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Research Article

Deformation Investigation of Weld Based Rapid Prototyping

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Abstract: This study investigates the deformation produced in the weld-based prototype and to optimize the welding parameters to minimize this deformation. Weld-based prototyping is a method to produce form-fit and near-net-shape or net shape prototypes. However, the large amount of heat exposure for the substrate plate and for previously built layers is one of the limitations of weld based prototyping. This causes high temperature gradient which results in deformation, residual stresses, warpage and poor surface quality. In this study a part is made by using welding by incremental layer buildup method. This yielded anisotropic material properties in the part with the non-homogeneous structure and porosity. In present study above mentioned problems were minimized by proper selection and optimizing the deposition parameters such as inter-pass cooling time, heat sink size, deposition speed, applying mechanical constraints and preheating. For analysis of present weld based prototype, experimental approach is adopted. In such developments, the phenomenon of deformation is very crucial to control. In this study a focus has been made on investigation of deformation produced and the parameters effecting this deformation.

Keywords: Rapid prototyping, weld-based prototyping, welding deformation

INTRODUCTION

In recent decades, the competition in the field of manufacturing has become very tough. Due to the adoption of new technologies and shorter product development cycle, it is obvious to market the product at faster pace too. This enables companies to make this more profitable and gain more market share. In order to achieve this competitive advantage, time to design, manufacture and market the product needs to be shortened and use of material resources needs to be optimized. These requirements call for new tools and approaches to meet them and as a result, many new tools and approaches have been evolved over the years and research has been still going on. In the development of a new part, it is always needed to verify its real time functional performance through the help of a single example or prototype for test and design evaluation before assigning a large amount of resources to setup a production facility for that product. To achieve this, a new technology called Rapid Prototyping has been introduced, which considerably speeds up the iterative product development process. Rapid Prototyping (RP) is based on CAD principle and is a fabrication process which makes engineering prototype to be manufactured in minimum possible lead-time (Mikell, 2002). It refers to the layer-by-layer fabrication of three dimensional physical models as per design specifications. This layered manufacturing process gives the designers and engineers the opportunity to print out, visualize and analyze the 3-dimensional physical parts before entering into mass production phase. The RP processes offer a fast and cheaper alternative for producing prototypes and functional models as compared to conventional fashion of part manufacturing. In addition, it also allows building parts with complex geometries that would otherwise be impossible to machine (Kenneth, 2007).

Rapid tooling: Rapid Tooling (RT) is a counterpart of RP to develop molds and tooling for the production of prototype products by using the same processes as those used in rapid prototyping (Gebhardt, 2003). RT can be achieved either through RP model as a pattern to develop a mold or using RP process directly to produce a tool for prototypes. The main distinguishing feature of RT, as compared to traditional tooling, are its much shorter time (one-fifth of conventional tooling), less tooling cost (less than five percent) and wider tolerances as compared to conventional tooling.

Rapid manufacturing: Rapid Manufacturing (RM) or Rapid Production refers to the use of RP technologies to develop end-user products or finished parts. These can be produced directly with rapid prototyping methods or with tools produced by rapid prototyping processes (Gebhardt, 2003). However there is a degree of uncertainty pertaining to these technologies e.g., built

Corresponding Author: Abdul Samee, Advanced Engineering Research Organization, Wah Cantt, Pakistan time, part cost and quality of parts developed through RM as compared to those produced from conventional manufacturing technologies. The core advantage of using RM process is its ability to develop customized parts. When the lot size is large the traditional manufacturing technologies are the best option. But when small number of parts has to be produced then traditional technologies never suits for their manufacturing because of high tooling and setup cost. In this situation RM comes to the surface having ability to produce customized parts in relatively short period of time (Kamrani and Nasr, 2006).

Use of welding as RP tool: The commercially available RP machines use the CAD model directly for the development of the product and produce it by layer manufacturing. These Rapid Prototyping (RP) techniques produce models that can mainly be used for visualization of the actual product and cannot be used in place of actual product. The properties of the materials (resins and plastics) that these processes use are far away than the product's actual properties. Presently, the focus of research has been to develop techniques that produce prototypes of the actual product with same shape and material and hence having same properties. Different deposition methods are available for metals but welding has shown potential for rapid prototyping of metallic parts. It has been recognized that welding as a deposition process is more economical and produce full dense metallic parts than other metal based deposition processes.

Now the efforts are being made to develop fully "functional parts" besides just producing "feel/fit/touch" parts. To establish form-fit and functional testing, the research is being carried out in the field of new and better materials, software development, tolerances and system design of RP processes. So far many new metal deposition processes have already been developed for the parts with metallic and functional properties due to the need of the market because metallic parts are of specific interest. Welding based RP has good potential in this regard; with the best possibility to produce fully functional metallic parts and tools.

