SIMULATION OF LAMINATED OBJECT MANUFACTURING (LOM) WITH VARIATION OF PROCESS PARAMETERS

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ABSTRACT

A previously developed and verified thermal model for Laminated Object Manufacturing (LOM) was used to investigate the effects of various processing parameters on the temperature profile in a LOM part during the build cycle. The mathematical model, based on 3-dimensional transient heat conduction in a rectangular geometry LOM part, allows calculation of the transient temperature distribution within the part during the application of a new layer as well as during other periods of the LOM build cycle. The parameters roller temperature, roller speed, chamber air temperature, base plate temperature, and laser cutting time were independently varied, and the LOM process response simulated. The results were analyzed in order to gain insight into potential strategies for intelligent process control.

INTRODUCTION

LOM users are fast becoming aware that an understanding of the thermal behavior of a LOM part during the build process is crucial for the fabrication of parts with good lamination characteristics. Low temperatures in the upper layers may result in poor adhesion of the individual layers causing delamination of the completed part. On the other hand, excessive build-up of heat in the body of the part may result in a general loss of structural rigidity during the build leading to excessive compression or shearing during application of pressure by the roller. While this is important for prototype parts made from standard LOM paper and plastic materials, it has become extremely significant now that the fabrication of high performance, functional ceramic and composite parts is being considered [1-8].

In order to obtain a better understanding of the transient thermal behavior of the part body during the LOM build cycle, a mathematical model was developed and its performance verified [9]. As part of a continuation of this work, it was decided to use this process model to investigate the effects of varying certain parameters during a number of simulated LOM builds. Use of this model allows a number of experiments to be conducted in a relatively short time, and also does not require use of the actual LOM apparatus with associated relatively high cost. In addition, this approach allows for variation of process parameters that are not currently implemented on the LOM machine, such as base plate and chamber air temperatures.

A series of simulation experiments was thus planned to see which of the process variables had significant effects on the transient thermal behavior and which variables could potentially be used for process control purposes. The results of these experiments are presented here together with a brief discussion of their significance.

BACKGROUND

Full details of the mathematical model have been previously documented [9] so only a brief description of the model and its capabilities as is pertinent to this discussion will be presented here.

The thermal behavior of a part during a LOM build is determined by heat transfer to the part from the roller, heat conduction within the part itself, heat loss from the part to the metal base plate, and heat loss to the surroundings. The appropriate differential equation and boundary conditions were set up for a rectangular geometry part (because all LOM parts are built as rectangular blocks) and then together with appropriate initial conditions, material properties and heat transfer coefficients numerically solved to reveal the temperature distribution within the part. The model is capable of handling the addition of new layers of build material as well as all other phases of the build cycle and generates the full 3-dimensional transient temperature profiles within the part. The model does not include a mechanical submodel, and therefore, the coupling of thermal and mechanical behavior cannot be fully simulated. However, by tuning one of the model parameters (roller to part heat transfer coefficient), excellent agreement was obtained between predicted temperatures within a part and the actual temperature as measured by embedded thermocouples [9], see Figure 1. Thus, the model is fully capable of measuring the thermal behavior of the LOM process.

MODELING EXPERIMENTS

A series of simulation experiments was designed around a base simulation taken from the previous work [9]. This work involved layup of 250μm-thick SiC ceramic tapes on a LOM2030 machine. A twenty-layer, 12.19 cm x 5.33 cm block of "green" ceramic material was produced. Material property data and simulation parameters for this base case are summarized in Table 1. All parameters were experimentally measured, except the roller to part heat transfer coefficient which was used as a tuning parameter.

Table 1: Material properties and machine parameters for base simulation [9].

Material	Silicon carbide ceramic tapes
Thermal Conductivity	1.25 $Wm^{-1}K^{-1}$
Density	1.98 g cm^{-3}
Heat Capacity	1.05 $Jg^{-1}K^{-1}$
Part dimensions	121.9 mm x 53.3 mm
Layer thickness	0.25 mm
Number of layers	20
Heat transfer coefficient (part to air)	18 $Wm^{-2}K^{-1}$
Heat transfer coefficient (part to base)	14 $Wm^{-2}K^{-1}$
Air temperature	22°C
Base plate temperature	22°C
Initial temperature of material	22°C
Roller velocity	25.4 mm sec^{-1}
Roller contact strip width	9 mm
Roller temperature	91°C
Heat transfer coefficient (roller to part)	3300 $Wm^{-2}K^{-1}$
Build cycle time	120 seconds

