. Density of the material was 7650 kg/m^3.

The ring laminations shown in Fig. 3 with an inner diameter (D_2) and an outer diameter (D_1) of 60 mm and 100 mm respectively were used in this paper. Schematic of the laser welding process of the ring laminations is shown in Fig. 4(a) and the fixture used in the experiment is shown in Fig. 4(b), the YLR-1500 ytterbium-doped fiber laser from IPG (IPG Photonics Co., Ltd., Massachussets, USA) was used as the laser source. The procedure for ring laminations fabrication is as follows:

Step 1: The electrical steel sheet was machined into the ring sample by electrical discharge machining (EDM). For sample used in the torsion experiment, eighty pieces of ring electrical steel sheets were laminated and aligned with a shaft. The laminations number of eighty was chosen to ensure that the height of the sheets was