Metal based RP: Rapid prototyping of metallic parts can be carried out through several processes such as droplet based manufacturing, sintering, laser deposition and brazing (soldering). In this context the research work of Ashley (1994) shows that nearly full density prototypes can be achieved through sintering process. But to attain full density product, post processing is also needed. Although laser deposition method is dimensionally more accurate than sintering, but it causes warpage and some surface finish defects in final product due to the constraining of materials having differing temperature. Soldering and brazing add undesirable bonding materials to the part. Droplet based manufacturing processes are flexible but it also have limits. These can produce full density metallic parts with desired material eliminating cost of post processing (Zhang *et al*., 2002). These processes include:

- Welding
- Micro-casting
- Thermal spraying

While Thermal Spraying and Micro-casting have their own advantages, they have many disadvantages and limitations too in terms of lead time and economic aspects. In this study, our focus is only on the Welding process as a mean to produce layer-by-layer rapid prototypes which provide the same properties as our desired final product.

Welding as RP tool: Although welding process is already in use for the fabrication of large components with simple geometry for many years, however, such applications of this phenomenon in aerospace industry are quite new. Production of aircraft parts based on titanium and nickel alloys are being manufactured by welding techniques. There is a lot of research available on the optimization of welding parameters for fabrication of simple parts having exceptional weld quality. But this information cannot help out in rapid prototyping by welding. A huge difference exits between the optimized parameters for "welding joints" and as those for "exceptional quality prototype layer". For example the penetration depth, build up height and ratio of both these variables are different for joining by welding and prototyping by welding.

For RP welding process there are some specific requirements to be met. For example low heat input is required for this process in order to retain geometrical features and to avoid high intensity level of residual stresses. Shallow depth of penetration is recommended for better metallurgical bonding between layers. Welding based RP system contains a welding apparatus (torch, gas cylinder, regulator etc.) and a mechanical system. Mechanical system contains 3 axis movement controls with a welding torch-holding mechanism. Numerically controlled mechanical systems are recommended to get desired shapes of the product. Feedback control is established by means of thermocouples, high frame-rate imaging or laser based control systems. This feedback system monitors the level of preheat, part temperature, pulse rate, droplet size and droplet detachment. A girt blasting nozzle may also be installed with a suction pump and vacuum nozzle to minimize the oxidation of the part (Mufti, 2009).

Different types of welding have been tested for rapid prototyping application e.g., Gas Metal Arc Welding (GMAW or MIG welding), Gas Tungsten Arc Welding (GTAW or TIG welding), Electron Beam Welding (EBW), Laser Welding and Variable Polarity Gas Tungsten Arc Welding (VPGTAW).

SCOPE AND OBJECTIVE OF THE PRESENT RESEARCH

Welding as a deposition process has shown promise for RP metallic parts. Welding is an old and mature technology and is recognized to be used for the development of a cost competitive method for layer-by-layer manufacturing to produce metallic parts and tools. However, welding is a process where high heat input results in large thermal gradient which causes the buildup of residual stresses, distortion and resulting into undesired quality of products. These problems can be reduced to some extent but cannot be eliminated. Post processing can be helpful for producing parts with good accuracy and surface finish. In order to produce accurate parts with less residual stresses, it is recommended to select welding deposition parameters by considering the following criteria necessary of weld based prototyping:

- Depth of *Remelt* should be shallow (for just reasonable metallurgical bonding).
- Low heat input imparted to the work piece.

This study investigates the effects of different welding parameters on the deformation produced in the weld-based prototypes. These parameters include mechanical constraints applied, geometry of the heat sink used and interpass cooling time. Objective of this investigation is to find out the optimum parameters under which we get minimum deformation in the substrate plate and hence in our weld-based prototype products.

EXPERIMENTAL SETUP AND ANALYSIS OF DEFORMATION

The experimental setup constituted of a test bed facility for deposition of weld metal and removing of metal by milling operation. It has the ability to build a single or multi layered plate shaped specimens with an optional intermittent machining after each deposited layer. Available experimental facility consists of a conventional milling machine and a MIG welding plant. Milling and welding machines are interfaced with each other for the control of deposition start up, end, weld bead size and layer position. Automatic feed of table of milling machine in X-axis was used to control the speed of the weld bead deposition. Distance between starting point of two beads was controlled by Y-axis feed of milling machine. The torch was held at a particular position by using a stand as shown in Fig. 1. Welding plant was used for deposition and welding parameters were maintained throughout the experimentation to ensure constant welding conditions. Welding torch was operated manually. Start of X-axis feed of the machine table and pressing torch button took place at the same time. Speed of weld deposition was controlled by the feed of the table in X-axis. Length of weld bead was controlled by controlling motion of the table which in turn controlled by adjusting the dogs of the table. After each weld pass the welding torch was offset by one half of the weld bead width for depositing the next pass and the process continued until the complete layer was obtained. This offset was done to ensure a proper overlap of the weld beads.

