APPLICATION OF LASER-BASED ADDITIVE MANUFACTURING TO PRODUCTION OF TOOLS FOR FRICTION STIR WELDING

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Abstract

This paper presents a feasibility study of application of laser-based additive manufacturing to production of tools for friction-stir welding (FSW) of materials. The design and rapid manufacturing of powerful tools has become one of the major challenges in expanding the application of FSW processes to new materials. The one-step laser cladding process is capable of creating a novel, fully dense and metallurgically bonded near-net-shape tool with microstructural and compositional gradients. In this paper, two kinds of FSW-tool materials are developed and evaluated for the applications of welding different materials. A pure H13 tool steel powder is used to build a FSW-tool for welding the materials with relatively low melting temperatures, such as aluminum alloys. A WC-based ceramet/tool steel functionally graded material (FGM) is synthesized to build a FSW-tool in order to weld the materials with higher melting temperatures and highly abrasive materials such as MMC materials. By controlling the amount of different supplied powders under the optimized laser cladding conditions, WC-based ceramet/tool steel FGMs are successfully synthesized layer by layer. FSW experiments are carried out to evaluate the deposited tools.

Introduction

A novel solid-state joining process, friction stir welding (FSW), invented by The Welding Institute (TWI, Cambridge, UK) in 1991, has recently caught the great attention of the welding community for fabricating high-quality butt and lap joints of aluminum alloys. The same potential exists for FSW of hard metals such as titanium, stainless steel, and nickel base superalloys [1-3]. One of the major challenges in expanding the application of FSW processes to new materials is the lack of suitable tools for welding materials with high melting temperatures [1]. To be effective, tool materials must resist physical and chemical wear, possess sufficient mechanical strength at elevated temperatures, and effectively dissipate the heat carried to the tool during the welding process. The development of new tooling made of polycrystalline cubic boron nitride (PCBN) appears capable of meeting the requirements, but the cracking of tool during the FSW of materials clearly causes the degradation of the tool life [1]. The suitability of FSW for hard metals such as stainless steel and titanium alloys has been investigating with a carbide tool [1-3].

Most manufacturers have been looking for a device that can make a tool directly from a computer-aided design (CAD) drawing with a designed composition, microstructure, and properties. Selective laser sintering (SLS), laser-engineered net-shaping (LENS), micro-casting, laser-based additive manufacturing (three-dimensional laser cladding), and shape deposition manufacturing (SDM) are some important layer-manufacturing processes for the rapid prototyping/manufacturing system. In the one-step laser cladding, the powder material is injected continuously into a laser molten pool and melts to form a clad track on the surface of the substrate. A layer is formed successively by tracks deposited side by side [4,5]. A variety of materials including metals, ceramets, ceramics, and composite claddings have been successfully deposited to develop a potential in non-equilibrium synthesis of advanced functional materials, alloy development and free-form near-net shape manufacturing [4,5]. Composite surface layers have been produced by injection either ceramic particles or a mixture of metal and ceramic powders at a certain ratio, into the laser molten pool [4,5]. Hard particles such as WC, TiC, SiC, and CrB_2 are usually employed to improve the wear resistance of the engineered surfaces [4,5]. WC particles are distinguished by a minimal plastic deformation capacity, a low thermal expansion and a high wettability by molten metals. With a high content of hard particle, the deposited surfaces are relatively rough and a high crack rate cannot be avoided. This result may be overcome with the use of solid state Nd:YAG lasers that allow improved control of the cladding process at low heat input [4]. High-power lasers in conjunction with a powder-feeding technique, have been used to produce functionally graded materials (FGMs) by the successive deposition of different clad layers. However, the large differences in thermal and physical properties between metals and ceramics cause serious problems in the fabrication of metal/ceramic FGMs by laser cladding [4]. Since the heating and the cooling rates are rapid during laser cladding, the cracks form more easily not only at the interfacial regions between different constituents but also within the ceramic particles. There are difficulties in controlling the porosity and cracking in some cases, and the chemical interaction between the matrix and ceramic particles due to high temperatures involved in laser cladding.

In this paper, a feasibility study has been carried out to produce a FGM FSW-tool consisting of WC-based ceramet and H13 tool steel using the laser-based additive manufacturing technique. A graded distribution of WC particles was realized by adjusting the flow rate of different powders for successive layers. The WC particles in the deposited FGM provides a high wear resistance, while the H13 tool steel exhibits an excellent combination of hardness and toughness at elevated temperatures.

