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Low cost integration of additive and subtractive processes for hybrid layered manufacturing

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ABSTRACT

While CNC machining (subtractive method) is the only option when it comes to high quality components, it demands greater human intervention to generate the CNC programs, making it a slow and costly route. On the other hand, Rapid Prototyping (additive method) is able to convert the design into the physical objects without any human intervention. But its total automation comes with compromises in the qualities of geometry and material. A hybrid layered manufacturing process presented here combines the best features of both these approaches. In this process the near-net shape of the object is first built using weld-deposition; the near-net shape is then finish machined subsequently. Time and cost saving of this process can be attributed to reduction in NC programming effort and elimination of rough machining. It is envisioned as a low cost retrofitment to any existing CNC machine for making metallic objects without disturbing its original functionalities. Near-net shape building and finish machining happening at the same station is the unique feature of this process. A customized software generates the NC program for near-net shape building. The intricate details of integrating arc welding unit with a CNC milling machine are presented in this paper.

1. Introduction

Rapid prototyping (RP), also referred to as layered manufacturing (LM) or 3D printing, has drawn a significant research interest owing to decreasing product development times and increasing complexity of the components. LM offers total automation in converting the virtual models into physical ones. This is archived by slicing the 3D geometric model into layers and realizing each layer at a time.

As LM was introduced as a design visualization tool, the early focus of the research was on the physical realisation of the shape rather than its functionality. Thus most of the existing LM processes produce objects using resins and other non-metals, limiting their applications. In comparison, metallic prototypes have a larger domain of applications [1]. Thus, efforts have been going on for extending LM for manufacture of metallic objects. Several techniques like laser-engineered net shaping (LENS), 3D welding, direct metal deposition (DMD), shape deposition manufacturing (SDM), laser based additive manufacturing (LBAM), 3D micro-welding (3DMW) and electron beam melting capable of producing metallic prototypes have been developed by different research groups [2–8]. Fig. 1 summarizes various existing methods for LM of metallic objects. When the metallic object is obtained in a layer by layer manner, it is known as direct process. If a casting process is used in conjunction with the consumable pattern manufactured in a layer by layer manner, it is known as indirect process. Quick cast patterns of SLA and polystyrene patterns of SLS are popularly used in indirect processes.

Based on the method of deposition, direct processes can be further classified into laminated tooling, powder-bed and deposition technologies (Fig. 1). In laminated tooling, the tool shape is achieved by usually cutting and stacking metal sheets together. It is a relatively fast and simple method to make metal tools directly for injection molding. In powder-bed technology, a layer of metallic powder is first spread and the required regions of the layer are sintered selectively. On the other hand when the metal is deposited only in the required regions of the layer, it is known as deposition technology. While powder-bed technology has the advantage of an inherent support mechanism, it generates only a porous structure. On the contrary the deposition technology cannot produce overhanging features but has better structural integrity. Furthermore, with the exception of 3DP, power-bed methods are not as amenable to produce functionally gradient materials (FGMs) as deposition methods are.

Direct LM processes generally use arc, laser or electron beam as the energy source for metal deposition. Table 1 lists various existing technologies in each category. Fig. 2 shows some metallic objects realized using different LM processes. Components

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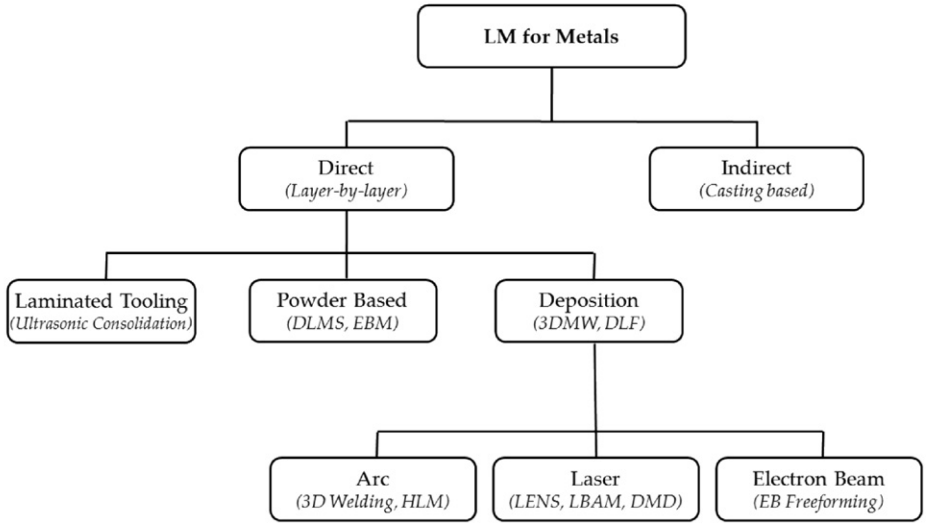

Fig. 1. LM for metallic tools and components.

Table 1
Various deposition based direct LM processes.

	Deposition
Laser	Direct metal deposition (DMD) [6]
	Directed light fabrication (DLF) [9]
	Laser additive manufacturing (LAM) [10]
	Laser aided manufacturing process (LAMP) [11]
	Laser based additive manufacturing (LBAM) [12–14]
	Laser based direct metal deposition (LBDMD) [15]
	Laser-engineered net shaping (LENS) [2]
	Rapid direct metal deposition [16]
Electron beam	Electron beam freeforming [17]
Arc	3D micro-welding (3DMW) [3]
	3D welding [4]
	3D welding and milling [18]
	Hybrid layered manufacturing (HLM) [19]
	Hybrid plasma deposition and milling (HPDM) [20]
	Micro-plasma arc welding (MPAW) [21]
	Shape deposition manufacturing (SDM) [5]

manufactured through LENS, EBM and Arc welding have an accuracy of 0.4, 0.1 and 0.2–0.5 mm, respectively [6,8]. Thus it can be inferred that all of them produce only rough surfaces and cannot be directly used for high precision applications like tooling where the accuracy required is of the order of 1 μm.