Parameters selected for investigation included the following: roller temperature, base plate temperature, chamber air temperature (surrounding air temperature), roller speed, laser cutting time. The roller temperature and speed influence the amount of heat transfer from roller to part. Base plate and chamber air temperatures influence the rate of heat loss of the part block. The entire part block as a whole gains negligible heat from the laser cutting (although this may not be true for the top layer or two), so the laser cutting time affects the amount of cooling between application of successive layers. All of these parameters directly influence the transient as well as long term thermal behavior of the part. Table 2 summarizes the parameter values used and the changes made to these parameters. In some cases (Trials 15-18) the parameter value was changed halfway through the simulation in order to observe the dynamic response of the process to that variable change. This information is important for process control purposes. The full experiment and results are documented elsewhere [10].

RESULTS AND DISCUSSION

During model verification [9] it was observed that the temperature below the 1st layer (bottom most) of build material was representative of the part body temperature, i.e. apart from surface transient behavior near the part block surface during roller activity, the temperature through the depth of the part was fairly uniform. Thus, in order to compare the behavior of the part when subjected to the different sets of parameters, it was decided to observe the first layer temperature only. Thus, the results shown in the various figures herein represent how the temperature below the bottom most layer varies with time during the build, and this can be interpreted as how the part body temperature as a whole varies with time (referred to as the "representative part body temperature"). In all cases, fluctuation of the representative part body

Table 2: schedule of investigated LOM parameters.

Trial #	Roller Temperature (°C)	Base Plate Temperature (°C)	Chamber Air Temperature (°C)	Roller Speed (cm/sec)	Laser Cutting Time (sec)
1	91	22	22	2.54	77
2	150	22	22	2.54	77
3	200	22	22	2.54	77
4	250	22	22	2.54	77
3	200	22	22	2.54	77
5	200	50	22	2.54	77
6	200	75	22	2.54	77
7	200	100	22	2.54	77
3	200	22	22	2.54	77
8	200	50	50	2.54	77
9	200	75	75	2.54	77
3	200	22	22	2.54	77
10	200	22	22	3.81	77
11	200	22	22	5.08	77
12	200	22	22	2.54	57
3	200	22	22	2.54	77
13	200	22	22	2.54	97
14	200	22	22	2.54	117
15	91	22 / 50*	22	2.54	77
16	91	22 / 100*	22	2.54	77
17	91 / 150*	22	22	2.54	77
18	91 / 200*	22	22	2.54	77

*Parameter changed halfway through the run from the first value to the second.

temperature tends to dampen as more layers are added, and an "average part body temperature" is also referred to throughout the discussion.

The first parameter investigated was roller temperature. The roller temperature was varied in the range 91°C to 250°C, and all other parameters were kept the same as the base case simulation (trial #1 *is* the base case simulation). Figure 2 reveals that peak temperatures are dramatically increased and the long-term part body temperature is only minimally affected. The average part body temperature increased about 10°C for every 50°C increase in roller temperature. Although not shown in Figure 2, the temperature of the surface layer (in direct contact with the roller) is most dramatically affected.

The next test involved variation of the base plate temperature only. At this point in the study, it was decided to deviate from the base case parameters by using a roller temperature of 200°C for many of the remaining trials. The reason for doing this was to amplify the effects of changes in the other parameters such as base plate temperature, chamber air temperature, etc. The results for parametric variations in the base plate temperature are given in Figure 3. As can be seen, higher base plate temperature resulted in higher temperatures of the part being built. The average part body temperature for this simulation seems to increase approximately 9°C for each 25°C rise in base plate temperature. This effect was considered to be more "efficient" or "sensitive" than the roller temperature effect.

The next test involved parametric variations in the chamber air temperature. It should be noted that in all cases the base plate temperature was assumed to vary with the chamber air temperature. This would seem to be reasonable considering the geometry and layout of the LOM apparatus. Figure 4 shows how the part body temperature varies with time for different LOM chamber air and base plate temperatures. The response of the part is similar to that of the previous test, with the exception that the magnitude of the part temperature change was more. The average part body temperature for this simulation increases approximately 20°C for each 25°C rise in air and base plate temperature. Thus, this effect was viewed as the most "efficient" or "sensitive" so far. With the previous test in mind, this result was qualitatively expected, i.e. the block loses less heat because all surfaces are maintained at elevated temperature, not just the base plate as before. From a process control viewpoint, however, it may be a lot easier and more practical to manipulate the base plate temperature only and not the combination of base plate and chamber air temperature.