Experimental procedures

Fig. 1 shows the schematic diagram of the laser-based additive manufacturing system setup used in this investigation. A 1kW continuous wave Nd:YAG laser with a 200-mm focusing optics is used to deposit the powders. Recently developed computer-controlled powder feeders are used for dosing and feeding the powder mixture into the desired composition, and allow for an exact setting and continuous change of the powder mixture during the cladding process. The alignment of the laser beam, powder nozzles, and their positioning in relation to the substrate must be accurate for the process to be reproducible. The feed rate of each of the powders and laser parameters are controlled automatically. All the deposited parts are built up on the substrate of an AISI 1018 mild steel. The clad materials studied are H13 tool steel powder and WC-based ceramet powder. The chemistry of H13 tool steel powder with a particle size range of +44 to -152 μm is tailored to allow the material to withstand the temperature, pressure, abrasion, and thermal cycling. The chemical composition of a WC-(NiSiB alloy) ceramet powder is a 35 wt.% Ni-Si-B self-fluxing alloy and 65 wt.% macrocrystalline WC with a particle size range of +46 to -122 μm. The processing parameters are given in Table I. For the FGM linear freeform structures (wall patterns), the WC particle content is varied stepwise from 0 at the bottom to 65 wt. % at the top layer of the deposited dense material. For the FGM multiple-dimensional parts, the WC particle content is varied stepwise from 0 at the inside core to 40.6 wt.% at the outside surface of the deposited pars. This process is carried out with an effective argon shrouding device to minimize oxygen contamination.

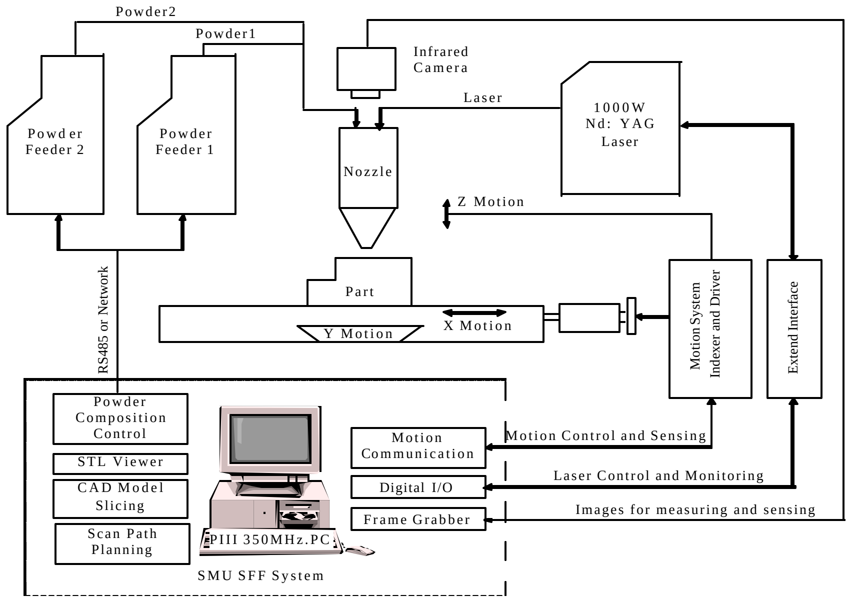


Fig. 1 Schematic diagram of laser-based additive manufacturing system setup

Table I Experimental conditions for the rapid manufacturing of FSW-tools

Laser power, W	200-600
Laser beam diameter, mm	1.0
Traverse speed, mm/s	5-15
Powder feed rate of H13 tool steel, g/min	0.5 –10
Powder feed rate of WC-(NiSiB alloy) ceramet, g/min	1.5-20
Offset between two subsequent clad tracks in the horizontal direction, mm	0.64
Offset between two subsequent layers in the vertical direction, mm	0.38
Gas flow rate of argon, l/min	12-20

The standard methods of metallography are applied to obtain microstructural and compositional analyses of the FGMs. All the microhardness tests are carried out using a Vickers microhardness tester and a 500-g load for 15 sec on polished specimens. For microstructural observations, all the samples are selectively etched using a modified reagent consisting of hydrofluoric acid and nitric acid, and then observed using an optical microscope. A surface texture-measuring device is used to study the surface roughness of the parts. The maximum profile roughness height is the distance between the lowest and highest points on a surface. All the friction-stir welds have been made in a butt-weld configuration using a laser-deposited FSW-tool and an FSW machine as stated in our previous paper [6].

