



The impact of composition dependent and process-related properties in the laser cutting of metallic glassy tapes

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Abstract

A short survey is reported on the advantageous and disadvantageous properties of soft magnetic glassy tapes to build stator and rotor elements for the increase of motor efficiency. The relative high saturation magnetization and the relative permeability of these alloy groups seem to be promising in this application field. On the other hand, the sample thickness (30 μm) displays limitations in terms of a filling factor. High hardness of tapes hinders the effectivity of mechanical shaping. Laser cutting can be successful as shaping method, presuming that the extension (thickness) of heat affected zone (HAZ) can be successfully reduced below 50 μm , avoiding the brittleness evolution.

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1. Introduction

Recently an attempt has been made to apply the soft magnetic glassy tapes to build stator elements for electric motors increasing the electric motor efficiency (Satoru Simizu, et al., 2018; Yannis, et al., 2017).

Mainly the Fe-based glasses are the candidates for this purpose, due to their favorable soft magnetic properties, as well as the advanced production technology of rapid quenching. (Malinowski et al., 2004; Singh et al., 1992). Despite all these benefits, several additional issues, such as the shaping (cutting) of the tapes to the desired form, have to be solved. In this paper a survey of magnetic, thermal and mechanical properties, as well as some process-related properties will be summarized and, subsequently, the characteristic feature of heat affected zone evaluated by laser cutting will be discussed.

2. Experimental

2.1. Requirements for soft magnetic properties applied as core material in electric motors

The selection of the base materials is made on the basis of mapping the related properties of different alloys developed for soft magnetic applications. The results are summarized in

Fig.1, where the relative permeability (measured at 1 kHz) versus the saturation induction are plotted for various family of soft magnetic alloys.

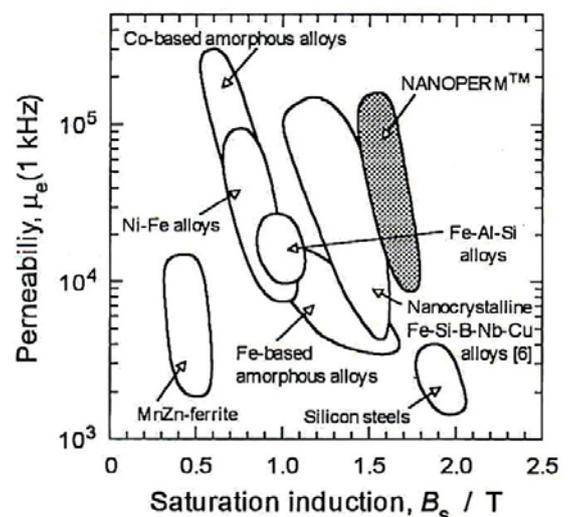


Fig. 1. The relation between saturation induction (B_s) and the relative permeability (μ_r) in various soft magnetic alloys (measured at 1 kHz) (Makino et al., 1995)

As Fig. 1. shows, in the crystalline state silicon steels the saturation induction (M_s) is outstanding, while, simultaneously, the permeability (μ_f) is poor. In contrast, the permeability of soft magnetic ferrites is good. Unfortunately, it coincides with low saturation induction. The amorphous alloys can offer an optimum between these properties which are equally important for the efficiency improvement of electric motors.

Based on the outlined properties, 2-3 group of glasses are the candidate as soft magnetic core production for stator elements. The selection is also motivated by the availability and also on the technical level of wide tape production. Based on the outlined restrictions, METGLAS and FINEMET type alloys are chosen and applied in the presented experiments.

