EVALUATING THE PROPERTIES OF PRODUCTS FABRICATED FROM COMMERCIAL STEEL POWDERS USING THE SELECTIVE LASER MICRO-WELDING RAPID MANUFACTURING TECHNIQUE

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ABSTRACT

Selective laser micro-welding (SLMW) is a recent rapid manufacturing technique that produces metal parts through the use of a laser beam that selectively scans over the powder layers and fully melts and micro-welds the metallic particles. The advantage of SLMW is that any type of commercial steel alloys or other metal powders can be used to build parts in a single step without the need to add low melting point additives to join the particles as in the former SLS process.

In this study, two types of low cost general purpose powders were evaluated as the raw materials for the selective laser micro-welding (SLMW): one powder is AISI304 stainless steel powder from Hoganas, Belgium (cost = \$11/kg) and the other is AISI1005 low carbon steel locally produced in-house from scrap steel using gas atomizing then de-oxidizing techniques (cost = \$1.2/kg). Twelve sample parts were fabricated using two different laser speeds, 70 and 100 mm/s. Dimensions, density, hardness, tensile and microstructure properties were evaluated. Results showed that both powders successfully produced complete parts with accurate dimensions and fine details. Both microstructure phases were austenite due to the rapid heating and cooling cycles. At the higher speed of 100 mm/s mechanical properties deteriorated because of the porosities inside the structure. Using low cost powders gives more potential for the SLMW to spread as an economical manufacturing process in the near future.

Keywords: Rapid manufacturing, Selective laser micro-welding (SLMW), AISI 304 stainless steel; AISI1005 low carbon steel.

1. INTRODUCTION

Rapid manufacturing (RM) of metal products using metal powders as raw materials is a recent tool for the manufacturing of products such as porous and light weight medical implants, metallic filters, micro-scale moulds and dies and spare parts. Selective laser sintering (SLS) and selective laser melting and micro-welding (SLMW) are common names for different RM systems that share the same concept of using a fast-moving laser beam to selectively melt and join the metal particles stacked layer by layer to build freeform products [1, 2].

Early SLS machines were built with low power laser, up to 50W, which was not sufficient to completely melt metal powders. To compensate, system manufacturers patented special raw materials that include polymers or low melting point elements mixed with base metals. In the first step, the laser melts the polymer part and partially joins the metal particles to form a "green" structure. Later, in a subsequent step, this structure is infiltrated with other metals like copper to improve strength and other mechanical properties. This is why SLS is identified as the "indirect process" [3, 4]. The cost of using these special mixtures is relatively high because manufacturers will not reveal the components and sell them as ready-to-use building materials packages at high cost (about 200 Euro/kg). For this reason, products manufactured by rapid manufacturing systems are still very expensive and are not yet considered as economical industrial solutions.

SLMW machines implement new lasers with power up to 200W which is sufficient to directly melt and micro-weld different metal alloys, like pure iron, stainless steel, tool steel and titanium powders, in a single process without the need to add low melting elements. This is why it is identified as the "direct" process [5, 6]. On the other hand, using laser energy could overheat or burn the metal particles or induce undesired thermal degradation to the metal properties, like producing other microstructure phases or hard face inclusions that become micro-crack or thermal stress initiators due to the rapid melting and cooling cycles at the very finite laser beam focus point. For these reasons, SLMW is considered to be a very complicated metallurgical process which is characterised by the following major points: (1) high heat input from laser energy; (2) very localised melting of the fine powder particles; (3) micro-welding of the fine particles in plan and with the lower layers; (4) fast cooling and heat sink to the base metal and the neighbouring powders; and (5) high sensitivity to the alloying elements and atmospheric gases due to the short thermal reactions [7, 8]. To assure that acceptable product quality and strength will be produced from the SLMW process, operators should provide very accurate control over the laser energy and beam scanning speed, selection of layer thickness based on the powder particle distribution, type and purity of shielding gases and post-processing surface finishing and heat treatment [9].

The major contribution for the SLMW as new rapid manufacturing process is that it is an open system which can use any type of metal powder as raw material on condition that the laser energy is sufficient to melt the particles. This could eliminate the dependence on the very expensive materials packed by the machine manufacturers and could respond to market demands to produce low cost products through using very low cost materials. However, this needs much research to study and optimise the above-mention parameters for different materials.