Results and Discussion

Rapid Manufacturing of a H13-steel FSW-tool

Fig. 2 shows the deposited linear freeform structure (wall) of H13 tool steel using a laser power between 250 and 500 watts, at a traverse speed of 8 mm/s to 20 mm/s. The wall is produced by deposition of tracks on top of each other. The feed rate of H13 tool steel powder is 3 g/min. The offset between two subsequent layers on the vertical direction is about 0.38 mm. A thin layer of the previous clad material is remelted when the subsequent layer is deposited.

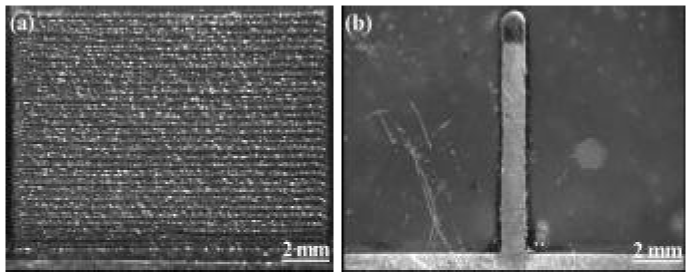
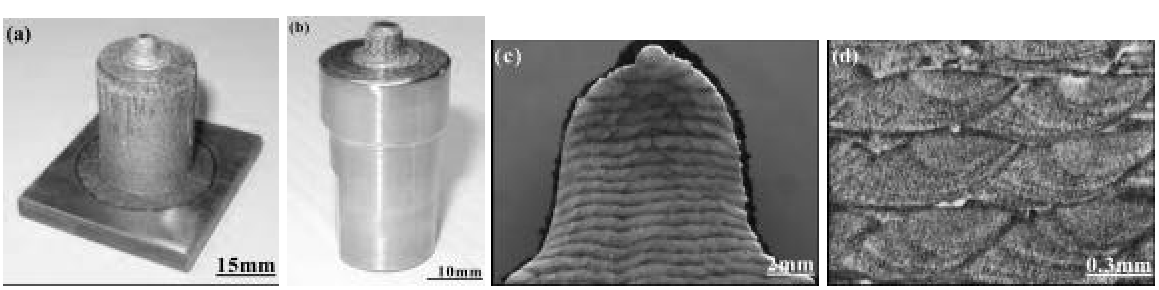


Fig. 2 Typical features of the deposited layers of the H13-steel wall: (a) surface morphology; (b) cross-section.

Fig. 3 shows a laser-deposited H13-steel FSW-tool for the friction stir welding of aluminum alloys. The laser cladding parameters are optimized to be a 350-W laser power, 1.0-mm beam diameter, 10-mm/s traverse speed, 0.64-mm horizontal offset between two subsequent clad tracks, and 0.38-mm vertical offset between two subsequent clad layers. The feed rate of the H13 tool steel powder is 3 g/min. The deposited H13 tool steel exhibits a finer, more uniform martensitic structure with possibly some retained austenite. The characteristic rows and layers of the deposited H13 material reflect solidification from the moving laser molten pool as shown in Fig. 3(d). Self-tempering phenomenon at the overlapping regions is observed at some overlapped regions by the extensive heat input as shown in Fig.3(e). The average secondary dendrite arm spacing that is representative of the cooling rate of the deposited H13 metal is about 0.5-1 µm from the microstructural analysis. The calculated cooling rate varies from 1×10^4 to 1×10^5 K/s depending on the locations in the deposit of the H13-steel prototypes. The maximum surface roughness of the deposited H13 FSW-tool is about 18 µm. The microhardness of the deposited H13 FSW tool is between 576 and 642 $HV_{0.5}$. The deposited H13-steel FSW-tool exhibits an excellent ability in welding the 6.5 mm thick 6061 aluminum alloy plates as shown in Fig. 3(f). No weld defects are observed in the weld cross-section of 6061-aluminum to itself as shown in Fig. 3(g).



