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In-Situ Preheating in Hybrid Layered Manufacturing for Tooling Elements

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Abstract

Solidification cracking of hard materials such as H13 tool steel is one of the major problems in metal based *Additive Manufacturing (AM)* processes. *Hybrid Layered Manufacturing (HLM)* is one of the metal based AM process which uses *Metal Inert Gas (MIG)* cladding for addition and CNC milling for subtraction of material. In this work, an in-situ induction heating based preheating system has been developed to solve the solidification cracking problem. The *Tungsten Inert Gas (TIG)* and Induction heating methods are compared and it has been found that the induction based preheating system can produce better microstructure and sound products. In the experimental procedure, before deposition of a layer the prebuild layer is preheated up to 350-500^{0}C. Also the effect of in-situ preheating on the microstructure of the deposited layers have been studied using *Scanning Electron Microscope (SEM)*.

Introduction

In the last three decades Additive Manufacturing (AM) is playing a great role in the industries in changing 3D CAD models directly to products and prototypes without the use of tooling. Researchers started developing metal AM using laser also called Selective Laser Sintering (SLS) to selectively melt metal powder [1]. Based on material input AM systems for metals nowadays are divided in to three main categories: (i) Powder bed system, (ii) powder feed system and (iii) wire feed system [2]. The comparative study of wire and powder feed metallic AM processes has been investigated by microstructure analysis of the deposited product [3]. The comparison study shows that the microstructure of both the samples are similar, however porosity have been found in the samples produced by powder based AM systems.

Wire-feed AM is divided into three groups based on energy sources, these are; laser, arc, and electron beam. Initially, a single bead of material is deposited to make a layer and upon subsequent passes is built upon to develop a 3D object. Wire feed AM are well suited for high deposition rate processing and have large build volumes. Deposition rate of laser or electron beam (EB) is of the order of 2–10g/min, whereas deposition rates of 50–100 g/min have been reported in arc- based AM [4, 5]. The fabricated product usually requires more machining between layers and after finish deposition. Therefore, to attain better dimensional accuracy and surface quality for building metallic dies and molds, it was proposed to develop a unique methodology with a hybrid approach of an additive and subtractive processes. It consists of *Gas Metal Arc Welding* (GMAW) and CNC milling machining respectively [6].

One of the applications of AM of metals is in the area of Rapid Tooling (RT). RT methods allow injection molding and die-casting inserts to be built directly from 3D CAD models. A computer aided system has been developed for rapid tooling process selection and evaluation of mold design for its manufacturability and cost effectiveness [7]. Arc weld deposition method through hybrid approach of addition of metal through GMAW deposition and subtraction using CNC milling was used to produce a tooling with mild steel material [8].

Most of the molds and dies are made out of tool steel materials and hence in this research H13 tools steel material is used to manufacture a tooling element and to see the details of the microstructure. Deposition of H13 tool steel in a wire form is an essential research area for the advantage of getting higher deposition rate. One of the drawback of tool steel welding or deposition is the issue of solidification cracking.

Pre-heating is often used to reduce the residual stresses and the risk of thermal distortion and cracking for tool steel cladding [9]. A research work has shown on 12% Cr steel welding the effect of preheating process on microstructure and to avoid cracking by martensitic microstructure [10]. To overcome this problem in this research induction preheating system is used and its effects are studied in detail.

Experiment Setup

In this study a hybrid approach of AM process is used, where Arc weld deposition, generally called MIG/TIG cladding is used as an energy source to deposit a material in a wire form and CNC machine for intermediate machining and final surface finish, figure 1. This alternate use of additive and subtractive process makes this metallic AM process a hybrid process and it is called Hybrid Layered Manufacturing (HLM). This setup contains a 3-axes milling machine and a MIG/TIG cladding gun that is vertically attached to the spindle housing. A retrofitting of synergetic MIG/TIG cladding on 3-axes milling machine is required in order to carry out the cladding process efficiently [11].