The low accuracy of the LM components is due to splitting of the component into slices. Automation is attained in LM by compromising on quality. Rapid prototypes are inferior in geometric and material quality to machined parts. CNC machining, the subtractive manufacturing strategy, on the other hand, can handle any material and offers high accuracy and surface finish demanded in the tooling applications. But it requires substantial human intervention for path planning and is limited in features that can be realised. hybrid layered manufacturing (HLM) processes, which combine the advantages of both additive and subtractive manufacturing, have been developed by many researchers [18,20,23]. However, as the creation of the near-net shape and its finish machining occur at different stations, it limits the foolproof implementation of computer aided process planning (CAPP). It also becomes expensive due to the use of two sets of motion controls. Considerable amount of time is also wasted in setting and positioning of the job on LM and CNC machines separately. IIT Bombay's arc hybrid layered manufacturing (ArcHLM) presented here overcomes these limitations by achieving both near-net metal deposition and finish machining on the same CNC machine.

ArcHLM employs arc welding for deposition as it has the added advantages of higher deposition rates, lower costs and safer operation. Deposition rate of laser or electron beam (EB) is of the order of 2–10 g/min, whereas deposition rates of 50–100 g/min have been reported in arc-based LM [6,17]. Furthermore, it also has the potential to control the size, flux, velocity, trajectory and thermal states of the droplet and the substrate thermal state precisely, which are critical to the geometric accuracy and metallurgical properties of the deposited part [24].

The following are some of the significant advantages of this process:

- Total automation across LM phase of building near-net shape and CNC phase of finish machining is possible.
- It uses arc weld-deposition, which is economical, faster and safer than competing laser and EB based processes.
- It can be retrofitted to any existing CNC machine as an optional feature.
- The retrofitment does not require any proprietary information from the machine builder. Therefore this integration is independent of the make of the machine.
- As the weld-deposition torch is mounted on the same spindle head no additional sets of axes and controller are needed.

The details of this novel integration method are discussed in the subsequent sections.

2. ArcHLM process

Automatic manufacture requires not only the automation of process but also of the process planning. This is achieved in ArcHLM through synergic integration of weld-deposition and CNC machining. Fig. 3 illustrates the various stages in ArcHLM process.

In the first stage, the near-net shape of the component is realized through weld-deposition, using GMAW equipment. As the deposition occurs in the form of weld beads, the surface of the deposited layer is uneven due to the scallops and has a thin oxide scale. These uneven surfaces will have a cumulative effect on the accuracy of the component in the Z-direction. To overcome these shortcomings, the deposited layer is face milled to the required slice thickness in ArcHLM. Once the face milling operation is done,

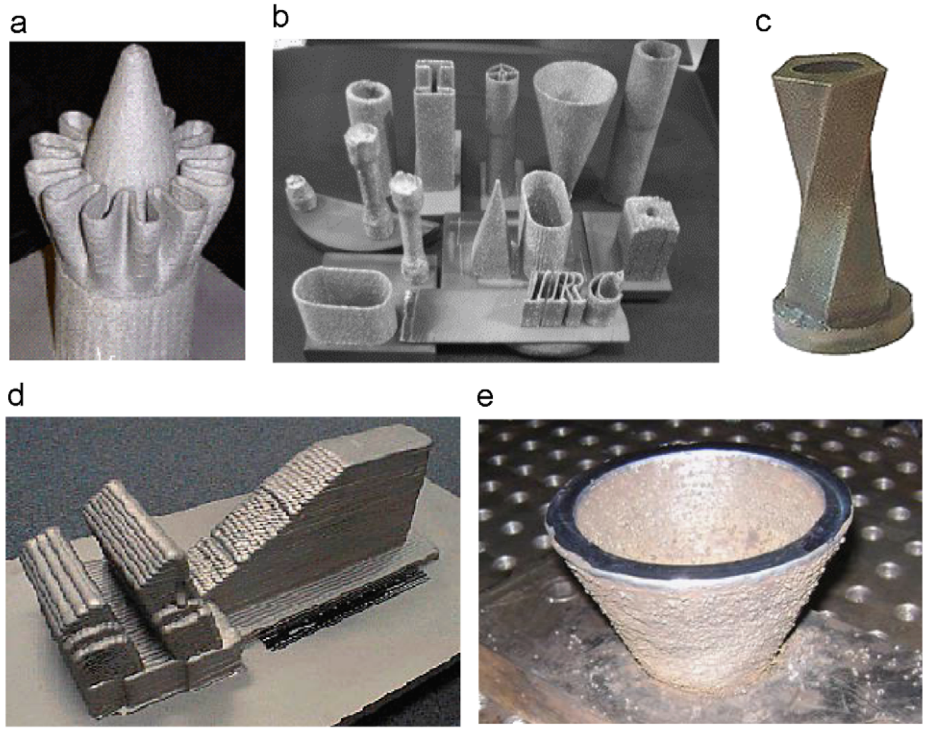

Fig. 2. Comparison of surface quality of RM processes using laser, EB and arc sources. (a) LENS (OptoMec) – Laser, (b) DLF(FhG, Dresden) – Laser [22], (c) Arcam-electron beam, (d) LAM (AeroMet) – Laser and (e) HLM (IIT Bombay – Arc.)

weld-deposition for the next layer happens on a nascent surface giving good quality of welding. The near-net shape thus obtained is finish machined in the second stage.