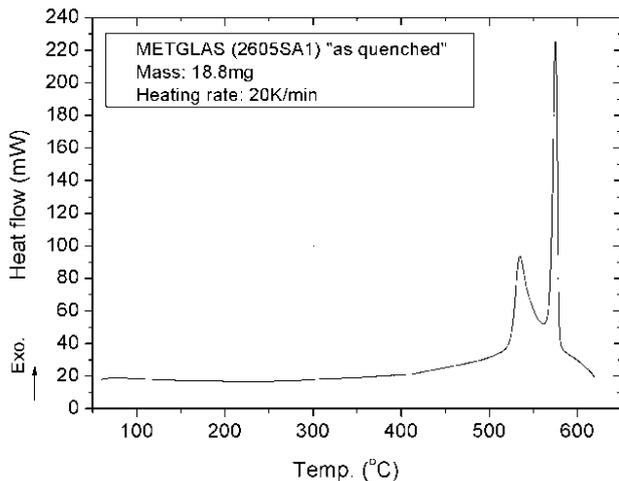


Fig. 2. DSC thermogram for the METGLAS sample

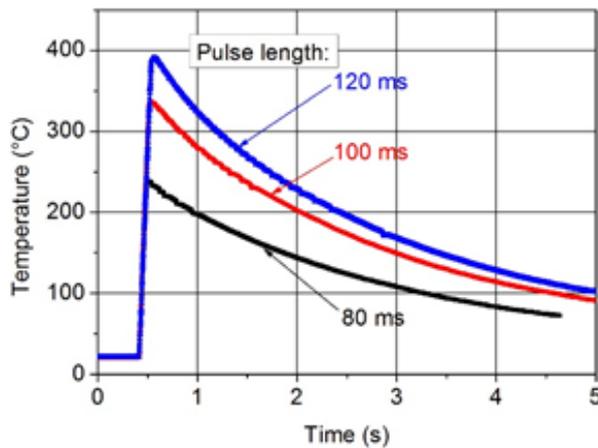


Fig. 3. Temperature dependence of FINEMET sample during pulse heat treatments at various pulse length (Kovac et al., 2015)

In addition to the requirements previously described (sufficient saturation induction and permeability), the following additional criteria can be defined and have to fulfilled:

- Sufficient thermal stability
- Insignificant tendency to the development of brittleness, especially at pulse-like heat effects.

To determine the thermal stability of the alloys, DSC measurements were carried out. Fig. 2. shows the DSC thermogram of METGLAS type alloy. The exothermic peaks in thermogram at around 500°C is a crystallization onset, where the amorphous state decomposes to Fe₃(SiB) solid solution (first peak). The second peak is attributed to the Fe-B compound precipitation from the remainder amorphous matrix. The thermogram also exhibits a slow exothermic heat flow between 300-500°C, which is the thermal manifestation of structural relaxation below the crystallization process. During this slow change, non-isotherm short range atomic reordering occurs in the glasses, which are responsible for the permeability-increase (decreasing coercive force, H_c). In this temperature range, an unfavorable brittleness can also be developed, but in case of laser cutting the heat effect occurs within a very short period of time.

The change of experimental modelling of temperature over time in terms of pulse annealing can be seen in Fig 3. where the temperature change is illustrated for various pulse lengths. Such pulse-like T-runs are supposed to be similar to a case when laser cutting is applied for the shaping of glassy tapes (see later). The experimental research results show that above the 300°C peak temperature, the glassy samples become brittle.

The theoretical treatment of brittleness evolution is based on the free volume theory of glass formation (Tsai-Wei Wu et.al, 1990). The macroscopic shear viscosity is supposed to describe the connection between the shear viscosity $\eta(T)$ and the average free volume v per atom. ΔG_m is the activation energy of displacement, v^* the critical free volume fluctuation, γ a geometrical factor between 0.5 and 1, and C a constant: This macroscopic tendency of viscosity change is considered as the phenomenological background for the evolution of brittleness in the rapidly quenched sample.

$$\eta(T) = CRT \exp\left(-\frac{\Delta G_m}{RT}\right) \exp\left(\frac{\gamma v^*}{v}\right) \quad (1)$$

According to the outlined consideration, the evolution of brittle behavior is a consequence of the rate-dependence of free volume annihilation, which is quenched-in the samples during the rapid solidification. The degree of pulse-like relaxation (which can fluctuate from site to site) may cause a spontaneous deformation of the samples during laser cutting heat treatments.

3. Results and discussion

3.1. Heat pulse effects associated with laser cutting

Laser cutting is based on the local melting of the ribbon according to the scheme in Fig. 4. The cut tapes exhibit macroscopic waviness (Koti et al., 2018) which has a strong laser power dependence (Fig. 5). During the laser cut, a thin layer of melt is formed along the cutting zone. Remaining small traces of molten alloy is adsorbed, however, on the neighboring age of tapes and resolidifies along the cutting edge. As the result, the local stress state changes, resulting in a waviness on the glassy tapes and a thermally affected zone is also developed inside the material which is being cut.