Fig. 1: Welding system coupled with milling machine

Table 1: Welding parameters for deposition process

Voltage (V)	25
Average welding current (A)	120
Weld speed (mm/min)	350
Wire speed (mm/sec)	16
Gas flow rate (SCFH)	35
Stick out (mm)	15
Weld bead to weld bead offset (mm)	3.5

A 1 mm diameter carbon-steel welding wire, ER-70S-6, was used to build a slab (100×50×30 mm) on the substrate plate and CO_2 being used as the shielding gas. The welding parameters which were used for deposition process throughout the experimentation are shown in Table 1.

Development of prototype: A 160×110 mm substrate plate was made out of a 12 mm thick Carbon steel plate. This substrate plate was machined on shaper machine then maintained to proper size on a surface grinding machine to a thickness of 10 mm. The plate was then taken to a furnace for stress relieving process. The thermal cycle adopted for stress relieving was as stated below:

- Heated up to 600°C
- Kept at 600°C for 60 min
- Cooled in furnace

A base plate of CS (200×130×34 mm) was used to support the substrate plate. The top and bottom surface of the support plate were also finished on a surface grinder to ensure a flat contact between base plate and substrate plate. This was also required to ensure a flat reference surface when placed on table of CMM machine for deformation measurements. The substrate plate was bolted on the base plate with the help of four bolts at corners. The flatness and the sizes of the plates are measured by CMM machines as shown in Fig. 2.

After necessary measurements, a single layer of weld metal (100×50×3 mm) was deposited at the center of the bolted substrate plate in thirteen weld passes with an interpass time of 60 sec. Raster pattern of deposition was used to build a slab as shown in Fig. 3. After depositing the weld metal, the plate was again taken to CMM for the measurement of deformation.

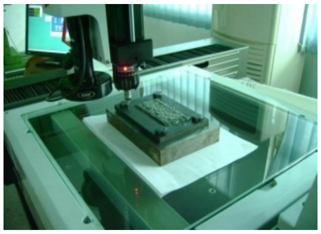

Fig. 2: Application of CMM for deflection measurement

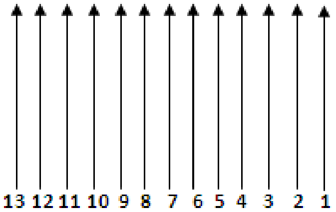

Fig. 3: Raster deposition sequence

Effect of welding parameters on weld based prototype: In weld based rapid prototyping, residual stresses and deformation produced is of great interest because of probability of occurrence of premature failure and variation in part tolerance which are directly related to residual stresses and deformation produced. Specifically efforts are made to optimize these factors while producing parts by using metal deposition by welding technique. Due to the high heat input resulting from direct contact of electric arc with substrate, the geometrical tolerances of underlying layers is destroyed resulting in large severe residual stresses and order of yield strength is distorted badly. Excessive and regular heat input not only affects the surface finish of the product but also the geometry of layers underneath is disturbed. Therefore determination of process conditions, which not only minimize the residual stresses and distortions but also ensure acceptable quality parts with good surface finish and tolerance control, is an important issue for the optimization of the process. The effect of process conditions on the build-up of residual stresses and distortions was estimated by performing a detail parametric analysis in which a process parameter is varied and its effect is monitored.

Selection of parameters: Minimization of the residual stresses and distortion requires proper selection of parameters. There are many parameters which affect the deposition process however build-up of residual stresses and deformations mainly depends upon those parameters that alter the thermal patterns and mechanical constraints. The parameters like current (I), Voltage (V), welding speed (Vs) and wire feed affect the thermal patterns. Moreover other deposition parameters like interpass cooling, heat sink characteristics, number of beads for a layer and deposition sequence also change the transient temperature distribution.

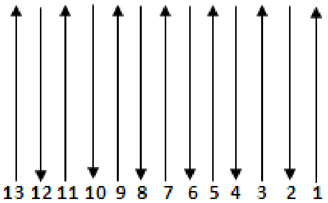

Fig. 4: Continuous depositions pattern

In present study the objective was to minimize the residual stresses and deformations by selecting particular deposition parameters i.e., heat sink size and mechanical constraint conditions. After thorough experimental investigation, we came with the welding parameters (Table 1). These parameters were kept constant during complete parametric analysis.

Hypothesis regarding parameters affecting deformation: From previous studies of Mufti (2009) and Junejo (2006), following hypothesis about the parameters affecting deformation can be assumed:

- By decreasing interpass cooling time, deformation is reduced in weld based rapid prototype.
- By applying mechanical constraint e.g., bolting substrate plate, deformation is reduced in weld based rapid prototype.

In addition to above two parameters about which hypotheses is assumed, there is another important parameter (heat sink characteristic of base plate) which has major effect on deformation. In present study this parameter was focused to get lesser deformation, hypothesis assumed about this parameter is that:

- By reducing heat sinking characteristic of the base plate, deformation is reduced in weld based rapid prototype.

Now in the subsequent paragraphs, above three hypotheses are discussed in details.

Effect of interpass cooling time: Interpass cooling time is the time interval between the end of one bead and start of next bead. Or it is the time required for the deposition torch to be aligned to a successive weld start positions. More interpass cooling time increases the deformation. As the substrate plate cools down during the Interpass delay duration, the substrate plates preheat available for the next row decreases which results in larger temperature gradients across the substrate plate thickness and hence deformation increases.