The residual stresses and distortions are the two interchangeable manifestations of the non-uniform heat input. If the distortion is prevented by rigid clamping, it may lead to internal stresses. Hence it is preferable to deposit the material in partially clamped condition so as to allow warping. The substrate can be rigidly clamped subsequently for face milling. This arrangement for partial/rigid clamping is shown in Fig. 4a and b. The location pins with conical head ensure the positional accuracy. During milling, the studs are pulled down by the pneumatic pads to withstand the face milling load. Fig. 4c and d shows this dynamic clamping in action. This arrangement is designed such that although it allows for the warping of the blank, it minimizes the positional dislocation. The distortion in the substrate is absorbed into the machining allowance.

A customized software, termed as hybrid layered manufacturing software (HLMSoft), was developed to generate the paths for weld-deposition and face milling. HLMSoft in future will be capable of producing the finish machining paths also. However, presently the path planning for finish machining is done using commercially available CAM packages.

The CAD model in STL format and the process parameters as listed in Table 2 are the inputs to the HLMSoft. The process parameters are selected by the user based on considerations like material used for deposition, diameter of the filler wire, cutters used for machining, etc. After reading the CAD model, the HLMSoft slices the model into layers of equal thickness, with slice thickness specified by the user. It then generates the weld-deposition paths for each layer based on the area-fill method, step-over increment, machining allowance set in the process parameters. As the weld-deposition torch is mounted onto the CNC head (discussed in detail in the next section), the deposition paths will be equivalent to the machine movement and thus can be output in the form of CNC readable NC file. This NC program is then sent to the CNC controller with the help of a direct/distributed numerical control (DNC) interface. The weld-deposition equipment subsequently creates each layer by depositing the metal in the required areas with the help of the tool path file. After the weld-deposition is complete, the face milling cutter flattens the scalloped surface. This cycle continues till all the layers are complete. The near-net shape of the part is thus obtained. Once the weld-deposition is complete, the DNC starts sending the cutter paths for finish machining producing the final component.

3. Integration of CNC and weld-deposition units

Synergic integration of weld-deposition unit with the CNC machine independent of its make and age is a key aspect in ArcHLM. The integration has to be done in such a manner that the weld-deposition can act as an additional feature without disturbing the other capabilities of the CNC machine. During the integration, changes to the mechanical and electrical systems are done without the need for any proprietary information from the machine builder or the control developer. The following are some of the issues to be addressed to achieve this:

3.1. Mechanical issues

- Mounting of the welding torch on the side of the spindle head so that weld-deposition is controlled through the same CNC controller.
- Suitable mechanism to take away the excess heat generated during weld-deposition.
- Appropriate safeguards to protect the machine elements from occasional spatter.

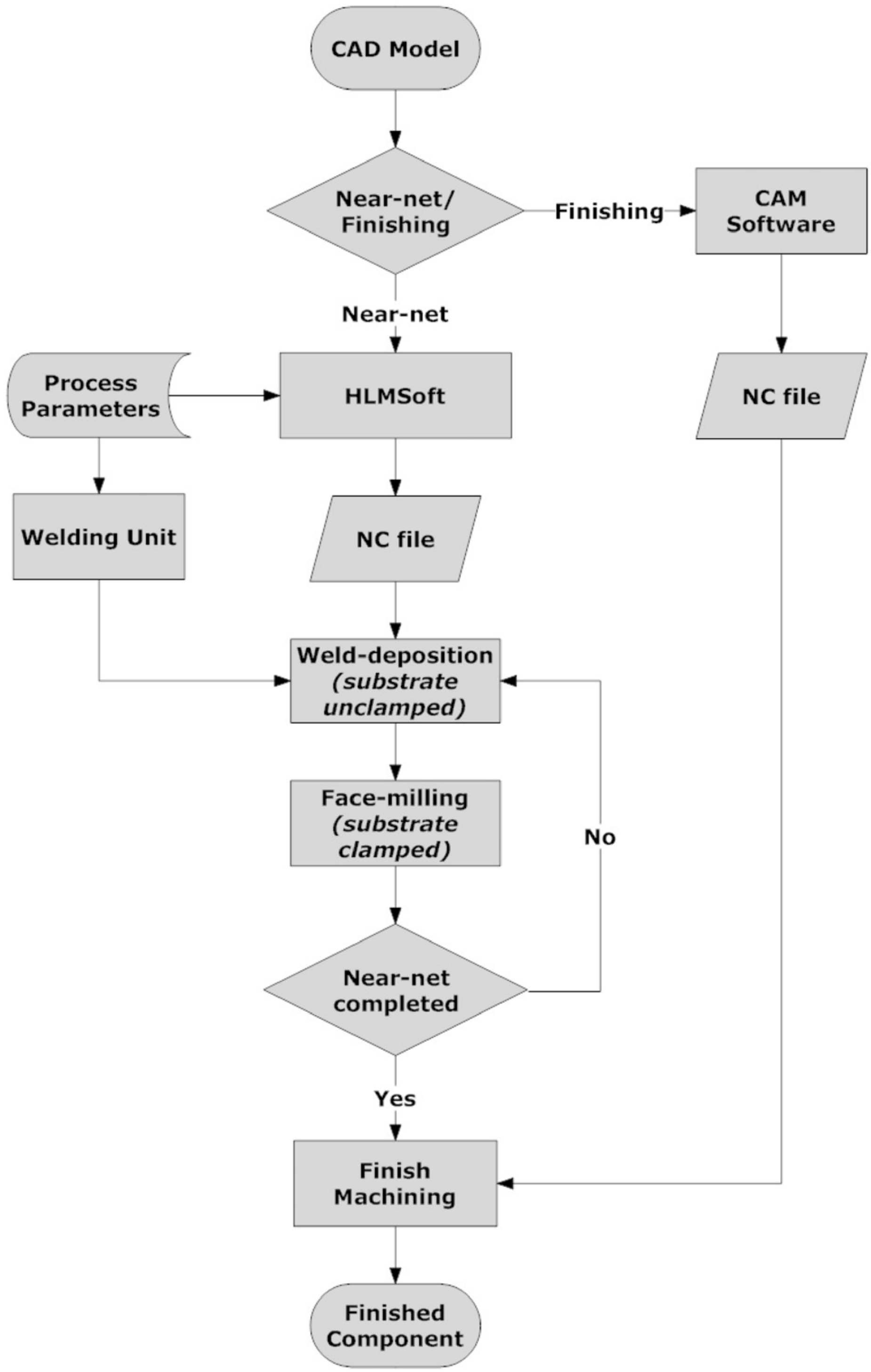

Fig. 3. Flow chart for ArcHLM process.