(a) Cladding or deposition Unit

(b) CNC machining unit

(c) Total Setup of MIG Cladding and machining

Figure 1 MIG/TIG cladding deposition unit and CNC machining or HLM setup at IIT Bombay

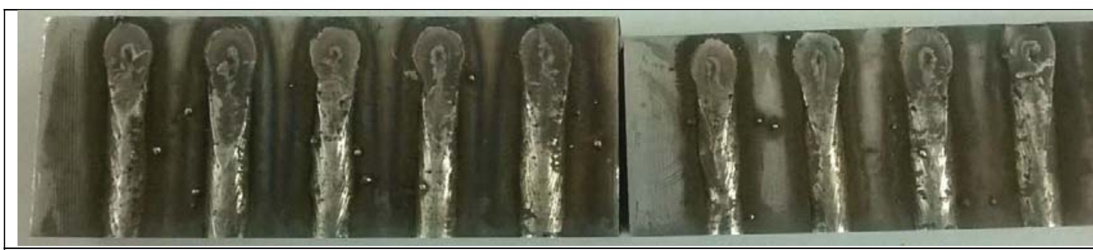
The first essential step in this process is to determine the optimum parameters of deposition. These parameters are welding current, standoff distance and the torch feed rate. The optimum process parameters were validated with the help of Taguchi design of experiments (DOE). Based on the orthogonal array nine different single weld bead depositions was done. In this experiment H13 tool steel substrate was used to see the overall effect. The composition of H13 tool steel material is shown in table 1. The metal plate was sectioned in to two pieces, perpendicular to the weld bead, by using wire EDM. The finishing of the surface was done by filling, polishing and using a 2% Nital etchant. The profile of the weld bead measurement such as weld width, height and penetration was taken using Stereo Microscope device. The details of the sample reading is shown in the figure 2. After taking the result the measured value was calculated using ANOVA method and the optimized MIG cladding parameters were selected.

Table 1 Composition of H13 tool steel material

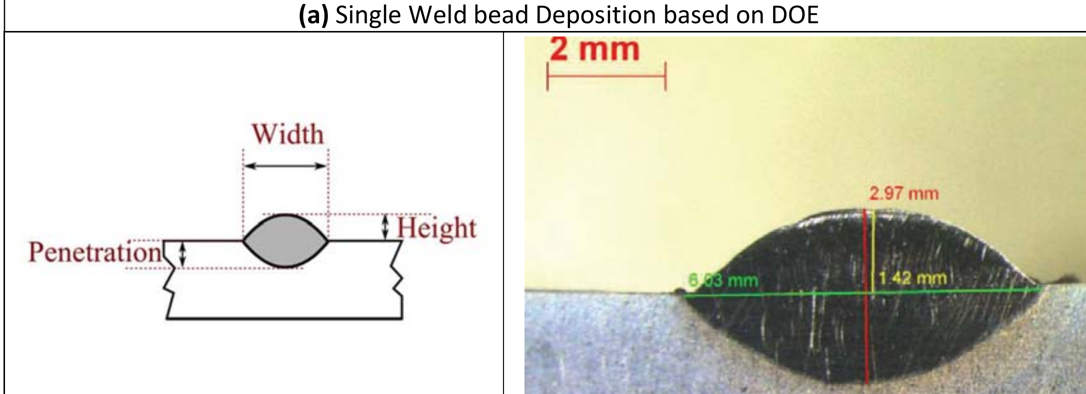
C	Mn	Si	Cr	Mo	V	P	S	Fe
0.38	0.39	0.94	4.96	1.66	0.97	0.019	0.018	Balance

Tool steels in the cold and hardened condition always should be preheated for welding or deposition to a temperature not to exceed the tempering temperature and should be maintained as closely as possible at this temperature during deposition operation. The material to be welded must be preheated slowly and uniformly to avoid uneven expansion through localized or partial heating which can lead to cracking. It is important to maintain the preheat temperature as constant as possible during welding [12].

In the development of the tooling using MIG cladding two types of preheating methods were used. These are TIG arc and Induction heating methods. There are few reasons preheating is essential for MIG cladding of H13 tool steel material. The first one is to slow down the cooling rate and second allows the back filling of molten metal to be fed in the proper dendritic position so that solidification cracking can be avoided [13].



(a) Single Weld bead Deposition based on DOE



(b) Nomenclature of single weld bead	**(c)** An image from the stereo microscope

Figure 2 H13 Tool steel single bead deposition experiment

In the first few layer of MIG cladding of H13 material, TIG arc was used for preheating the substrate. This preheating system was selected based on the availability of the setup, figure 3a. After few layers of MIG cladding it is observed that the cracking started at the point of the neck of the part, see figure 3b and 3c. This problem might be happened because of two reasons. The first one is the insufficient retention of preheating temperature before MIG cladding. The second reason might be oxidation of the substrate material due to TIG arc heating. This claim is clearly seen on figure 3a. This type of oxidized surface was observed while building a part for the few layers.