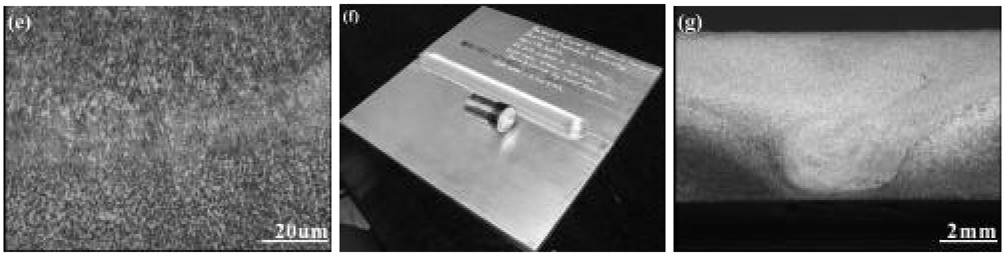


Fig. 3 A laser-deposited H13-steel FSW-tool for the friction-stir welding of aluminum alloys: (a) the as-deposited tool; (b) the tool after hard-turning; (c) cross section of the deposited tool pin; (d) the overlapped laser clad tracks; (e) microstructure at the overlapped region; (f) the tool and the welded 6061 aluminum alloy plate of 6.5 mm in thickness after FSW; (g) cross section of a friction-stir weld of 6061 aluminum to itself.

Rapid Manufacturing of a FSW tool of WC-(NiSiB alloy) ceramet/H13 tool steel FGM

Fig. 4 shows the deposited freeform structures of FGM are deposited using a laser power between 250 and 500 watts at a traverse speed of 8 mm/s to 20 mm/s. The weight fraction of the WC particles varies stepwise from 0 at the bottom to 65 wt.% at the top of the as-deposited wall as shown in Fig.4. The walls are produced by a stepwise deposition of tracks on top of each other. The offset between two subsequent layers on the vertical direction is about 0.38 mm. For the functionally graded walls that start with the pure H13 tool steel powder, the amount of the WC-(NiBSi alloy) ceramet in the powder mixture is increased steadily to generate material with a compositional gradient. The designed distribution of WC particles (wt.%) in the deposited FGM walls is 0, 23.1, 40.6, 54.2, and 65 from the bottom layer to the top layer. The graded wall in Fig. 4a is 40 mm in length and 12 mm in height, consisting of 31 discrete layers. The wall thickness is approximately 1.0 mm. At a low magnification, the layered structure of the wall is also visible. The surface contains a number of white WC particles originating from the powder-feeding process. The clad layer consists of the WC particles, ?-Ni primary dendrites, and the eutectics at the interdendritic regions. From the cross section (Fig. 4(b)), the composition of the FGM changes gradually from the pure H13 tool steel at the bottom layer to the pure WC-(NiBSi alloy) ceramet at the top layer. By adjusting the powder variants and the laser processing parameters used, laser cladding process is capable of fabricating crack-free FGM wall patterns that are dense, metallurgically bonded, and geometrically accurate. Fig. 4(h) shows the deposited pattern consisting of several FGM walls. The deposited walls are 20 mm in height and 1.0 mm in thickness. Although the walls are easily made from the pure H13-steel powder, the addition of hard-phase particles like WC brings along a significantly higher cracking susceptibility. Since the unavoidable stresses caused by the thermal cycle of the deposition process accumulate with the clad process, crack-free walls are obtained only when the dimensions of the samples are kept small. Different microstructures are obtained with selected carbide contents as shown in Fig.4(c)-(g). With the increase of the carbide content, a large number of carbide particles remain undissolved or only partially dissolved. As the content of the WC particles increases to 65 wt.%, the WC particles grow significantly coarser as shown in Fig.4(g).

The aggregation and bridge connection growth of the undissolved WC particles produce flower-like clusters in the molten pool as shown in Fig. 5. When more WC particles are dissolved or partially dissolved, the chemical composition of the matrix alloy is greatly changed.

From Fig. 5(a)-(c), the matrix alloy consists of ?-(Fe, Ni) primary dendrites and eutectics of ?-(Fe, Ni) plus carbo-borides at the interdendritic regions. The content of the eutectics depends on the dissolution degree of the WC particles. The content of eutectics in Fig.5(c) is clearly lower than that in Fig. 5(a). At the regions with a low content of carbon and boron as shown in Fig. 5(d), no eutectic constituent is observed.