3.2. Electrical and control issues

- On/off of the weld-deposition unit through the CNC program.
- Easy and quick change-over between ArcHLM mode and regular CNC mode.
- Elimination of any direct electrical contact between the CNC controller and the weld-deposition unit.

The implementation details for achieving these objectives are presented in the following sub-sections.

3.3. Weld-deposition unit

Traditionally welding is used as a joining process. In a joining process, penetration, productivity and stability of the process are the important criteria in choosing the welding parameters. Penetration is the depth to which the melting takes place; the higher the penetration the better is the quality of joint. Productivity is related to the melt-off rate of the filler. The third property is stability of the process; instability causes spatter, which increases the post-welding efforts in cleaning the joint. However, when welding is used for metal deposition applications,

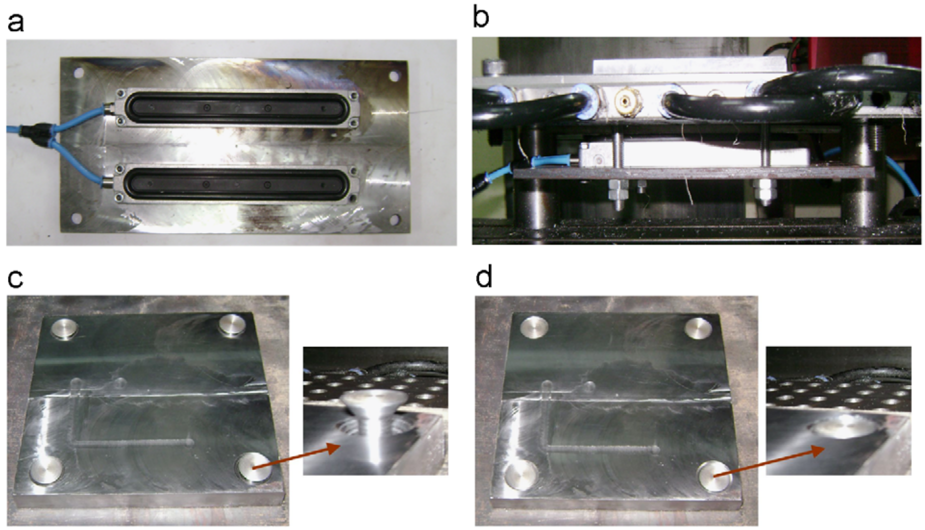

Fig. 4. Dynamic clamping. (a) Diaphragm actuator used for dynamic clamping, (b) Clamping devise mounted onto the table, (c) Soft clamping before pneumatic activation and (d) Rigid Clamping after pneumatic activation.

Table 2
Input parameters for ArcHLM

Deposition related parameters	Type of area-fill (direction-parallel or contour-parallel) Slice thickness Step-over increment Torch speed Machining allowance
Face milling related parameters	Diameter of the face milling cutter Spindle speed Feed rate
Offsets	Torch offset in X with respect to spindle Torch offset in Y with respect to spindle Torch offset in Z with respect to spindle Nozzle gap

higher resolution, spatter-free operation and less heat input become the prime criterion. Accordingly, the following welding features are desirable in ArcHLM:

- Process stability
- minimum heat input
- sharp feature definition
- high deposition rate
- minimum machining.

Based on the above inferences, pulsed synergic GMAW was found to meet the requirements of ArcHLM process. In pulsed synergic mode, the weld transfer can be precisely regulated, providing extremely smooth welds [19]. It also permits higher torch speeds and minimizes spatter. Accordingly TPS4000 GMA welding unit manufactured by Fronius, Austria, was selected for weld-deposition (Fig. 5a). It is possible to switch on/off the welding unit both manually and through a signal, hence making it ideal for integration in ArcHLM.

The control panel of the welding unit is shown in Fig. 5b. It shows two modes of torch operations as marked. One is called “2-step mode” and the other is “4-step mode”. In the 2-step mode, the trigger has to be held pressed throughout the welding. When the trigger is released, welding will stop. On the other hand, in the 4-step mode, welding starts the moment the trigger is pressed; it continues even after the trigger is released. In this mode, the same trigger should be pressed once more to stop welding. In other words, the trigger acts as an on/off switch in 2-step mode and it acts as a toggle switch in 4-step mode. Thus 4-step mode is preferred for manual operations and 2-step is suitable for automatic applications. Fig. 5c shows the connector for automatic control of welding. When the two bottom pins shown in the figure are shorted, weld-deposition unit is switched on and is switched off when opened.

3.4. *Mounting of welding torch*

An ARGO 1050P model 3-axis CNC machine was chosen for implementing ArcHLM (Fig. 6). During the fabrication of the near-net shape, weld-deposition and surface milling will happen alternately (Fig. 3). Though many CNC machines have automatic tool changer (ATC) arrangement, the torch cannot be accommodated in one of the pockets as it has a long hose. This problem was overcome by mounting the torch on the side of the spindle head. Initially, as shown in Fig. 7a, the torch was mounted on a pneumatically operated slide with about 50 mm traverse [25]. However, it was observed that due to the up and down motion of the welding torch, a considerable delay occurs in the welding on/off command in the NC file and actual on/off of the welding unit. Over a couple of layers, this delay will have cumulative effect on the deposited layer. To avoid this effect, the pneumatic cylinder arrangement was removed and the weld-deposition torch was directly mounted near the CNC head. During the face milling operation, the thickness of the machined surface is normally between 0.5 and 1.0 mm. Although weld blobs may occur at times, they are never more than 2.0 mm. Therefore, it was possible to eliminate the pneumatic cylinder arrangement. The torch was permanently fitted 5 mm above the face-mill. As the nozzle gap is generally kept as 10 mm, this gives a gap of 5 mm between the end mill and the substrate. By mounting multiple torches near the CNC head, as shown in Fig. 7b and c, even composite objects can be achieved.