The roller speed was also investigated since time of roller contact will also influence the amount of heat transferred to the part. Changing the roller speed also has the effect of changing the overall build time of the part, so these result are not so easily compared graphically. It was discovered that for a 50% increase in roller speed, the average part body temperature decreased by about 7°C, and for a 100% increase by about 23°C [10]. Again, the surface layer in direct contact with the roller was the most affected.

A laser cutting time of 77 seconds was used in the base simulation. Changing the laser cutting time between the application of successive layers of build material should affect the part temperature due to the fact that increasing this delay time allows additional time for the part to cool by heat loss to the surroundings and base plate. The reason for investigating this effect is because the cycle time usually varies throughout a build due to changes in the laser cutting from layer to layer. It was discovered that this effect was fairly small, in most cases resulting in only about a 3°C drop in part body temperature for every 20-second increase in delay time. [10]

Some dynamic tests were also conducted where the base plate and roller temperatures were changed halfway through the build process. This was done to estimate how many cycles (or layers) were required for the part to respond to the change in the parameter value. The effect of changing the base plate temperature halfway through the build is shown in Figure 5. It can be seen that the part body temperature typically reaches its new average temperature within 3 to 4 cycles. A similar result was observed for the change in roller temperature (Figure 6). These results are significant when considering on-line control of the process and gives one some idea of the overall speed of response.

CONCLUSIONS

Use of the LOM process for the fabrication of functional ceramic and composite parts has resulted in additional requirements being placed on the LOM build environment to ensure the integrity and functionality of the produced parts. One of these requirements concerns the thermal environment of the part. Control of this environment thus has become an important consideration for the development of LOM using ceramic and composite materials.

The simulation and modeling work done has revealed that a number of parameters have influence over the thermal environment of the part and that some of these show promise as being suitable for manipulation of the process during online control. In particular, the chamber air temperature and base plate temperature combination would seem to be the most effective for control of the overall part temperature. From an overall practicality viewpoint, limited control could also be achieved using the base plate temperature only. The roller temperature proved to be the most effective in affecting the temperature of the surface layers of the part, i.e. those close to the roller during lamination. Thus, if high temperatures are required in the surface layers and somewhat lower temperatures throughout the remainder of the part, then control of the roller temperature would provide a means to accomplish this. However, large fluctuations in the temperatures near the surface would have to be tolerated.

The simulations also revealed some useful information with regard to the dynamic response of the temperature of the part. While this is known to be a function of the overall part dimensions and thermal properties of the build material, the response times obtained indicated that online control of the process is feasible and that reasonable dynamic responses should be obtained.

REFERENCES

1. Klosterman, D., R. Chartoff, N. Osborne, G. Graves, A. Lightman, G. Han, A. Bezeredi, S. Rodrigues, S. Pak, G. Kalmanovich, L. Dodin, S. Tu, "Curved Layer LOM of Ceramics and Composites," *Prototyping Technology International '98*, (Annual Review Book), ed. Jonathan Lawson, UK & International Press, Surrey, UK, April, 1998, pp.145-149.
2. Klosterman, D., R. Chartoff, et al., "Automated Fabrication of Monolithic and Ceramic Matrix Composites via Laminated Object Manufacturing (LOM)," *Proceedings of the Solid Freeform Fabrication Symposium,* Austin, TX, August, 1997, pp. 537-549.
3. Klosterman, D.A., B.E. Priore and R.P. Chartoff, "Laminated Object Manufacturing of Polymer Matrix Composites", Proc. 7th Int. Conf. Rapid Prototyping, University of Dayton and Stanford University, San Francisco, CA, March 1997.
4. Steidle, C.C., *Automated Fabrication of Bioceramic Bone Implants Using Laminated Object Manufacturing*, M.S. Thesis, Chemical Engineering, University of Dayton, May, 1998.
5. Chi, C., L. Dodin, and S. Pak, "Development and Fabrication of Metallic LOM Objects", *Proc. 7th Int. Conf. Rapid Prototyping*, University of Dayton and Stanford University, San Francisco, CA, March 1997.
6. Griffin, A., et al., "Bioceramic RP Materials for Medical Models", *Proc. 7th Int. Conf. Rapid Prototyping*, University of Dayton and Stanford University, San Francisco, CA, March 1997.