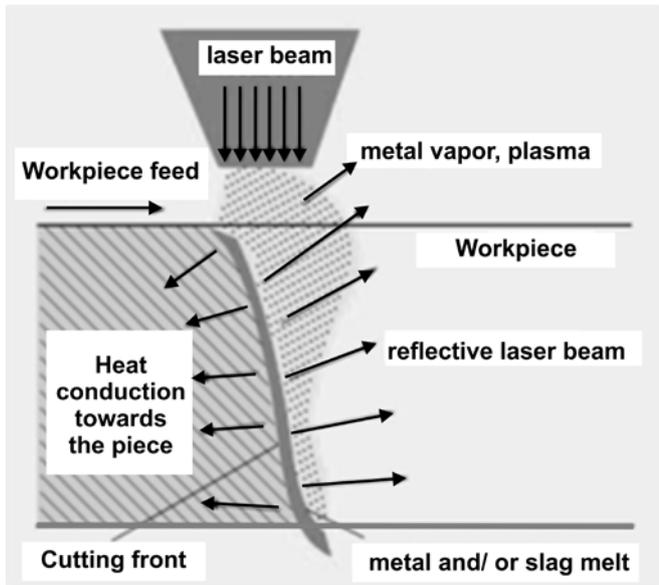


Fig. 4. The scheme of laser cutting



Fig. 5. Macroscopic waviness is developed due to the local pulse-like heat transfer (Koti et al., 2018)

3.2. The mechanism of "heat affected zone" evolution: changes in the local structure

During the cutting process, the warming up and local melting is pulse-like, and small volume of material is involved only. In addition, the warming up (including the melting process) is strongly asymmetric due to the unidirectional movement of laser spot, resulting in a strong gradient of overheating in the ribbon and even in the molten drop.

The cutting process can be divided into the following sub-processes, involved in the small transformed volume when cutting the ribbons (Ban et al., 2018):

- amorphous-crystalline transformation (during the warming period)
- local melting
- local solidification (liquid-crystalline transformation)
- crystallized layer from solid state
- development of structurally relaxed zone (in the vicinity of intact tape)

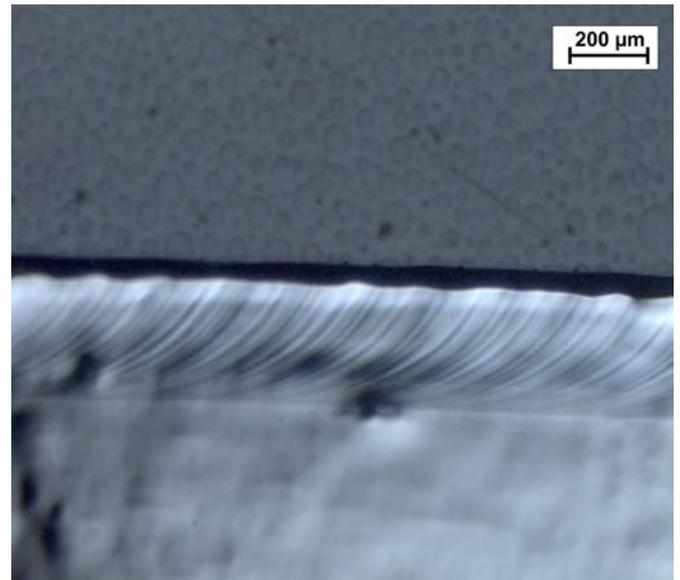


Fig. 6. The optical micrographs of heat affected zone, obtained on the cross section

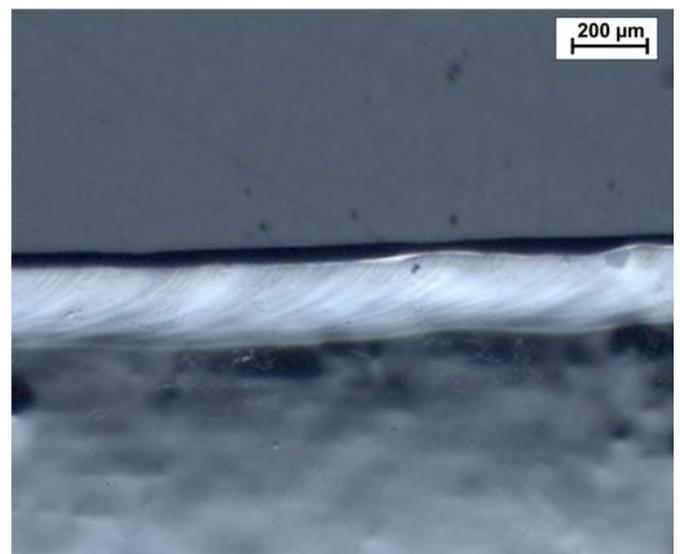


Fig. 7. The optical micrographs of heat affected zone, obtained on the cross section

As the results of these transformations, optically detectable continuous zone can be observed on the surface of tape in the vicinity of the front which is cut. The visibility is based on the different optical reflectivity between the crystallized and untransformed part of the tape.