By decreasing the interpass time deformation can be reduced. In continuous deposition (Fig. 4) Interpass time is zero, so minimum deformation will be achieved in this type of deposition. But continuous deposition may cause excessive heat input which may result in high temperature area and larger remelting of the substrate plate or of underlying layers which cause loss of control over dimensional tolerances. Moreover the surface finish of the buildup is affected. Due to these problems, a compromise is required between employing Interpass cooling to avoid above problems as well as maintaining enough preheat to reduce the deformations so value of Interpass time should not be so small or large. Raster pattern of deposition provides promising results to build a slab and is shown in Fig. 3.

Effect of mechanical constraint: Mechanical constraint means some sort of constraint applied on substrate plate. It is a fact that whenever constraint is applied on substrate plate (by bolting it with base plate at four corners), then substrate plate would not be able to warp as result of thermal gradient produced during deposition in weld based prototyping. On the contrary if substrate plate is unbolted, the plate would move freely, consequently more deformation will be produced in this condition as compared to bolted condition. Moreover amount of torque applied to bolts also affect the deformation results. Higher the torque applied more constraint will apply and consequently less deformation will produce and vice versa.

To study the effect of this parameter on the deformation of weld-based prototype, number of experiments was performed by applying different constraints to substrate plate (having same dimensions) using constant welding parameters. First of all a weld slab was built on the substrate plate placed on the base plate in unbolted condition. Results of deformation of this plate are shown in Fig. 5 and 6. Deformation along line AA and BB are shown in Fig. 5. This trend is showing that substrate plate warp from ends and these ends are showing maximum deformation. This warpage of the plate is because of the compressive reaction forces caused by thermal cycling during deposition. Deformation results along line CC are shown in Fig. 6.

After this, experiments were performed by bolting the substrate plate at its corner. This bolting effect will not allow ends to move freely. Reaction forces because of thermal cycling will cause the substrate plate to deflect upward. This deflection has a maximum value at the mid-length of the plate and decrease down both sides. First plate was bolted at 50 lbf and deformation results of this plate in bolted form along line AA and BB are shown in Fig. 7. Deformation along line CC is shown in Fig. 8.

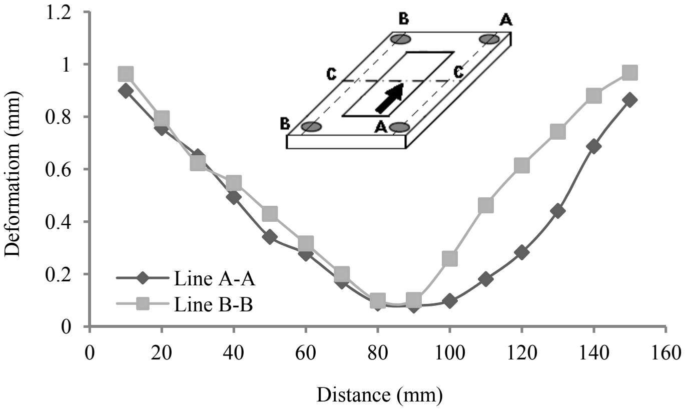

Fig. 5: Deformation in substrate plate along line AA and BB (unbolted)

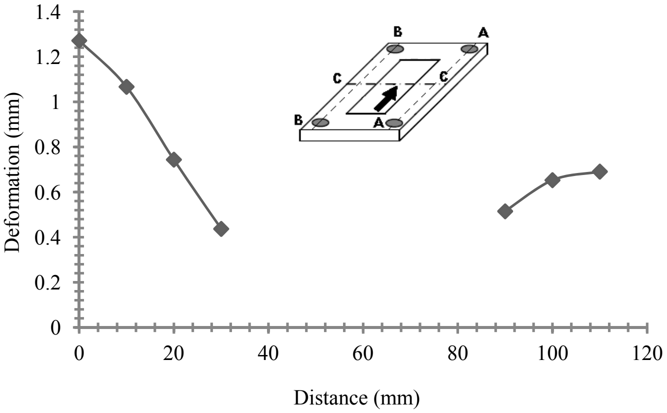

Fig. 6: Deformation in substrate plate along line CC (unbolted)

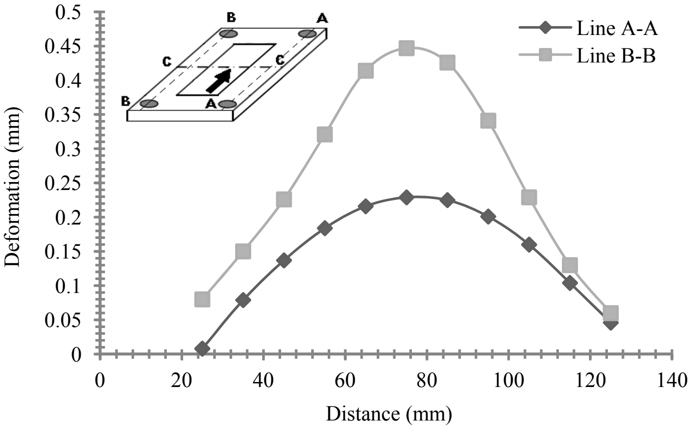

Fig. 7: Deformation in substrate plate along line AA and BB (bolted at 50 lbf)