In this study, two types of general purpose commercial powders are evaluated to build products using the selective laser micro-welding (SLMW) techniques: one powder is AISI304 stainless steel powder from Hoganas, Belgium (cost as ordered = $11/kg) and the other powder is low carbon steel (grade AISI 1005) which is locally produced in CMRDI, Egypt from scrap steel using gas atomizing then de-oxidizing techniques (cost = $1.2/kg). Process parameters and product quality and properties are investigated and discussed.

2. EXPERIMENTS

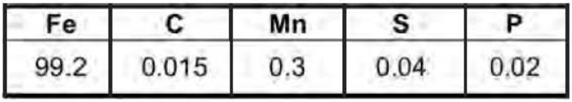
2.1. Materials

Tables 1 and 2 show the chemical analysis results for the two powders as revealed by x-ray diffraction analysis. Tables 3 and 4 show the particle size distributions as resulted from the stacked sieves analysis. Fig. 1 shows scanning electron microscope (SEM) images for the powders. It is observed that the shape of AISI304 powders (Hoganas, Belgium) is spherical and homogeneous and the shape of AISI 1005 powders is elongated and cylindrical which could be due a defect of the "in-house" production of the powders. Still the cost of AISI 1005 powers is $1.2/kg which makes it acceptable for the purpose despite the potential to entrap more porosity due to irregularity.

Table 1: Chemical analysis for AISI 304 powder:

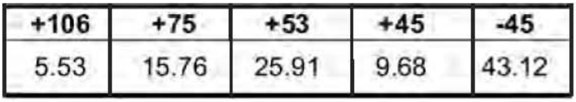
Fe	C	S	N	Cr	Mn	Si	Oxy
70.2	0.02	0.01	9.4	18.1	0.8	0.9	0.214

Table 2: Chemical analysis for AISI 1005 powder:



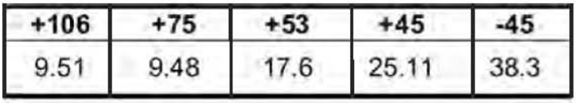
Fe	C	Mn	S	P
99.2	0.015	0.3	0.04	0.02

Table 3: Particle distribution for the AISI 304 powder (Microns):



+106	+75	+53	+45	-45
5.53	15.76	25.91	9.68	43.12

Table 4: Sieve analysis of AISI 1005 powder (Microns):



+106	+75	+53	+45	-45
9.51	9.48	17.6	25.11	38.3

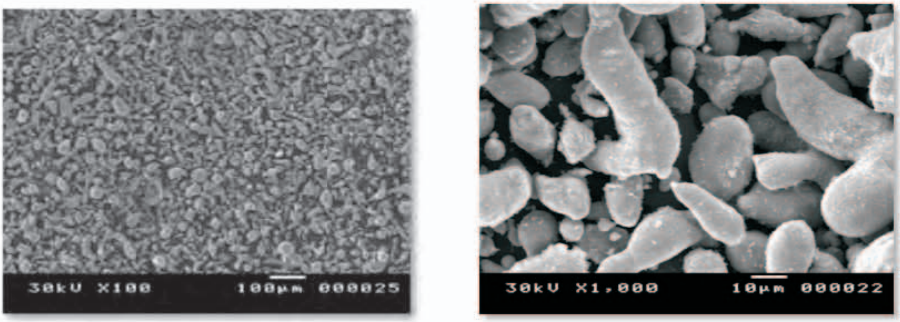
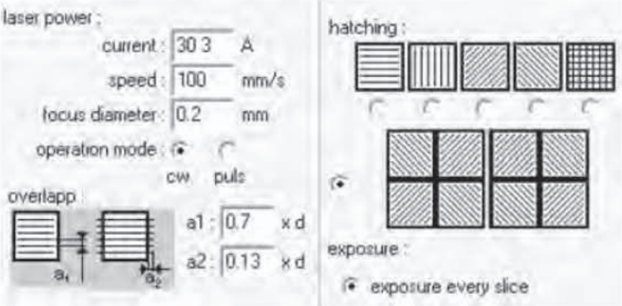