7. Griffin, E.A., D.R. Mumm, D.B. Marshall, "Rapid Prototyping of Functional Ceramic Composites," *The American Ceramic Society Bulletin*, Vol. 75, No.7, July 1996.
8. Pope, M., M. Patterson, W. Zimbeck, M. Fehrenbacher, "Laminated Object Manufacturing of Si3N4 with Enhanced Properties," *Proceedings of the Solid Freeform Fabrication Symposium,* Austin, TX, August, 1997, pp. 529-536.
9. Flach, L., D. Klosterman, R. Chartoff, "A Thermal Model for Laminated Object Manufacturing Process," *Proceedings of the Solid Freeform Fabrication Symposium*, Austin, TX, August, 1997, pp. 677-688.
10. Jacobs, M.A., *Thermal Modeling and Control of the LOM Process*, Undergraduate Honors Thesis, Chemical Engineering, University of Dayton, April, 1998. (note, trial numbers in this paper and Jabob's thesis do not correspond).

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ILLUSTRATIONS

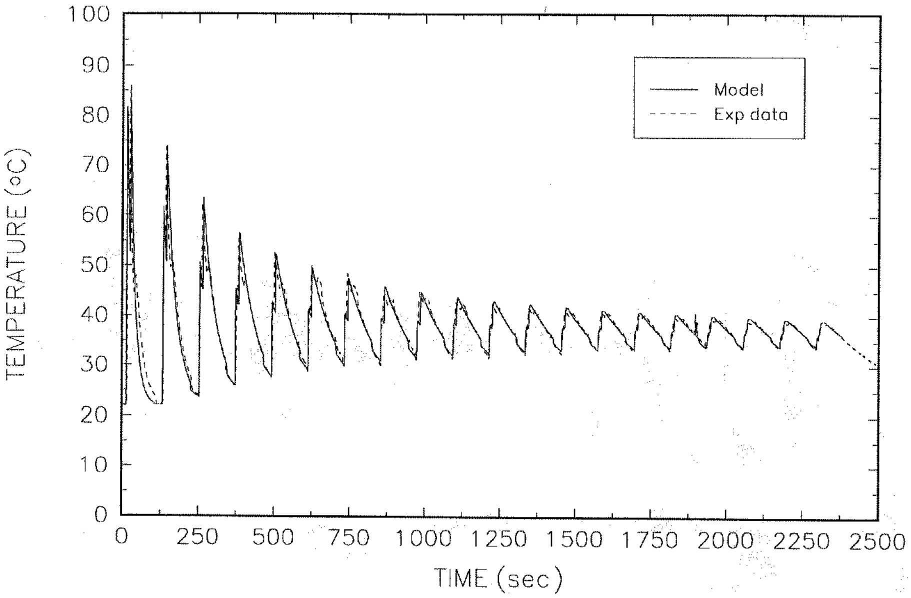

Figure 1: Base simulation and experimentally measured temperature profile for a 20-layer, SiC LOM part, as measured by a thermocouple just above the 0^{th} layer (foam tape base) during the build process [9]. The cycle time is 120 seconds per layer. The experimental conditions are given in Table 1 and Table 2 (trial #1).

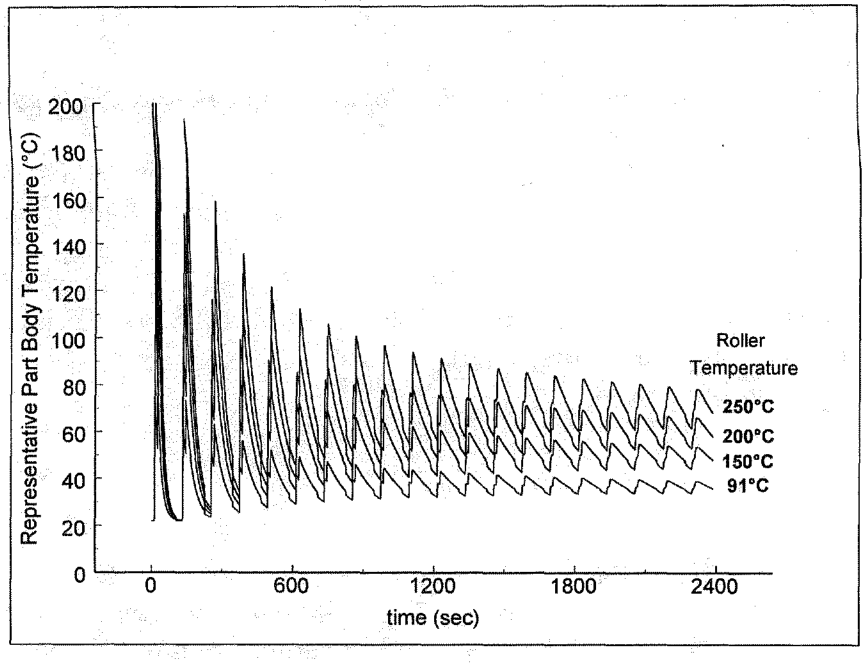

Figure 2: Parametric variation of roller temperature: simulated, dynamic temperature profiles inside a 20-layer SiC LOM part during the building process (120 seconds per layer) using the parameters given in Table 2 (trials 1-4).