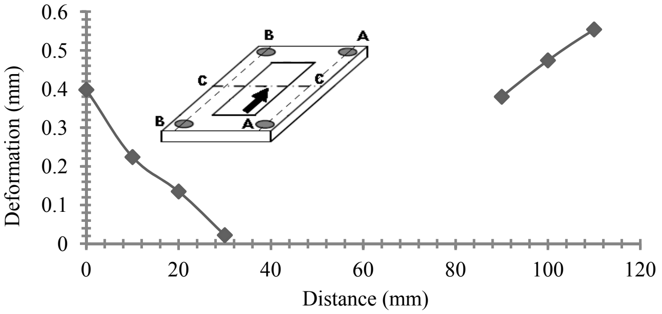

Fig. 8: Deformation in substrate plate along line CC (bolted at 50 lbf)

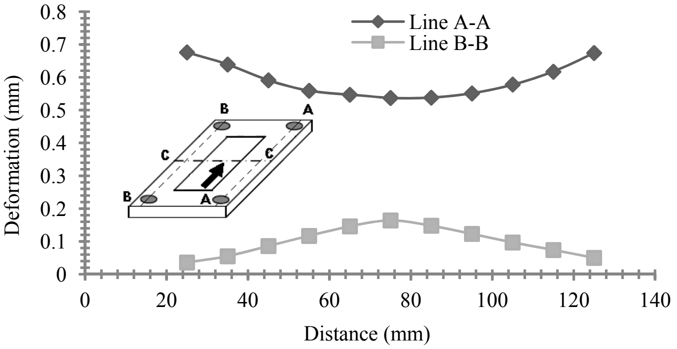

Fig. 9: Deformation in substrate plate along line AA and BB (unbolted at 50 lbf)

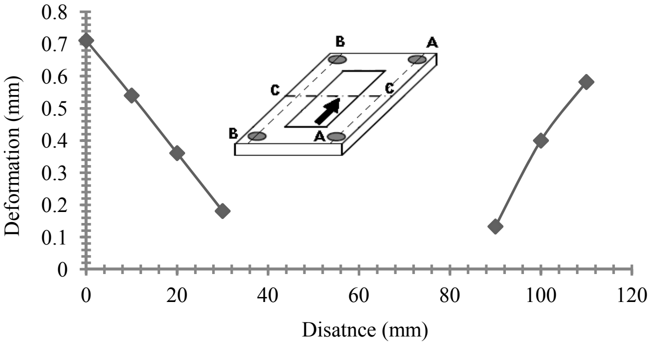

Fig. 10: Deformation in substrate plate along line CC (unbolted at 50 lbf)

After measuring deformation in bolted form, this plate was unbolted from base plate and then deformation was measured in this form, results of this plate are shown in Fig. 9 and 10. It is quite clear from these figures that when plates were unbolted stresses entrapped in plates tend to warp the plate.

Since the deformation in the plate along line AA was less, therefore stresses warp this side easily. That is why in unbolted condition deformation pattern along line AA is opposite as compared to bolted condition. On the other hand in bolted condition, deformation along line BB was relatively high so stresses tried to wrap this side (when it is unbolted) but these stresses were not able to do so, therefore deformation pattern remained same but the magnitude decreased relatively (Fig. 9). Figure 10 depicting trend of deflection along line CC.

Substrate plate was then bolted at 100 lbf. Under this condition of bolting, deformation in plate is shown in Fig. 11 and 12. From these figures we can see that trend along all the measured lines is same but there is a difference in the magnitude of deformation. Following the same pattern of study as in previous experiment, this plate was unbolted and its deformation was measured. Deformation results in unbolting condition are shown in Fig. 13 and 14. Again trend is same but magnitude of deformation is different that's an effect of increasing bolting force.

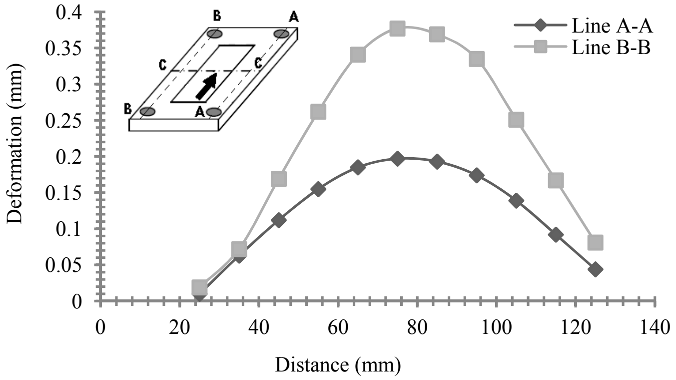

Fig. 11: Deformation in substrate plate along line AA and BB (bolted at 100 lbf)