3.5. *Control of weld-deposition unit*

Fig. 5c shows the connector for automatic control of welding. Shorting of these pins initiates the weld-deposition and can be accomplished through a binary output from the CNC machine. The following are some of the considerations regarding this binary output:

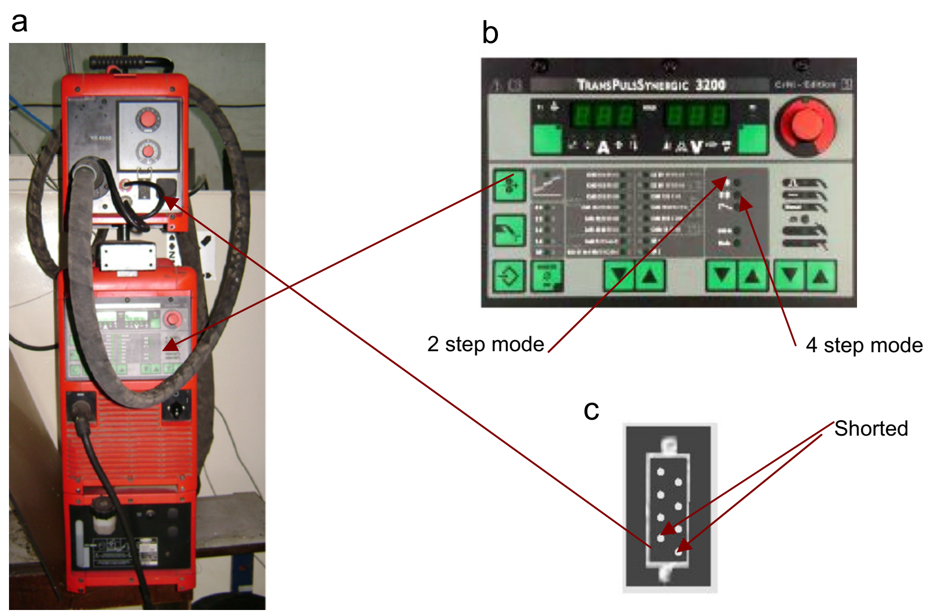

Fig. 5. Control of weld-deposition unit. (a) GMAW power source, (b) Control Panel of the Welding Unit and (c) Connector for Automatic Control of Welding.

Fig. 6. CNC machine with the weld-deposition unit mounted on it.

- Need for a specific pair of M-codes and a corresponding relay to control the weld-deposition unit.
- Availability of an extra relay in the CNC machine for this purpose.
- In the absence of an extra relay, identification of an existing relay that can be redirected for on/off of the weld-deposition unit without affecting the other functions of the CNC machine.
- Provision for operating the machine in both ArcHLM and regular CNC mode.
- Minimum changes for switching between ArcHLM and regular CNC modes are desirable. Even an unskilled operator must be able to switch from one mode to another easily.
- As ArcHLM is envisioned as a retrofitment to an existing machine, the integration must be generic in nature, applicable to majority of the CNC machines.

If the CNC machine has a spare relay, it can be used for on/off weld-deposition. But many old CNC machines do not have spare relays. Also, use of existing relay will ensure that the process can be extended to any CNC machine. An existing relay meant for another purpose can be re-routed to activate weld-deposition unit. But the relay chosen must be a non-essential relay during the ArcHLM process and shall be addressable by a pair of M-codes. A typical CNC milling machine uses relays for spindle on/off, coolant on/off, tool clamp/unclamp etc. Among these, relays for spindle and tool clamping cannot be disturbed as they are required during near-net shape fabrication. However coolant relay can be spared. Therefore the coolant relay is identified for ArcHLM implementation in the absence of spare relays. Most CNC controllers use M08/M09 for coolant on/off. M08/M09 will control weld-deposition in ArcHLM mode and coolant in regular CNC mode.

Switching between ArcHLM and regular CNC mode was achieved by using a double pole double throw (DPDT) switch. Fig. 8 shows this DPDT switch and the detailed circuit diagram for integrating welding process with CNC machine is shown in Fig. 9. When the switch is in Regular position, the circuit is connected to coolant motor. When the DPDT switch is toggled to ArcHLM position, the circuit is connected to the weld-deposition unit.

As shown in the circuit diagram of Fig. 9, when the DPDT switch is in ArcHLM mode, the M08/M09 signal is routed to a DPDT relay. When this DPDT relay is energized, it shorts the connectors of weld-deposition unit, hence switching it on. When the DPDT switch is in regular mode the M08/M09 signal controls the coolant flow.

3.6. *Isolation of CNC machine to the effects of weld-deposition*

Frequent short circuiting is inherent in welding and hence it is believed to generate spikes. CNC controllers are very sensitive to these spikes; the effect of the spikes may be as simple as just loss of memory to damage to the circuits. Due to this reason CNC installations used to be kept away from the welding unit. Therefore the proposal of the authors to retrofit the CNC machine with the welding unit was received sceptically in the beginning. However modern welding units with their built-in isolation systems emit negligible spikes and the CNC controllers also have become more robust and forgiving. Therefore these fears are found invalid today.