(a) TIG arc preheating	**(b)** Few layers of MIG cladding	**(c)** After machining

Figure 3 TIG arc preheating unit and Cracked H13 MIG cladding object

In the second attempt the experiment was done using induction preheating method. In this method the substrate was heated up to 450^0c and above before each layer of MIG cladding. The induction heating device was designed for cladding purpose to get an output of 3.2KW power and frequency range of 10 - 20 kHz. In this preheating method the required temperature was achieved in short period of time and relatively less oxidation was seen. The shape of the heating coil is called pancake type as shown in the figure 4.

Figure 4 Induction preheating unit

The 350^0c and above preheating temperature maintained while layer by layer deposition was done. In the development of the tooling element using H13 tool steel material deposition the geometry of the part to be deposited was selected based on the demand from the tooling industry.

Result and Discussion

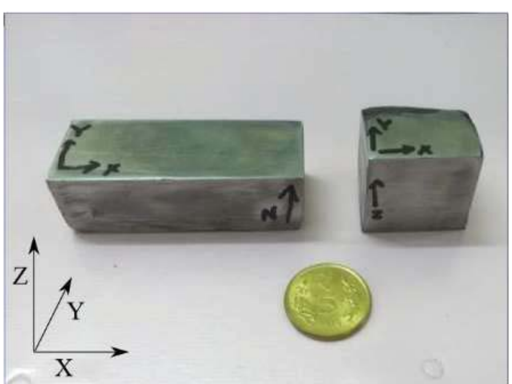
In this research to see the effect of induction preheating on MIG cladding of H13 tool steel material, two samples were prepared. One sample is using induction preheating of temperature above 350^{0}c and the other is without preheating. The deposition parameters taken for the for the MIG cladding are current 210A, stand of distance 10mm and torch speed 1800 mm/min. The deposited near net shape and finished machined block are shown in figure 5a and 5b.

(a) Near net shape

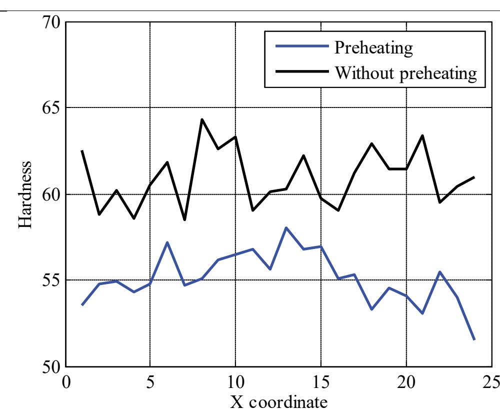
(b) Finished machining

Figure 5 H13 tool steel samples for microstructure test with and without Induction preheating

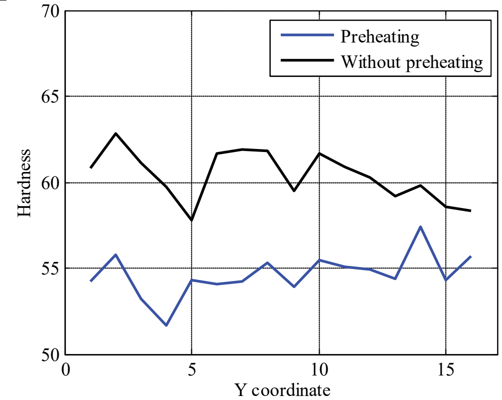
The micro hardness of the samples in the coordinate directions were tested. The deposition direction was along x-axis, the successive weld bead or pitch direction was along y-axis and the block was completed adding layer by layer in the z-direction. The part was finished machined and removed out from the substrate material by EDM wire cut. In figure 6a shows two machined blocks deposited using in-situ preheating process and without preheating respectively. Micro hardness machine was used to measure the hardness in the coordinate directions. The result is shown in figure 6b, 6c & 6d. The hardness of the deposited H13 tool steel block without preheating shows more hardness than the part produced by In-situ preheating system. The trend looks similar in all coordinate directions.