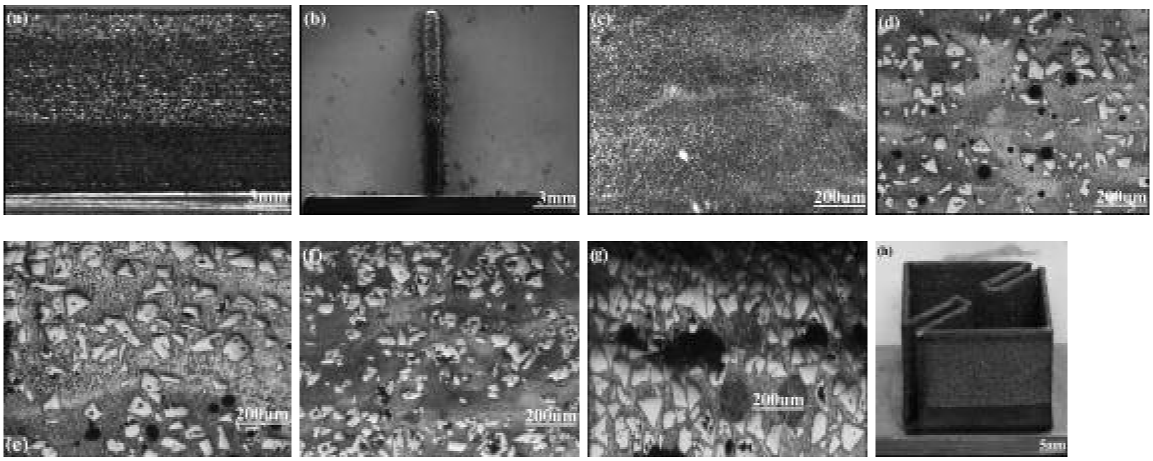


Fig.4. Typical features of functionally graded layers of the deposited WC-(NiSiB alloy)/H13 wall: (a) surface morphology; (b) cross-section; (c) pure H13 tool steel at the bottom layer; (d) 23.1 wt.% WC particle; (e) 40.6 wt.% WC particle; (f) 54.2 wt.% WC particle; (g) 65 wt.% WC particle at the top layer; (h) FGM wall pattern.

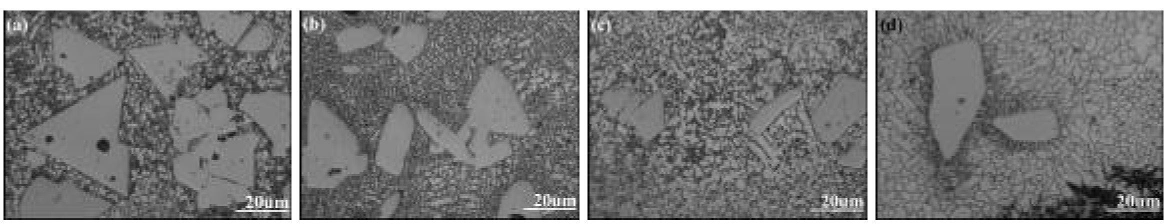


Fig. 5 Effect of the partial dissolution of individual WC particles on the microstructure of the matrix in the deposited FGM: (a) at the top layer with a high content of WC particles; (b) in the middle of the as-deposited FGM; (c) at the low layer with a low content of WC particles; (d) near the interface between pure H13-steel to ?-(Fe, Ni);.

Fig. 6 shows a laser-deposited FGM FSW-tool for the friction-stir welding of hard metals. One of the major challenges in expanding the application of the FSW process to new materials is the design and rapid manufacturing of powerful tools. A WC-based ceramet/tool steel functionally graded material (FGM) is synthesized to build a FSW-tool in order to weld the hard metals. By controlling the amount of different supplied powders under the optimized laser cladding conditions, the content of WC particles around both the tool pin and the shoulder is varied stepwise from 0 at the inside core to 40.6 wt.% at the outside surface. The hardness of the WC particles, measured at a load of 500 g for 15-s, is between 1845 and 2435 $HV_{0.5}$ and depends on its partial dissolution, reprecipitation, and growth process. In contrast, the matrix alloy, which is a resolidified products of H13 and the molten WC-(NiBSi alloy), is found to be in the range of 400 to 540 $HV_{0.5}$. The hardness of the matrix alloy is greatly affected by the content and partial dissolution of the WC particles. The surface roughness of the FGM FSW-tool is between 12.5 and 16.7 µm. The FGM prototypes that have a smaller surface roughness than the H13 tool steel prototypes may be due to the self-fluxing nature of the NiSiB matrix alloy. The feasibility study of using this FGM tool to friction-stir weld the 6.5 mm thick Ti-6Al-4V alloy has recently been carried out as shown in Fig.6(c) and (e). Although some weld defects such as the voids are found in the weld, distinct plastic flow of titanium alloys is developed by the stirring action of the FGM tool. This progress is still under development together with the friction stir welding of a 316L stainless steel to itself.