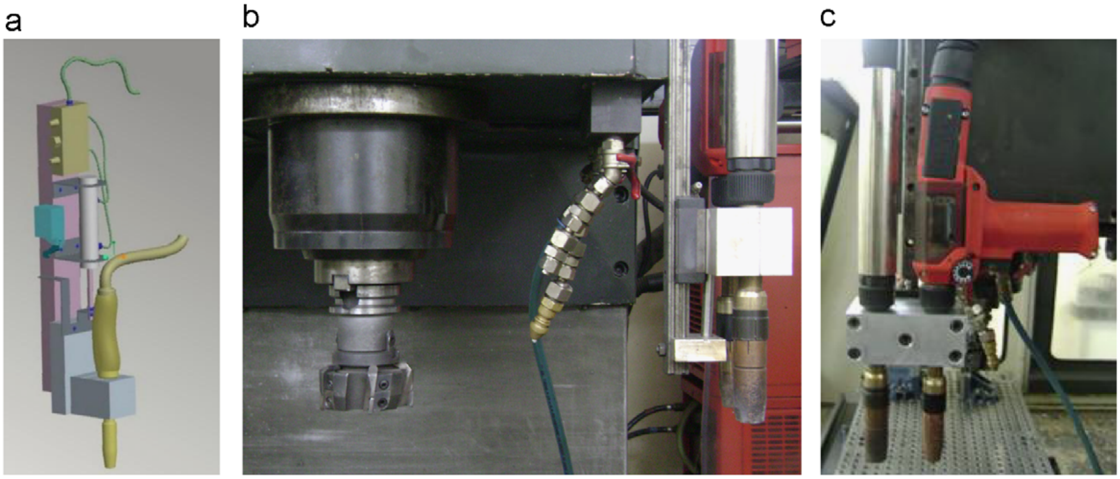

Fig. 7. Two weld-deposition torches mounted near the spindle. (a) CAD model of the pneumatic arrangement, (b) Front view of the modified torch mounting and (c) Side view of the modified torch mounting.

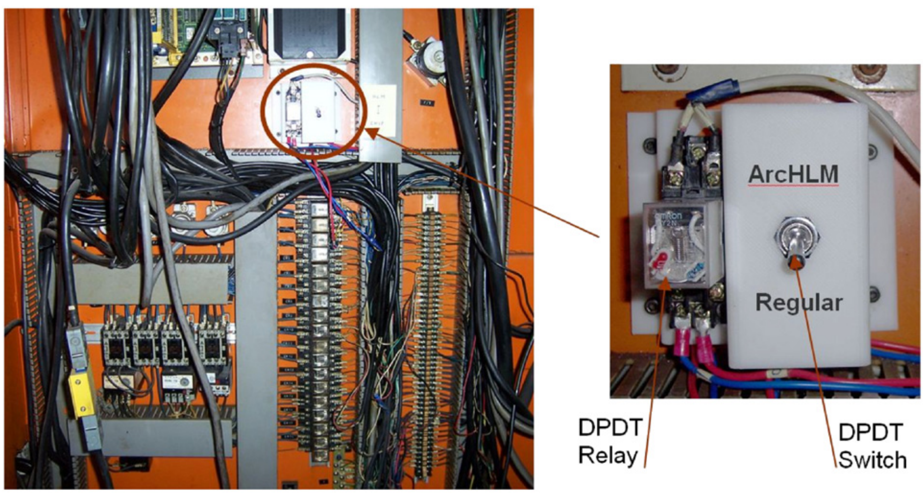

Fig. 8. Frame for mounting DPDT switch and relay on CNC.

The following are some of the important facets that need to be addressed for achieving physical and electrical isolation of CNC machine and welding unit:

- Electrical isolation of the CNC machine with the weld-deposition unit to ensure that the spikes generated during the welding process do not damage the CNC machine.
- The heat generated during weld-deposition should be carried away to ensure that the table, guide ways and other parts of the CNC machine remain unaffected.
- Protection of CNC machine components from occasional spatter during the welding process.

Electrical isolation was ensured by eliminating any type of direct electrical contact between the CNC machine and weld-deposition unit and carried out with the help of a DPDT relay. Proper grounding of the equipment is also warranted to ensure that any fault currents and spikes generated during the process are transferred quickly to the ground, without affecting the CNC machine.

The job is mounted on a universal fixture of dimensions 1000 mm $\times$ 480 mm $\times$ 150 mm with zig–zag cooling ducts (Fig. 10). This fixture can be used during regular as well as ArcHLM operations. It has a grid of M12 tapped holes at an interval of 25 mm. These are used for clamping the substrate plate, vice and other clamping devices. During weld-deposition, the coolant will be circulated through the zig–zag ducts, taking away the excess heat. All the features of this fixture, including the Ø8 mm $\times$ 475 mm through holes, were machined on this machine itself.

Another major concern during weld-deposition is the spatter. It may stick to vital machine elements like spindle head, tool holder and face milling cutter, seriously affecting the functionality of the CNC machine. To overcome this problem, it was preferable to enclose the substrate on which material is deposited. The material used for enclosure should be strong enough to prevent spatter. At the same time it should be able to absorb the shock during any error in the program without damaging the cutter or welding torch. Considering these requirements, a 0.2 mm thick MS sheet was selected for this purpose. The sheet can be easily cut to required dimension and used as a shroud around the substrate (Fig. 11). It was found to be quite effective in containing the spatter.