Figure. 1: SEM images for (a) AISI 304 and (b) AISI 1005 powders

2.2. Machine and procedure

The SLMW machine: m3Linear was used to manufacture the evaluated samples of each powder [6]. All building processes were done under 99.95% pure nitrogen environments. The standard process parameters for iron-based alloys were used. Figure 2 shows the process parameters used to build parts as printed from the machine control screen. Two laser scanning speeds were evaluated, 70 and 100 mm/s respectively. Laser power was fixed at 100W (about 30A) and layer thickness was fixed at 50µ.


laser power :

current : 30 3 A

speed : 100 mm/s

focus diameter : 0.2 mm

operation mode : ● cw ○ puls

overlapp :

a1 : 0.7 x d

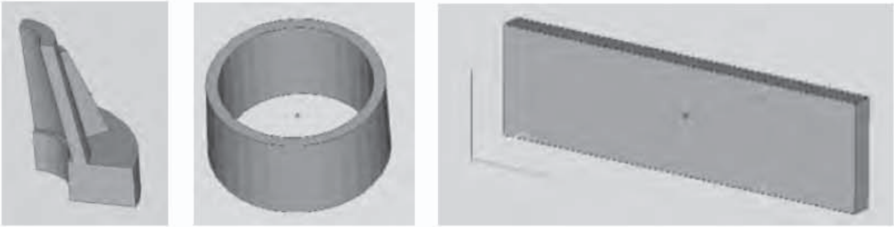
a2 : 0.13 x d

hatching : ○ ○ ○ ○ ○ ●

exposure : ● exposure every slice

Figure. 2: Laser process parameters for the m3Linear machine

The three sample CAD shapes shown in Figure 3 were designed using Magics software and built from each powder. Shape (a) was designed to evaluate the ability of materials to build thin walls up to 1mm at angle 60 with fine details, shape (b) to evaluate the dimensional accuracy and ability to build true circular walls and (c) the rectangle shape was used to form different tensile test specimens according to ASTM E8. The process was repeated for each powder at the two different speeds 70 and 100 mm/s. A total of 12 parts were built. After building, parts were separated from the building plate using EDM wirecut. Side surfaces were finished using ultrasonic air lap device. Dimensions were measured using Renishaw 3D digitizer. Surface hardness was measured on different faces of each sample using micro Vicker hardness apparatus (load 10 kg for 15 sec.) Microstructure specimens were prepared according the standard procedure for each type of steel.



(a) (b) (c)

Figure 3: Sample CAD shapes that were built out of each powder

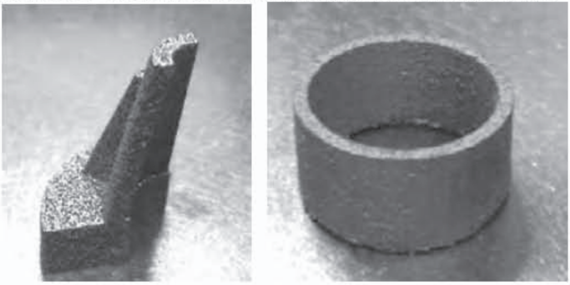


Figure 4: Examples of the products, the left is AISI304 and the right is AISI1005

3. RESULTS AND DISCUSSION

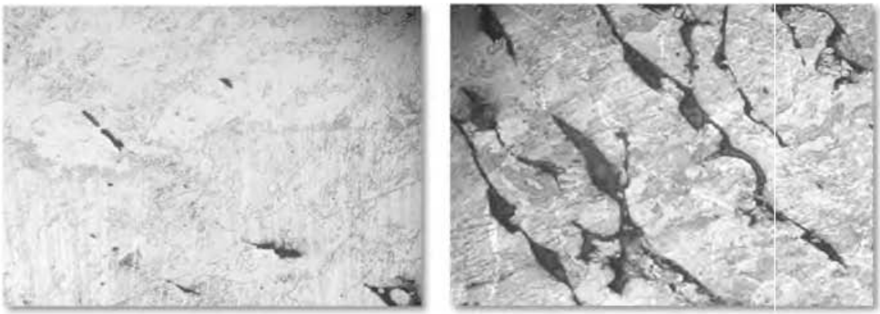
3.1. Shape and dimensions

As shown in Fig. 4, the two powders successfully produced parts with complete details and accurate dimensions. The thin walls were straight and complete. Curved walls were also fine. XY dimensions in the 12 samples were 1.5~3% less than the designed CAD file. This can be explained by the shrinkage during solidification and/or the surface finish process that removed the weakly attached powder particles at the side surfaces. There were no noticeable indicators for the effect of the powder type on the dimensions. There were also no visual indicators for the effect of scanning speed on the dimensions. For both powders, the visual evaluation revealed no surface cracks or separations between layers. Layers at macro-scale were very coherent together, which means that complete melting of metal powder particles had been achieved during the process.

