Microstructure and mechanical properties of Mn-Cu based damping alloy fabricated by laser melting deposition

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Abstract—The M2052 (Mn-20Cu-5Ni-2Fe, at%) damping alloy specimen was prepared by laser melting deposition (LMD). We studied the mechanical properties and microstructure of M2052 alloy. Columnar dendrite penetrating multiple cladding layers appeared in the as-deposited sample, and the size of dendrite tends to coarsen with the increase of laser power. Microsegregation and martensitic transformation occur in the as-deposited M2052 alloy. The tensile strength of samples in different directions under the same process, and in the same direction under different processes is all exceeds 500 MPa. The fracture surfaces exhibit intergranular fracture model. This work shows great potential for fabricating Mn-Cu based damping alloy by LMD technology.

1. Introduction
Mn-Cu based alloy is a kind of structural-functional integrated metamaterial with good mechanical properties and high damping properties. The micro twin interface generated by martensitic transformation in the alloy moves reversibly under the periodic stress, causing the static lag of strain and stress phase. Then the vibration energy will be dissipated by transforming into heat energy, so as to the damping effect is achieved [1, 2]. Yin F X developed commercial M2052 (Mn-20Cu-5Ni-2Fe, at%) alloy and it has been widely used [3].

At present, Mn-Cu based damping alloys are mainly fabricated by casting [4]. There are some limitations in the casting process. High manganese damping alloy has poor fluidity and is easy to oxidize at high temperature. Vacuum induction melting equipment cannot prepare high manganese damping alloy in large volume and batch. The process of forging and hot rolling is complex and lengthy, so it cannot respond to the requirements of design quickly. Laser melting deposition (LMD) technology uses high-power laser to melt the metal powder transported synchronously, and accumulates the required near net shape three-dimensional parts layer by layer without mold [5]. The fabrication of Mn-Cu based damping alloy by LMD has urgent practical needs and extensive research prospects. Some researchers prepared M2052 alloy by selective laser melting (SLM) and explored the influence of forming and heat treatment process on damping and mechanical properties [6-8], however, no research on Mn-Cu based high damping alloy by LMD is reported.
In this study, M2052 high damping alloy is fabricated by LMD technology, and the mechanical properties and microstructure in different process parameters are examined. The results have important practical significance for promoting the application of high damping alloy by LMD in aerospace, precision instruments fields, etc.

2. Materials and methods
Vacuum induction melting gas atomization (VIGA) prealloyed M2052 alloy powder was used for preparing the test specimens. The morphology of M2052 alloy particle is shown in Fig. 1(a) and the distribution of powder size is shown in Fig. 1(b). Most of the particles were circular, and satellite balls can be seen on the surface of the particles. The M2052 alloy powder has a normal measure of 188.0 μm within 111.6~280.9 μm range, which is suitable for LMD.

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Fig.1 (a) Particle morphology of M2052 alloy powder, (b) particle size distribution of M2052 alloy powder

LMD system utilized in this research consists of 3 kW semiconductor laser system, YC52 dedicated coaxial feeding head, GTV powder delivery system, 4 axis CNC motion stage. The experiment was carried out in an atmosphere protection box, and the content of O can be controlled to less than 500 ppm. Argon is used for the powder feeding protective gas and carrier gas. The wavelength of the laser beam is 1060 nm, and the diameter is 3 mm. Table 1 shows the parameters for preparing the M2052 sample.

Table 1 Parameters for preparing the M2052 sample

| parameters                  | Process I | Process II | Process III |
|-----------------------------|-----------|------------|-------------|
| Laser power (W)             | 750       | 1000       | 1250        |
| Velocity (mm/s)             | 10        | 10         | 10          |
| Powder feeding rate (g/min) | 7.8       | 7.8        | 7.8         |
| layer thickness (mm)        | 0.2       | 0.2        | 0.2         |

The sketch map of LMD process is shown in Fig. 2(a). 25 mm thick 0Cr13Ni4Mo alloy plate was chosen as the substrate, and the surface was cleaned with sandpaper and acetone. Fig.2 (b) appears the tensile testing sample, and Fig.2 (c) appears the sketch map of tensile testing sample. M2052 sample with the measure of 85×4×95 (x×y×z) mm, 85×4×45 (x×y×z) mm, 85×4×45 (x×y×z) mm prepared by LMD is appeared in Fig. 2(d), (e), (f), individually.

The microstructure of the as-deposited test samples were studied through FEI Tecnai G2 F20 S-Twin transmission electron microscopy (TEM) equipped with energy dispersive spectrometer(EDS), JSM-6510 scanning electron microscope(SEM), and axiovert 200 MAT optical microscope(OM). The samples for OM and SEM observation were etched with 25 ml H2O+ 20 ml HCl+ 5 g FeCl3 solution.

Mechanical properties of the as-deposited M2052 samples were characterized by tensile testing, and the results take the average of 3 samples. NT100 electronic tensile testing machine was used for tensile testing at room temperature with the loading speed of 0.5 mm/min. Fracture surface of tensile samples were studied through SEM.
3. Test Results and Discussions

3.1. Microstructure of M2052 alloy fabricated by LMD

Table 2 appears the component of the powder and as-deposited specimen. Inductive coupled plasma emission spectrometer (ICP-AES) was used to analyse the component of Fe, Ni. Titration method was used to analyse Mn, Cu, and inert gas pulsed infrared method was used to analyse O. The component of the deposited specimen is profoundly consistent with those of the powder. Due to the function of atmosphere protection box, the content of O in the LMD-M2052 alloy is relatively low.

| Element (wt. %) | Cu  | Ni  | Fe  | O   | Mn   |
|-----------------|-----|-----|-----|-----|------|
| M2052 alloy powder | 20.81 | 4.72 | 1.56 | -   | Bal. |
| LMD-M2052 alloy  | 19.79 | 4.53 | 1.53 | 0.036 | Bal. |

Fig. 3 shows the microstructure of as-deposited M2052 thin-wall sample on XOY section under different processes. The microstructure is randomly distributed dendrite, and the size of the microstructure tends to coarsen with the increase of laser power. Therefore, the microstructure of the Mn-Cu based alloy can be regulated by controlling the process of LMD.