The optical micrographs of the zones are illustrated in Fig. 6., and Fig. 7. The thickness of the transformed zone depends on the applied scanning rate during the laser cutting according to the different pulse-like local power density. Accordingly, with increasing cutting speed, the thickness of the zone decreases. (See Fig. 8).

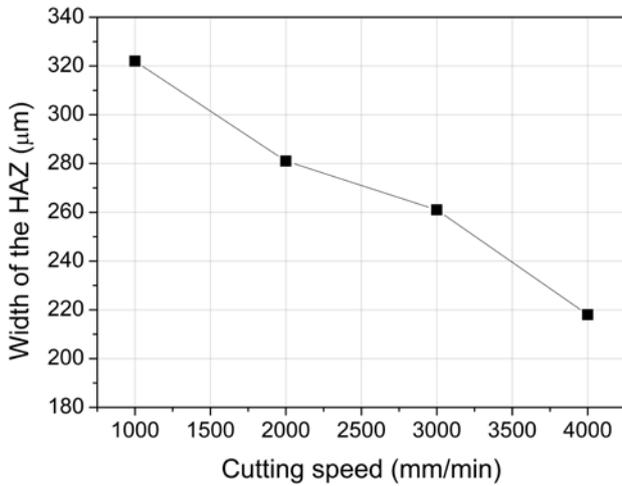


Fig. 8. The thickness of heat affected zone versus the applied cutting speed

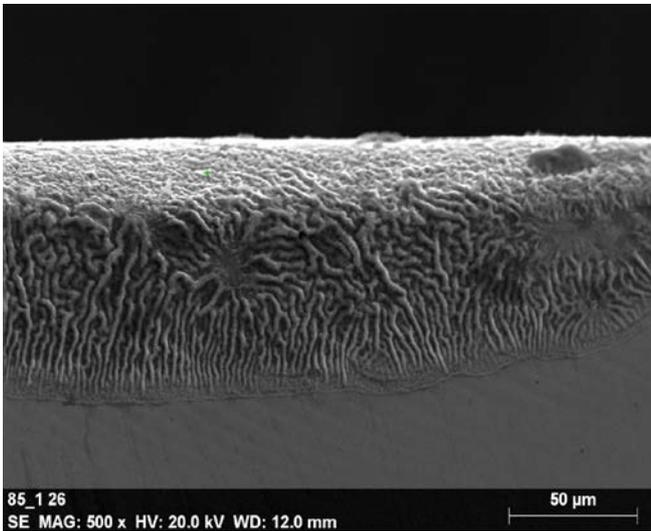


Fig. 9. The fine structure of heat affected zone obtained by scanning electron microscope

In Fig. 9, a high resolution picture of the heat affected zone is shown. A columnar microstructure is typical with increasing coarsening of structure as the cutting age is approached. This columnar microstructure resembles to the eutectically solidified microstructure, where the solidification started from double nucleation centers. The ultrafine structure is found in the vicinity of untransformed region and seems to be correlated with the pronounced temperature gradient (starting from the cutting age) across the transformed layer.

Local hardening effect can be observed within the heat affected zone (Ban, 2018), which also supports the local crystallization in the heat affected zone. It is typical when crystallization from amorphous state occurs. The hardening is in good agreement with the layer thickness of the transformed zone (HAZ), as it can be observed in the optical micrographs.