4. Illustrations

An industrial case study carried out subsequently demonstrated the commercial viability of ArcHLM vis-à-vis the

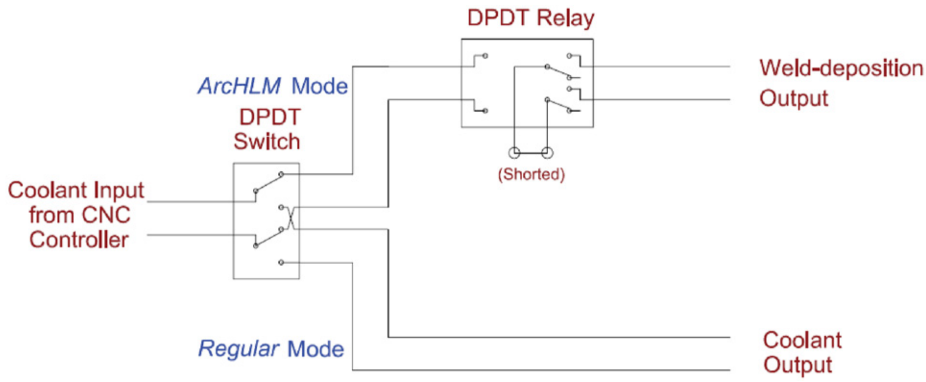

Fig. 9. Circuit diagram for integration of weld-deposition unit with CNC controller.

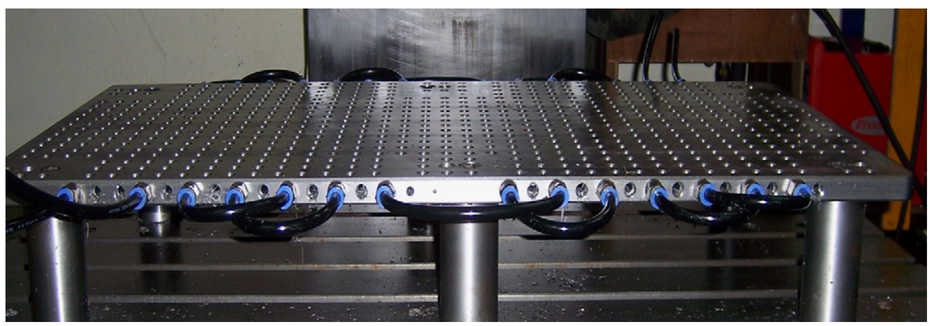

Fig. 10. Universal fixture with coolant ducts.

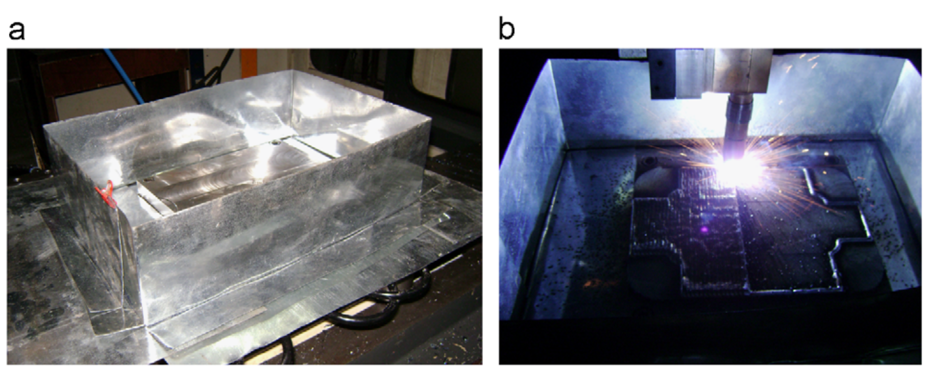

Fig. 11. Sheet metal shroud to arrest spatter.

conventional tool making method, viz., CNC machining from a block [26]. Fig. 12(a) shows the cavity and punch inserts of these molds in exploded view. Both of them were built together as shown in Fig. 12(b) over a 30 mm thick substrate. The near-net shape of these molds obtained in the 30 layers of 1.5 mm thick and with a machining allowance of 1 mm is shown in Fig. 12c. A mild steel wire of 1.2 mm diameter, operating at a mean current value of 100 A and torch speed of 1000 mm/min, was used for weld-deposition. Each weld-deposited layer was subsequently machined by a face-mill cutter of 60 mm diameter. Direction-parallel area filling with a step-over increment of 1.5 mm was used for realising each layer. The near-net shape thus realised was then finished machined to obtain the final mold (Fig. 12(d)).

The near-net shape in CNC route is obtained by rough machining the block and the same is obtained by depositing layers in ArcHLM. HLMSoft can generate the weld-deposition and face milling paths in about 10–15 min whereas the NC programming activity for rough milling using CAM software may take several hours. The finish machining is almost same in both cases. The following interesting inferences were made from this case study:

- ArcHLM route for this case took 42% less time than that of the CNC route.
- ArcHLM route for this case cost 28% less than that of the CNC route.
- Cost of the raw material was lower in ArcHLM for this case study.

ArcHLM's unique capability is the economic manufacture of composite injection molds with conformal cooling ducts in discrete adaptive layers. Note that these cooling ducts have triangular cross-section so as to build them without support structure in this deposition process. Fig. 13 shows the CAD model of the punch of an injection mold. Its case of 10 mm thickness