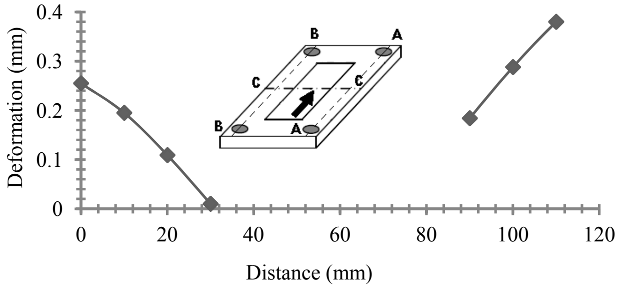

Fig. 12: Deformation in substrate plate along line CC (bolted at 100 lbf)

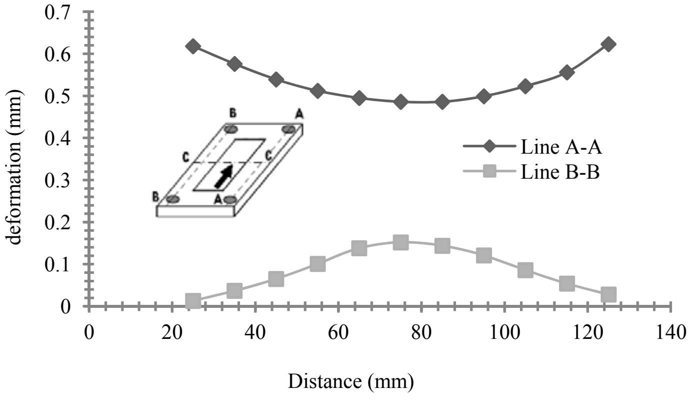

Fig. 13: Deformation in substrate plate along line AA and BB (unbolted at 100 lbf)

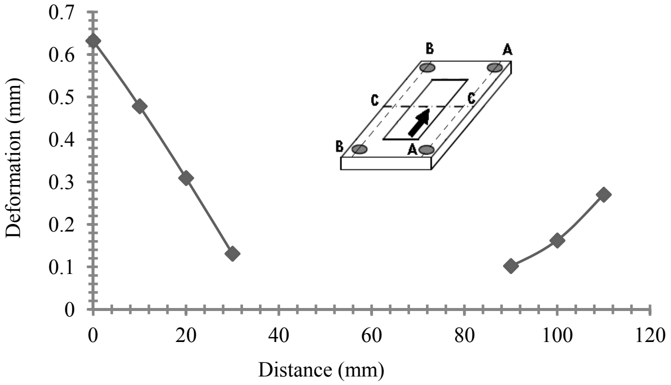

Fig. 14: Deformation in substrate plate along line CC (unbolted at 100 lbf)

Fig. 15: Plate with blind holes at it base

It is clear from above mentioned diagrams that deformation reduced as the mechanical constraint were applied. Maximum deformation is when no constraint was applied but as some constraints were applied by bolting the corners, deformation reduced (both in bolted and then unbolted forms) significantly. This is because bolts provide stiffness at the corners which provide resistance to deformation in the plate and ultimately results into reduction of deformation. More the force will be used for bolting the plate, more will be stiffness and consequently lesser will be deformation as it is proved from the results. Another thing in previously described figures is that deformation in bolted plates along line AA is lesser than that in line BB. This is because along line AA already built beads will increase the stiffness and because of this self-stiffening phenomenon deformation along line AA will be relatively less.

Effect of heat sink characteristics: During deposition, the substrate plate is placed over the base plate which acts as a heat sink. The thermal properties of the base plate play a major role in the buildup of residual stresses and deformation. More heat sunk by base plate will result in rapid cooling and heating during the deposition. This will cause more thermal gradient resulting in more deformation in the plate. So if a plate has such a design or properties that it sinks less heat it will cause lesser deformation. Heat sink capacity can be minimized to zero by using base plate of insulated material which gives more uniform temperature distribution throughout the substrate plate, resulting in an overall lower deformation. But drawback is the reduction of efficiency in terms of surface quality and control on dimensional tolerance because of overheat.

To determine the effect of this parameter on the deformation different experiments were performed with different base plate configurations. These configurations are as follow:

- Solid plate (used in all previous experiments)
- Plate with blind holes at its base
- Plate with slots and beams at its base

By using above mentioned base plates, experiments were performed with the help of same welding parameters as mentioned in Table 1. Deformation results of substrate plate in each case were measured by using CMM. These deformation results were drawn against distance on the plate along their representative line to show the trend of the deformation along the length.

To investigate the effect of heat sink characteristic, same bolting factor (i.e., 50 lbf) was applied to all plates which were bolted in these experiments. A substrate plate was bolted with the fully solid base plate. A slab (100×50×3 mm) of weld metal was deposited on it due to which deformation produced in the substrate plate. Investigation of deformation was done by using different base plates having different heat sink properties.