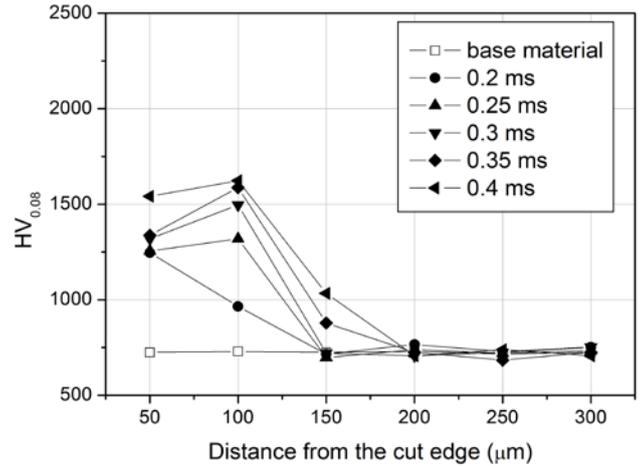


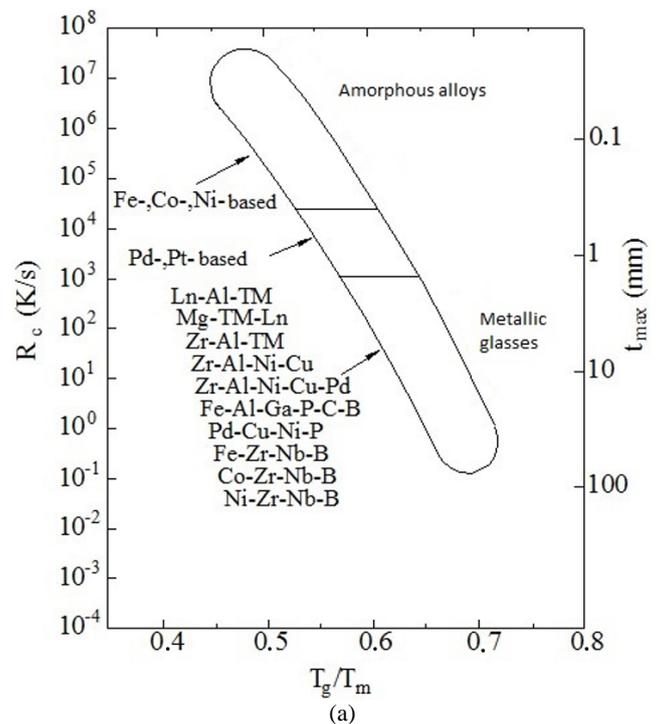
Fig. 10. The local microhardness increase crossing the heat affected zone

3.3. Process-related limitations of glassy tapes in the application in asynchronous motors

Filling factor and the ribbon thickness

The main limitation of glassy alloy application in the asynchronous motors is the unfavorable filling factor arising from the $\sim 30 \mu\text{m}$ average thickness of the available tapes. Significant increase of thickness is limited by the relative poor glass forming ability of Fe-based alloys. This limitation can be observed in Fig. 11a and Fig. 11b., where the maximum available thickness is plotted together with the critical cooling rate for a number of glass forming system.

Soft magnetic glassy tapes (Fe-based) with sufficient magnetic properties can be prepared in the form well below $100 \mu\text{m}$ thickness.



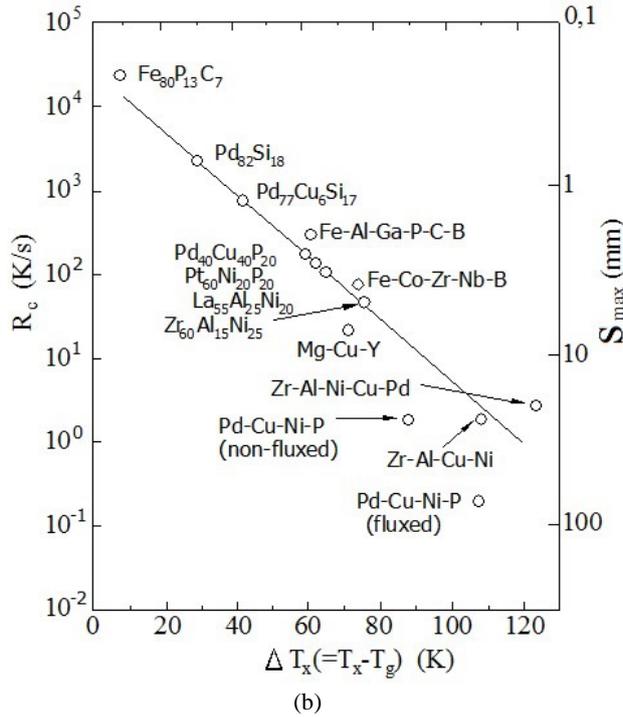


Fig. 11.(a, b) Connection between the critical cooling rate and the maximum sample thickness for several glass forming system (Inoue, 1999)

Hardness, as limiting factor in the shaping of glassy alloys

Mechanical properties in glassy state represent obstacle in the shaping of glassy tape. The hardness of transition metal-based glasses is high, due to their metalloid (especially B) content. The disorder itself also contributes to the hardness increase.