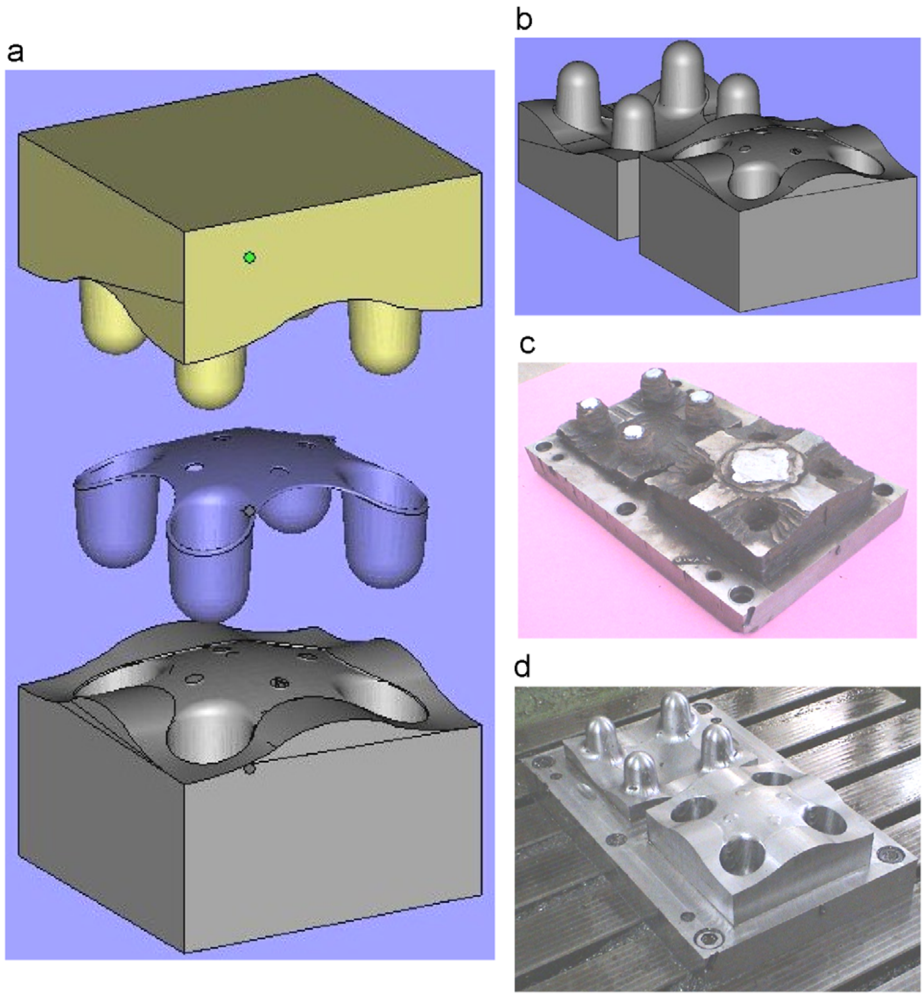

Fig. 12. Industrial trial—Injection molding dies of a massager. (a) Massager and its Dies, (b) Both Dies Arranged in Hybrid RP, (c) Near-Net Shape of the Die Pair and (d) Finished Die Pair.

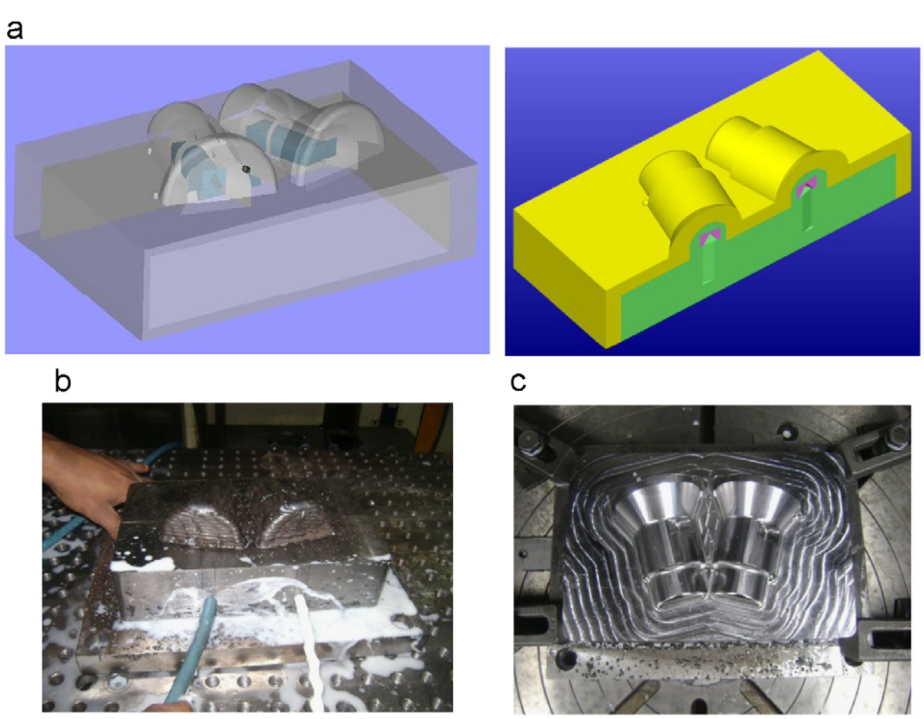

Fig. 13. Manufacture of the punch of a composite injection mold with triangular conformal cooling ducts using the 3-axis HLM. (a) CAD model of the punch, (b) Testing of the conformal cooling duct in the near-net punch and (c) Finish machining of the punch.

shown in yellow color is made of P20 tool steel. Its core (depicted in green color) consisting of a conformal cooling duct is built using mild steel. The building process used discrete adaptive thicknesses, i.e., while the yellow and green zones are built in layers of 1.5 mm, the pink zone around the triangular cooling duct is built in layers of 0.5 mm.

5. Conclusions

ArcHLM combines the best features of additive and subtractive manufacturing processes. While the quality of ArcHLM is adequate for most engineering applications, with its fast deposition rates, it is considerably faster than the other deposition methods. ArcHLM is a low cost retrofitment to any existing CNC machine for making metallic objects. The intricate details of this process achieved through integrating an arc welding unit with a CNC milling machine are presented in this paper. It also addresses the various issues pertaining to the safety and ease of operation. The commercial viability of ArcHLM for tooling has been demonstrated through a case study. ArcHLM's ability to achieve FGMs particularly dies with tougher core and harder surface by using multiple torches is also illustrated.

The methodology of retrofitment outlined in this paper can be adapted for laser weld-deposition too. Similar concepts can be used to extend the capabilities of existing CNC machines without the need for any proprietary information from the machine builder.

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