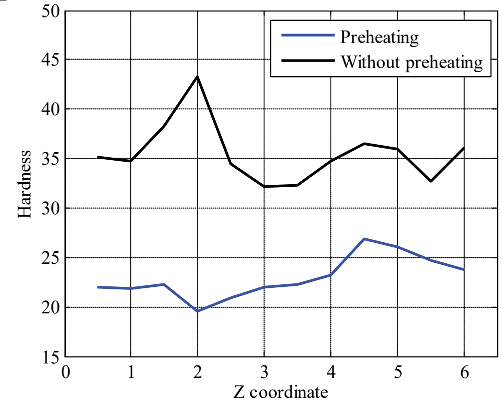
(a) Samples for hardness test



(b) Harness variation along x direction



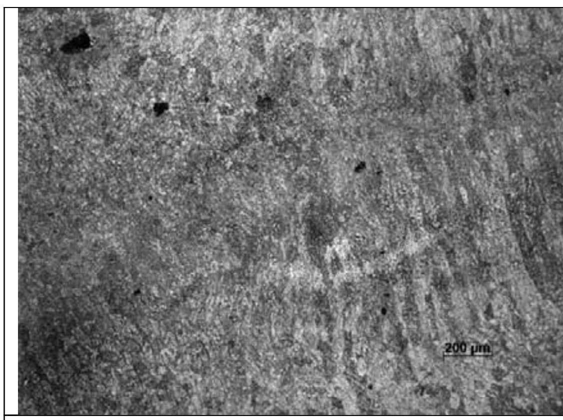
(c) Hardness variation along y direction



(d) Hardness variation along z direction

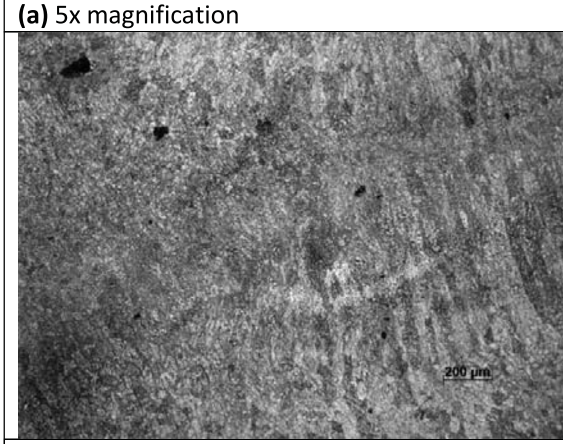
Figure 6 Hardness comparision along the coordinate axes direction

The required specimen was prepared by cutting out a size 10 X 10mm from the center of the deposited sample using EDM wire cut. The samples were polished using a polishing machine and then socked in an etchant solution of 2% Nithal for about one minute. The microstructure of both samples were seen using electron microscope (Axiocam iCc3, ZEISS). The picture of the two sample results with induction preheating and without preheating are shown in figure 7.