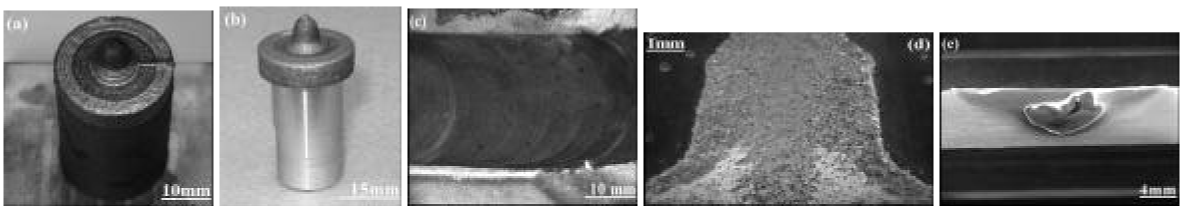


Fig.6. An FGM FSW-tool with a shoulder diameter of 25 mm and a compositional gradient of the WC particles from 0 (the inside core) to 40.6 wt.% (the outside surface) along the radial direction including the tool pin: (a) before hard-turning; (b) after hard-turning of the H13 deposit base; (c)plan view of a friction-stir weld of Ti-6Al-4V alloy to itself; (d) the cross-section of the FGM FSW-tool pin (tip) and the graded distribution of the WC particles from the center to the surface; (e) cross-section of a friction-stir weld of Ti-6Al-4V alloy to itself.

Fig.7 shows a distribution of the WC particles along the radial direction of the cross section of the deposited FGM FSW-tool shoulder (left side). From the pure H13 tool steel (top of Fig. 7(b)) to the WC-(NiSiB alloy) ceramet (bottom of Fig. 7(d)), the content of the WC particles covered in the images increases gradually from 0 to 40.6 wt.% along the radial direction. The characteristic rows and layers of the deposited H13 material reflect solidification from the moving laser molten pool (top of Fig.7(b)). However, these features are not quite clear in the layers containing a high content of WC particles (Fig.7(c) and (d)).

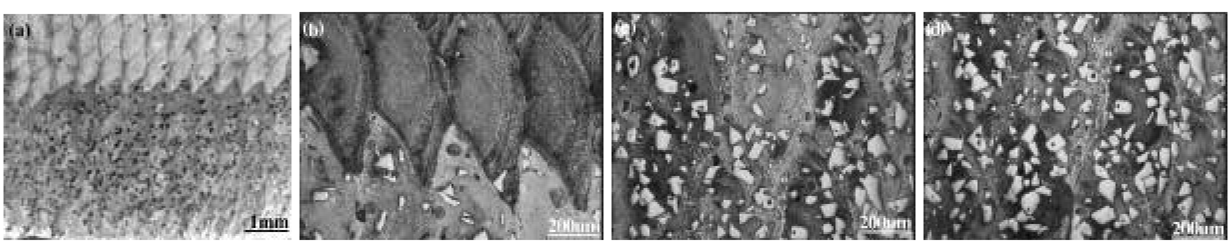


Fig. 7 Distribution of WC hard particles along the radial direction of the cross-section of the deposited FGM FSW-tool shoulder (left side in Fig.6(a)): (a)morphology of cross-section (top: inside core; bottom: outside surface of the tool shoulder); (b) interfacial region; (c) 23.1 wt.% WC particles; (d) 40.6 wt.% WC particles.

Conclusions

A feasibility study of application of laser cladding technique to the rapid manufacturing of tools for friction-stir welding (FSW) of materials is carried out. The one-step laser cladding process is capable of creating a novel, fully dense and metallurgically bonded near-net-shape tool with microstructural and compositional gradients. Two kinds of FSW-tool materials are developed and evaluated for welding different materials. A pure H13 tool-steel powder is used to build a FSW-tool for welding the materials with relatively low melting temperatures, such as magnesium and aluminum alloys. A WC-based cermet/tool steel functionally graded material (FGM) is synthesized to build a FSW-tool in order to weld the materials with higher melting temperatures and highly abrasive materials such as MMC materials. By controlling the amount of different supplied powders under the optimized laser cladding conditions, WC-based cermet/tool steel FGMs are successfully synthesized layer by layer. The FGM exhibits an expected gradient structure, a high bonding strength, and a distribution in functionality of synthesized layers between the superhard surface with an excellent wear resistance and the inside core with a combination of toughness and hardness at elevated temperatures.

Acknowledgement

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