3.2. Microstructure

3.2.1. AISI1005 powders

Microstructures for the two materials where evaluated using an optical microscope, SEM and x-ray diffraction analysis. As shown in Fig 5, the microstructure at laser scanning speed of 70 mm/s was solid and homogeneous with little porosity between layers. At the higher speed of 100 mm/s larger porosities and micro separations between layers appeared. This can be explained by several factors including the lower laser energy applied at 100 mm/s which could not make complete melting and metal diffusion to eliminate these porosities, and the presence of oxygen between iron particles due to storages and handling which formed gases like CO_2 that were entrapped inside the melt or iron oxides layers that barred the complete melting of particles at this high speed. Another important reason for the formation of voids and porosity inside the metal could also be the differences between particle sizes and the presence of particles larger than the layer thickness (Tables 2 and 4). Large particles are removed by the leveling blade which moves over the powders before laser scanning, leaving large voids inside the layers. Small particles entrap air gaps and form porosity after melting and shrinkage.



(a) Laser scanning speed = 70 mm/s (b) Laser scanning speed = 100 mm/s

Figure 5: Microstructure images (x200) for AISI1005

XRD analysis, Fig. 6, revealed that the microstructure of AISI1005 was 90% austenite phase. This is also explained as the result of the localised heating by laser to more than 1000°C then the very rapid cooling to less than 100°C within a few seconds due to heat sink in the big base plate and the neighbouring powder pool. The very short heating and cooling cycles entrapped the austenite structure and suspended the phase transformation back to ferrite [12].

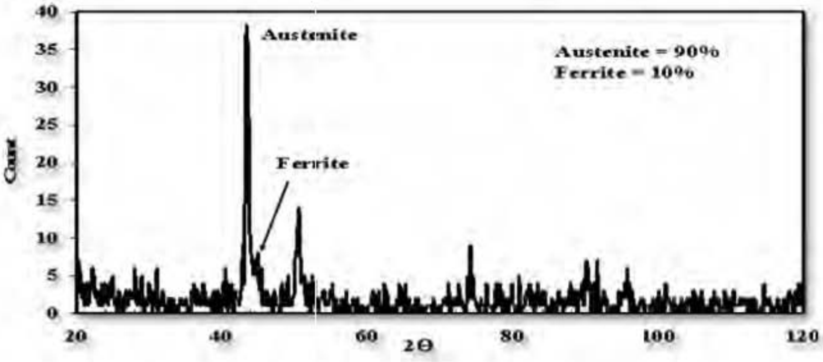
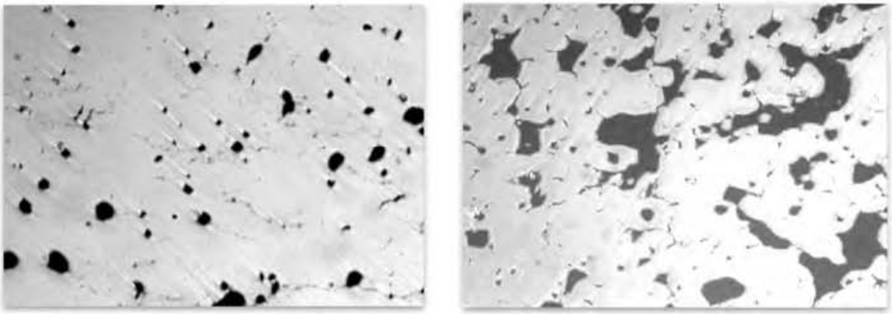


Figure.6: XRD analysis for AISI1005 powders reveals 90% austenite phase

3.2.2. AISI304 powders

For AISI 304 (Fig. 7), similar to AISI1005, increasing the speed from 70 mm/s to 100 mm/s resulted in more porosity, cracks and layer separations. Porosities occurred for different reasons like forming and entrapping of CO_2 due to the presence of C and the traces of oxygen between powders, etc. XRD analysis revealed austenitic phase which is identical to the welded materials subjected to rapid cooling cycles in the presence of near to 10% Nickel. The same ideas for the effect of powder particles applies as well.