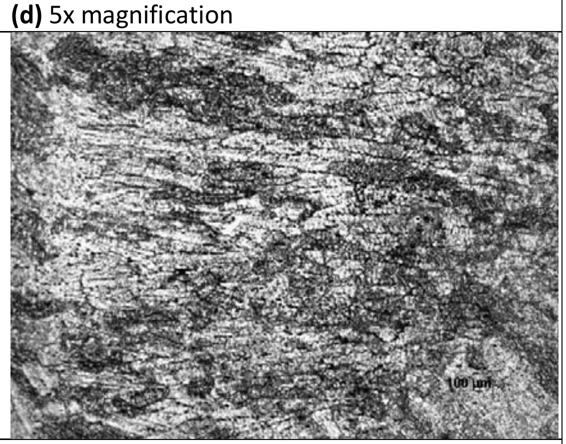


(a) 5x magnification

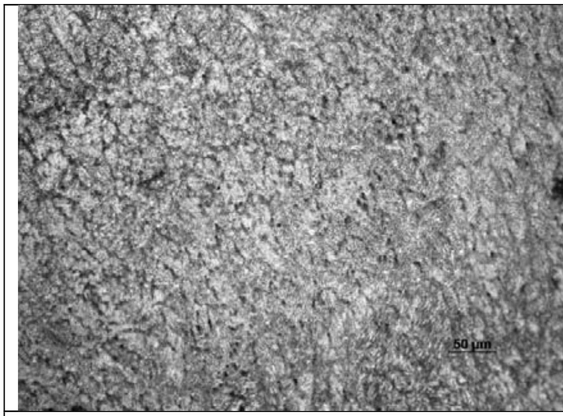
(d) 5x magnification



(b) 10x



(e) 10x magnification

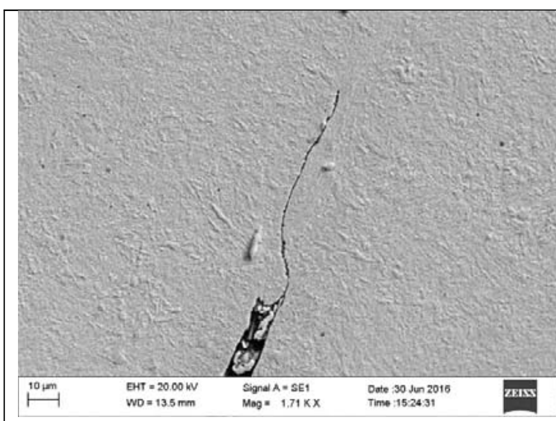


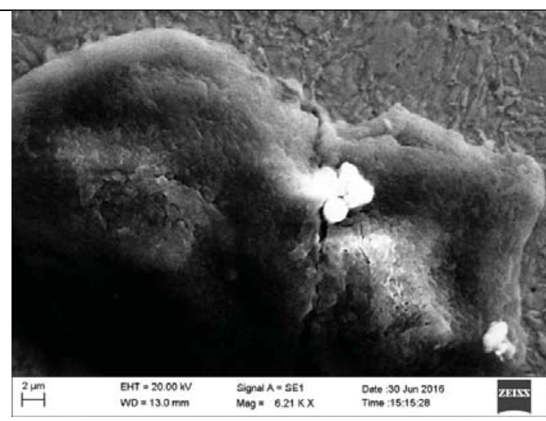
(c) 20x magnification	**(f)** 20x magnification

Figure 7 a, b, & c are microstructure pictures without preheating and d, e, & f are with In-situ preheating

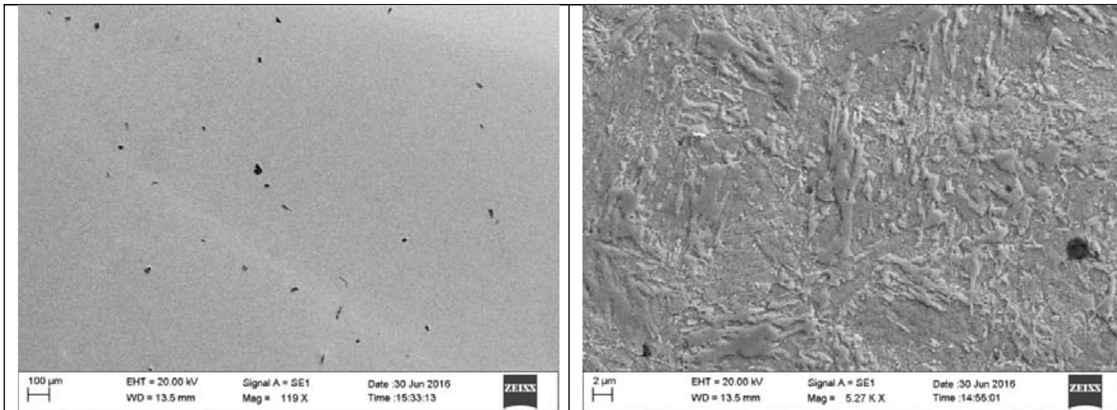
The pictures taken using electron microscope clearly shows the difference between the two methods. Figure 7a is a part produced without preheating, shows more number of porosity and figure 7d a part produced with in-situ preheating, shows few porosities. Figure 7e & 7f are the pictures of the part deposited using in-situ preheating shows clear elongated grain structure and dendritic formation, whereas figure 7b & 7c deposited without preheating the pictures are shown finer grain structure arraignment. This might be one of the reason the H13 tool steel produced with MIG cladding without preheating are shown more hardness.

Another issue in H13 tool steel MIG cladding is the solidification cracking phenomena. This effect is observed using *Scanning Electron Microscope* (SEM) (EVO/18 ZEISS). Figure 8a shows that the porosity is the starting point of solidification cracking in the deposition process without preheating. Figure 8b shows the number of porosity in a specific area of the sample. The microstructure formation of the part looks good at specific area, figure 8c.