Holes were drilled in the base of a plate as shown in Fig. 15 and then it was used as base plate to bolt the substrate plate on it. After building a weld slab on the substrate plate deflection or deformation in the plate was measured. Results of deformation of plate in bolted form are shown in Fig. 16 and 17. When this welded substrate plate is unbolted from the base plate this will warp due to stresses, this deformation was measured and is shown in Fig. 18 and 19. Trend of

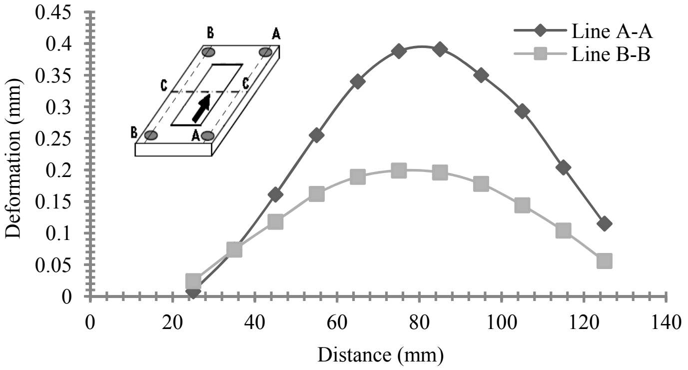

Fig. 16: Deformation in bolted substrate plate along line AA and BB (base plate with holes)

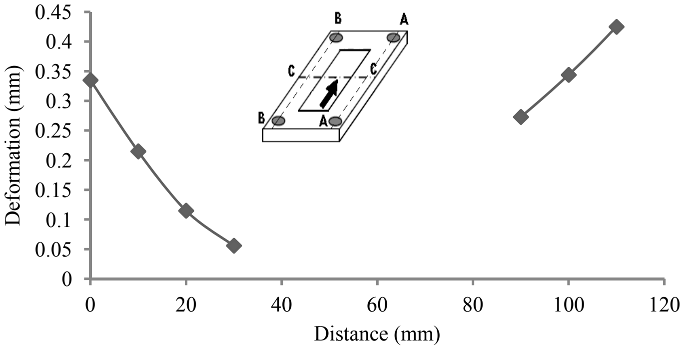

Fig. 17: Deformation in bolted substrate plate along line CC (base plate with holes)

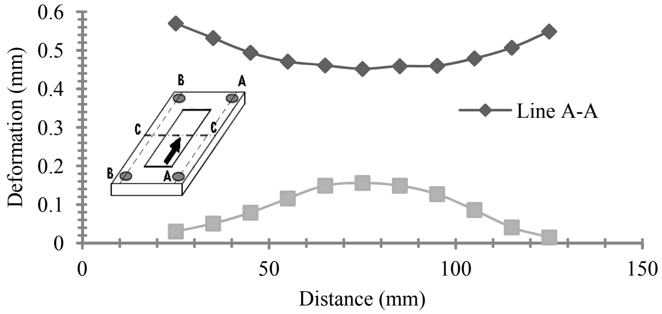

Fig. 18: Deformation in unbolted substrate plate along line AA and BB (base plate with holes)

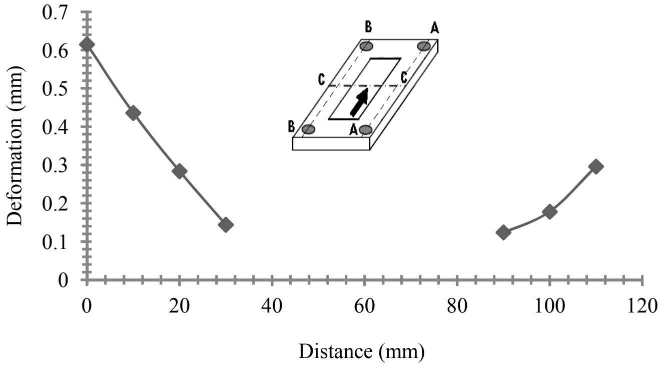

Fig. 19: Deformation in unbolted substrate plate along line CC (base plate with holes)

Fig. 20: Plate with slots and beams at its base

deformation in plate both in bolted and unbolted form are discussed earlier but deformation magnitude is less as compared to plate that was bolted at same force on solid base plate.