(a), (d) Process I; (b), (e) Process II; (c), (f) Process III

Fig. 3 Microstructure of as-deposited M2052 thin-wall sample on XOY section
Fig. 4 shows the microstructure of as-deposited M2052 thin-wall sample by Process I on XOZ section under different magnification. Columnar dendrite structure penetrating multiple cladding layers appeared in the sample. Zhao C Y et al. [9] also found the columnar dendrites in the Mn-Cu binary alloys fabricated by SLM. Based on the classical solidification theory, the morphology of primary grain is mainly determined by solidification rate and temperature gradient. During the grain growth process, solute atoms are enriched at the front of solid-liquid interface, and then constitutional supercooling is formed through microsegregation. Due to the high solidification rate and temperature gradient, columnar grains will dominate the microstructure in directed energy deposition (DED) process [10, 11]. The characteristic size of columnar grains is controlled by solidification conditions and is stable only in a certain temperature gradient range. At a sufficiently low temperature gradient, the primary crystal axis develops and grows a secondary crystal axis, and at a lower temperature gradient, it grows a tertiary crystal axis and forms dendrites.

![Fig.4 Microstructure of as-deposited M2052 thin-wall sample on XOZ section](image_url)

Fig. 5(a) and Fig. 5(f) shows the TEM bright field image of the as-deposited M2052 alloy. Fig. 5(b) ~ (e) shows the distribution of elements in Fig. 5(a), and it can be seen that microsegregation occurs in the as-deposited M2052 alloy. Mn and Fe are rich in the dendrite core and Cu and Ni are rich in the interdendritic region. The solid solubility of Fe in Mn is 100%, while it is almost insoluble in Cu, which is consistent with the experimental results. Twin crystal can be seen in Fig. 5(f), indicating that martensitic transformation has occurred in the as-deposited M2052 alloy. EDS results at different sites in Fig. 5(a) are shown in Table 3. The component is consistent with the element distribution shown in Fig. 5(b) ~ (e). It can also be seen from Table 3 that the Mn content in the Mn rich area is as high as 95.80%, indicating that the alloy has undergone spinodal decomposition in the process of LMD, which provides conditions for the formation of martensitic twins.

![Fig.5 (a), (f) Bright field images of as-deposited M2052 alloy, (b) Mn distribution map, (c) Fe distribution map, (d) Ni distribution map, (e) Cu distribution map](image_url)
Table 3 Element content of different positions in as-deposited M2052 alloy (wt. %)

| Element | 1      | 2      | 3      |
|---------|--------|--------|--------|
| Mn      | 95.80  | 84.22  | 51.58  |
| Cu      | 1.07   | 9.96   | 39.16  |
| Ni      | 0.77   | 3.50   | 7.92   |
| Fe      | 2.36   | 2.32   | 1.34   |

3.2. Mechanical properties of M2052 alloy prepared by LMD

Fig. 6 shows the tensile properties of as-deposited M2052 alloy. The ultimate tensile strength (UTS) of X-I specimens is 541±4 MPa and the UTS of Z-I specimens is 527±3 MPa. The elongation of X-I specimens is 4.5±0.4%, and the elongation of Z-I specimens is 4.0±1.1%. The tensile strength parallel to X is slightly higher than that of Z, while the elongation along different direction is almost the same. Along the stretching direction of Z, the tensile strength of process I, II and III is basically the same, which are 527±3 MPa, 520±30 MPa and 523±31 MPa respectively. With the increase of laser power, the elongation tends to increase, and the elongation is 4.0±1.1%, 4.2±0.0% and 6.2±0.4% respectively. The mechanical properties of the as-deposited sample can be adjusted by post heat treatment [12-14], and the related contents need to be further studied.

Fig. 6 Tensile test results of as-deposited M2052 samples. X stands for the tensile direction is parallel to X; Z stands for the tensile direction is parallel to Z

Fig. 7 shows the tensile fracture along X and Z directions of the sample prepared by process I. Since the X direction is perpendicular to the epitaxial growth direction of dendrite, it can be seen from Fig. 7(a) that the sample breaks along the dendritic boundary. While Z direction is parallel to the epitaxial growth direction of dendrite, no morphology of dendritic boundary can be seen. The characteristics of intergranular fracture can be seen both in Fig. 7(b) and (d).

Fig. 7 Tensile fracture along X (a), (b) and Z (c), (d) directions of the sample prepared by process I
4. Conclusion
Based on the results and discussions presented above, the conclusions are obtained as below:

(1) The Mn-Cu based damping alloy thin wall sample can be fabricated by LMD. Microsegregation and martensitic transformation occurs in the as-deposited M2052 alloy. Columnar dendrite penetrating multiple cladding layers appeared in the as-deposited sample, and the size of the dendrite tends to coarsen with the increase of laser power.

(2) The tensile strength of as-deposited samples fabricated by LMD is all exceeds 500MPa. The fracture surfaces exhibit intergranular fracture model. This work appears incredible potential for manufacturing Mn-Cu based damping alloy by LMD technology.

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