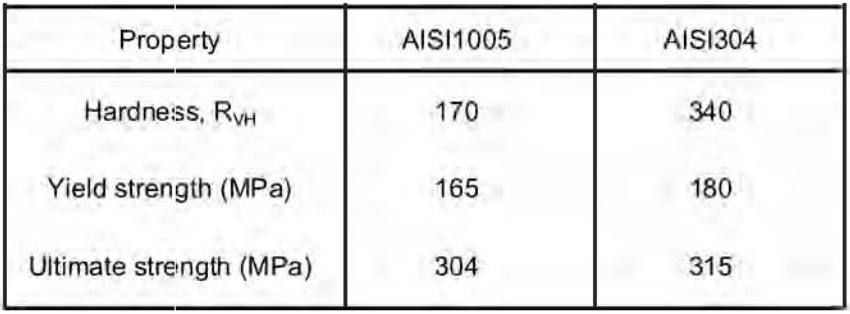
(a) Laser scanning speed = 70 mm/s (b) Laser scanning speed = 100 mm/s

Figure 7: Microstructure (x50) for AISI304

3.3. Mechanical properties

Tensile properties where evaluated according to ASTM E8 by forming standard specimens from shape c (Fig. 3) then testing on universal testing machines. Hardness values were measured at five spots in each sample then readings were averaged for each material. Mechanical properties were evaluated only for scanning speed 70 mm/s because of the porosity shown in the microstructure images at speed 100 mm/s which badly deteriorated the mechanical properties. As shown in Table 5, hardness values for both materials are high compared to raw material blocks. This could be attributed to the FCC structure maintained through the austenite phases due to the rapid heating and cooling cycles. Tensile strengths were expected to be high as well for the same reason. The presence of porosity and the very small layer separations even at 70 mm/s acted as stress concentration initiators and reduced cross section areas. There were no indicators for the effect of material type on mechanical properties. Only scanning speeds and particle sizes affected the properties.

Table 5: Average measured properties for AISI1005 and AISI304 (speed = 70mm/s)



Property	AISI1005	AISI304
Hardness, R_{VH}	170	340
Yield strength (MPa)	165	180
Ultimate strength (MPa)	304	315

3.4. Process time and cost

Based on the previous results, process time and cost are influenced by laser scanning speed and layer thickness which is a function of the powder particle sizes. The optimum scanning speed for AISI1005 and AISI304 should be less than 70 mm/s as discussed before in order to maintain minimum porosity and higher strength for the structure. Layer thickness should be selected not to be high to permit laser penetration and the full melting of the powders and the joining with the lower layers and not to be very low to double the building time and waste the powder particles with sizes larger than the layer thickness (Tables 2 and 4). Layer thickness 50 to 70 is acceptable and provided building time near to 1.3 CC / hour which is a good rate for SLMW.

The major factors influencing product cost are the powder cost, machine service cost and electricity, which could be up to 2KW/hr for the 100W laser. The cost of the human operators is limited because SLM is a non-attendant, fully automated process. Using low cost powders as described in this paper reduced the product cost to less than $1 for all the parts in Fig. 4.

4. CONCLUSION

This study has discussed the use of two types of general purpose low cost powders, less than $12/kg, to build metal products using Selective Laser Micro-Welding (SLMW) rapid manufacturing techniques aimed at reducing the product cost while maintaining accuracy and properties. Two types of steel powders, AISI 304 and AISI 1005, were investigated.

Results showed that both powders built the designed shapes with accurate details, sharp corners and thin walls. Increasing the laser speed from 70 mm/s to 100 mm/s induced porosity and layer cracks which caused the mechanical properties to deteriorate. Microstructure phases were maintained as austenite due to the rapid cooling and heating cycles.

Selective laser micro-welding (SLMW) techniques were very successful using these low cost materials and this can provide the potential for the use of SLMW to spread as an economical manufacturing process in the near future.

Further work should be done to optimise the laser energy and beam speed and to investigate the effect of cooling rates on both materials.

5. REFERENCES

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