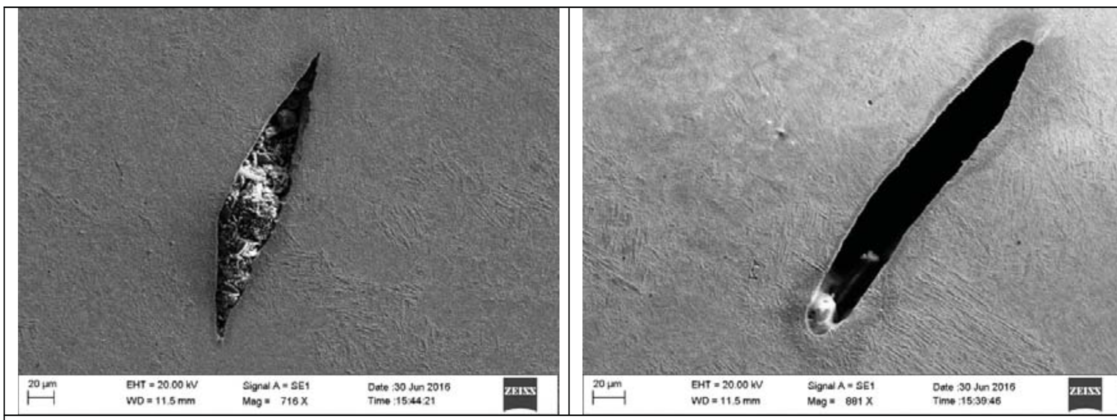
(a) Porosity observed with SEM and the formation of solidification cracking



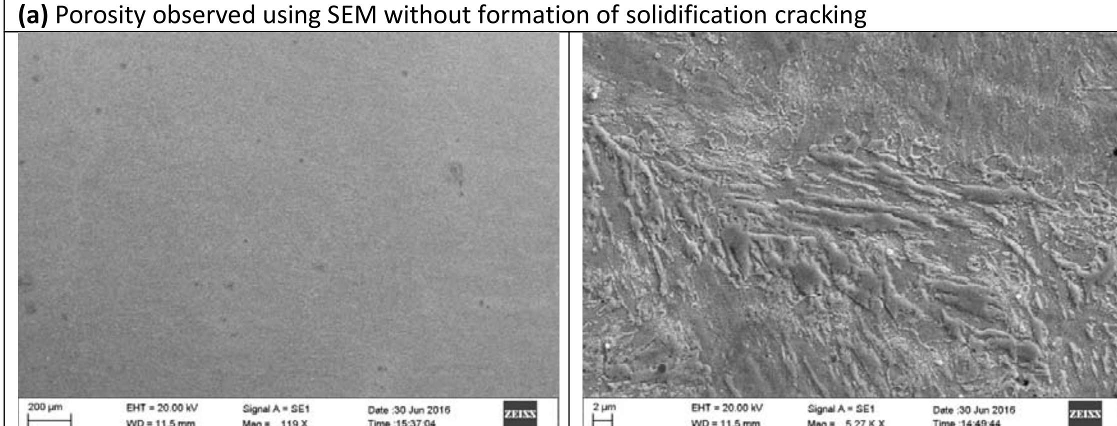
(b) Porosity seen at the magnification of 119x	**(c)** Microstructure seen at 5.27kx magnification

Figure 8 The microstructure and porosity of H13 MIG cladding without preheating

The SEM reading of the sample of H13 tool steel material deposited with In-situ preheating shows no solidification crack formation around the porosity. This phenomenon is clearly shown in the figure 9a. The microstructure shows a better dendritic formation and the number of porosity observed few compared to the part produced without preheating, figure 9b & 9c.



(a) Porosity observed using SEM without formation of solidification cracking



(b) Porosity seen at the magnification of 119x	**(c)** Microstructure seen at 5.27kx magnification

Figure 9 The microstructure and porosity of H13 MIG cladding with In-situ preheating

Conclusion

In this work, an induction based in-situ preheat procedure has been developed for metal based *Additive Manufacturing (AM)* processes. This preheating process has been studied for the deposition of H-13 tool steel. The hardness tests are carried out and microstructure analysis has been done. It is observed that preheating can reduce the hardness of the final component in all three directions. The results obtained by electron microscopy clearly shows that the number of porosities are more in case of non in-situ preheating. Also the growth of grains are more finer in this case which may further lead to the crack formation. The cracks and porosities are more clearly visible in the case of non-pre-heated samples using *Scanning Electron Microscopy (SEM)*. While the sample made by using in-situ heating have less porosity and no crack related issues. Hence, induction based in-situ preheating is recommended for the manufacturing of H13 tool steel components by AM processes through MIG cladding process.

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