For further reduction of deformation by using heat sink property, a new design of base plate was made in which base plate has slots and beams at its base as shown in Fig. 20. This design was chosen because heat sink property was to be minimized by extracting more material from plate but integrity of base plate was also

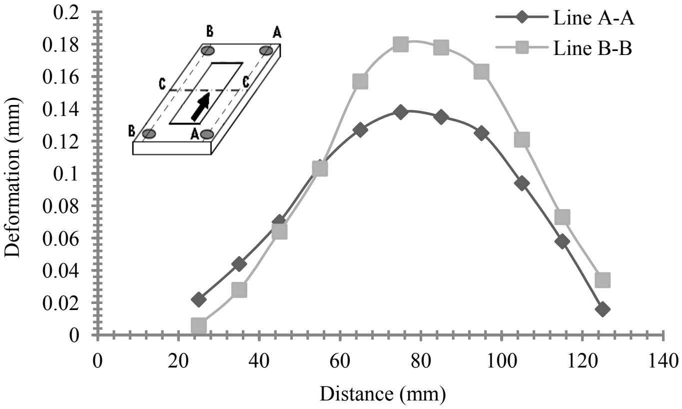

Fig. 21: Deformation in bolted substrate plate along line AA and BB (base plate with slots)

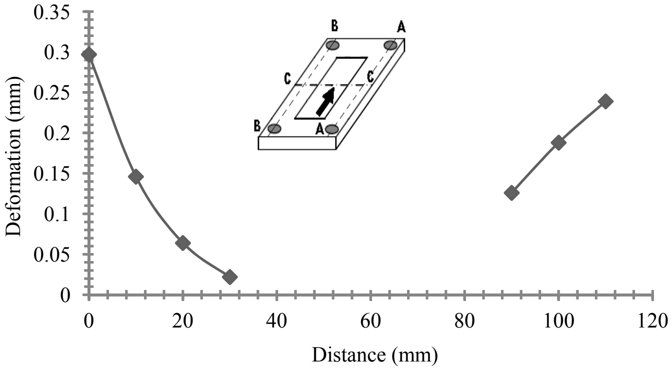

Fig. 22: Deformation in bolted substrate plate along line CC (base plate with slots)

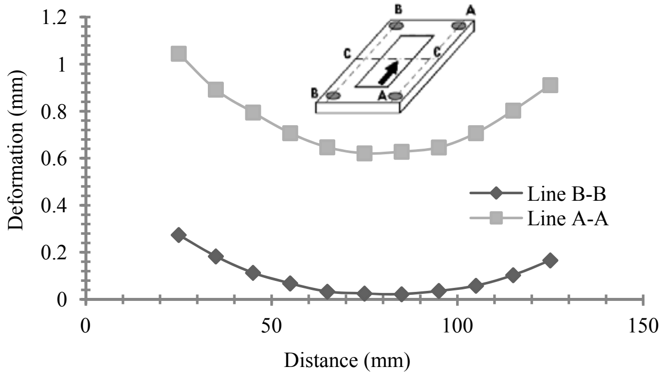

Fig. 23: Deformation in unbolted substrate plate along line AA and BB (base plate with slots)

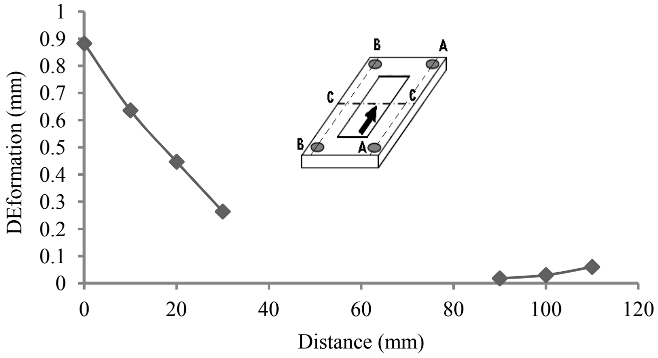

Fig. 24: Deformation in unbolted substrate plate along line CC (base plate with slots)

to be kept reasonable for which beams were made in the design. Deformation in the substrate plate bolted on this design of base plate is shown in Fig. 21 and 22. Deformation along all three lines in bolted state is normal but in this case reduction in deformation is significant. In Fig. 23 and 24 deformation patterns of this plate in unbolted form are shown. Trend of deformation along line AA and CC is normal but this time plate is also warped along line BB in unbolted form. This is because of significant lesser deformation along this line in bolted form and on unbolting stresses will warp plate along line BB also.

It can be seen from these results that smaller the heat sink property lesser will be the deformation in the plate. It is clear that when material is extracted from the solid plate by drilling hole it gave us less deformation as compared to deformation in substrate plate with solid base plate. By removing more material and providing reasonable integrity, as it was done in final design of base plate, significant reduction in deformation of the plate was achieved.

CONCLUSION

Continuous deposition method (zero interpass time) makes sure the availability of greater preheat which give less deformation but at the same time this results in high temperature which reduces the efficiency of the process in terms of surface quality and control on dimensional tolerance. In order to avoid these problems some interpass time may be required. Similar case is with heat sink characteristics, we need small heat sink size but at the same time elimination of heat sink size can also cause problems. Therefore, to get optimized results from this process (weld based prototyping) parameters affecting the process have to be optimized. By combining different parameters we can attain minimum deformation which can be done experimentally.

The parametric studies have shown that interpass time and heat sink capacity are two driving factors which have major affect on deformation as compared to other parameters. A fully constrained substrate plate and base plate with optimized heat sink size along with enough interpass cooling time to avoid excessive heat are required to minimize residual stresses which results in deformation.

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