The increasing covalent bonding character among the components triggers the development of brittleness, especially in a structurally relaxed state. High hardness and brittleness are typical especially for multicomponent, high glass-forming alloys.

On the other hand, the replacement of Fe-host with other transition metals results only in insignificant outcome as far as the hardness value is concerned. (see Fig. 12b) (Lovas et al., 1995).

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In summary, high hardness, combined with low ribbon thickness represent serious limitation to the application of mechanical stamping of glassy tapes.

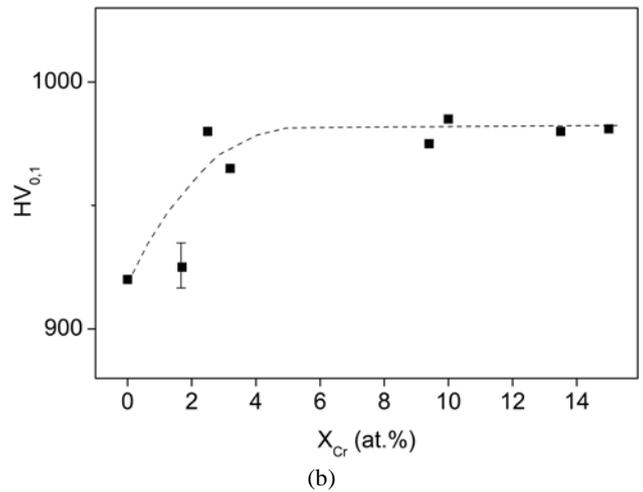
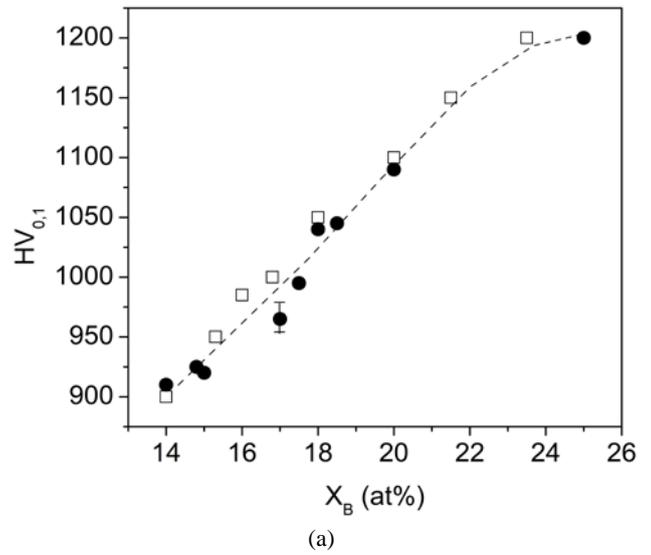


Fig. 12.The change of microhardness in Fe-based glasses versus the B content(a) versus the Cr-content (b) (Lovas et al., 1995)

4. Summary and conclusion

For the efficient increase of electric motors the impact of soft magnetic, mechanical glassy alloys are investigated:

- From the point of view of magnetic properties, both the high saturation induction and the high permeability are inevitable for this application.
- The high hardness (and the tendency to the evolution of brittleness) associated with the presence of metalloid content (glass formers), as well as the limited thickness of the tapes represent serious limitations for the mechanical shaping (stamping) of the glassy tapes.
- Though the laser cutting is promising technology for the shaping of glassy alloys, the evolution of „heat affected zone” is found during the CO2 laser cutting. This zone consists predominantly from the crystallized part of ribbon in the vicinity and parallel to the cutting front.

- Local hardness increase is typical within the heat affected zone. The origin of this zone complex partially arises from the local crystallization, and, partially from the localized -pulse-like structural relaxation.

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成分依赖性和工艺相关性质对金属玻璃带激光切割的影响

關鍵詞

激光切割金属玻璃带，
脆性演变，
胶带的厚度与填充系数的
关系

摘要

报道了软磁玻璃带的有利和不利特性的简短调查，以构建定子和转子元件以提高电动机效率。在这个应用领域中，这些合金组的相对高的饱和磁化强度和相对磁导率似乎是有希望的。另一方面，样品厚度（30 μm）在填充因子方面显示出限制。高硬度的胶带阻碍了机械成形的有效性。激光切割成功的方法可以成功，假设热影响区（HAZ）的延伸（厚度）可以成功地降低到50 μm以下，避免了脆性的演变。