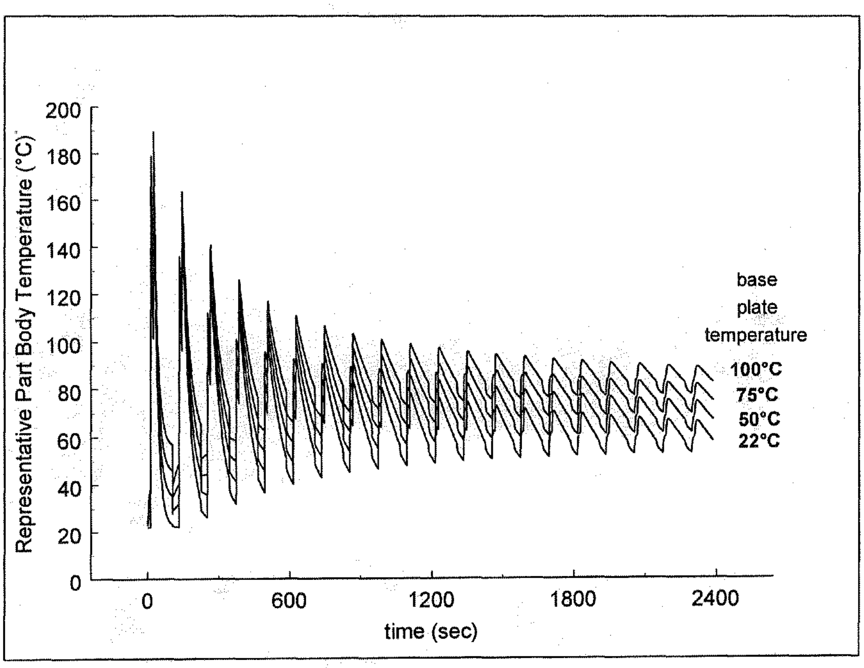

Figure 3: Parametric variation of base plate temperature: simulated, dynamic temperature profiles inside a 20-layer SiC LOM part during the building process (120 seconds per layer) using the parameters given in Table 2 (trial 3, 5, 6, 7).

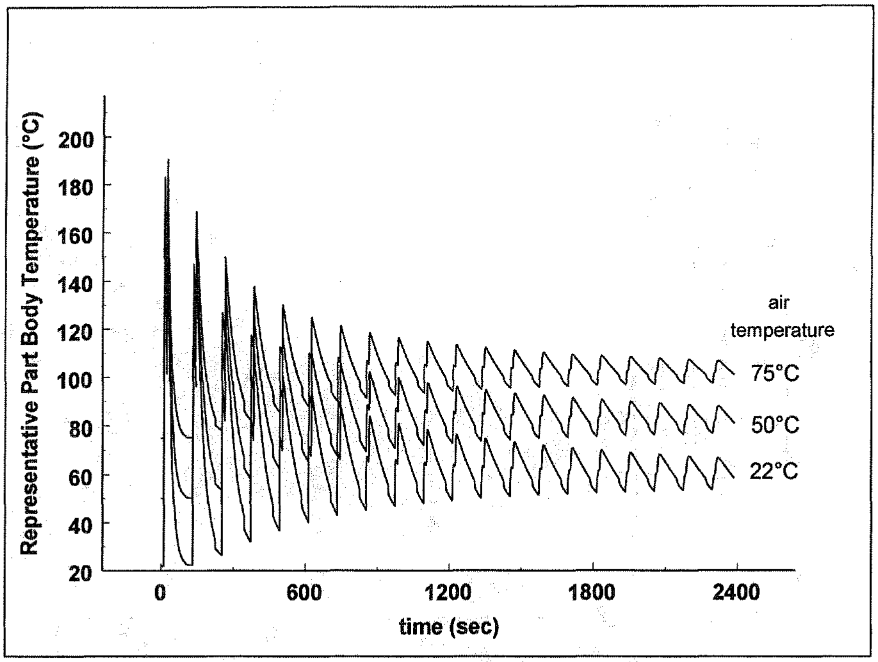

Figure 4: Parametric variation of chamber air temperature: simulated, dynamic temperature profiles inside a 20-layer SiC LOM part during the building process (120 seconds per layer) using the parameters given in Table 2 (trials 3, 8, 9).

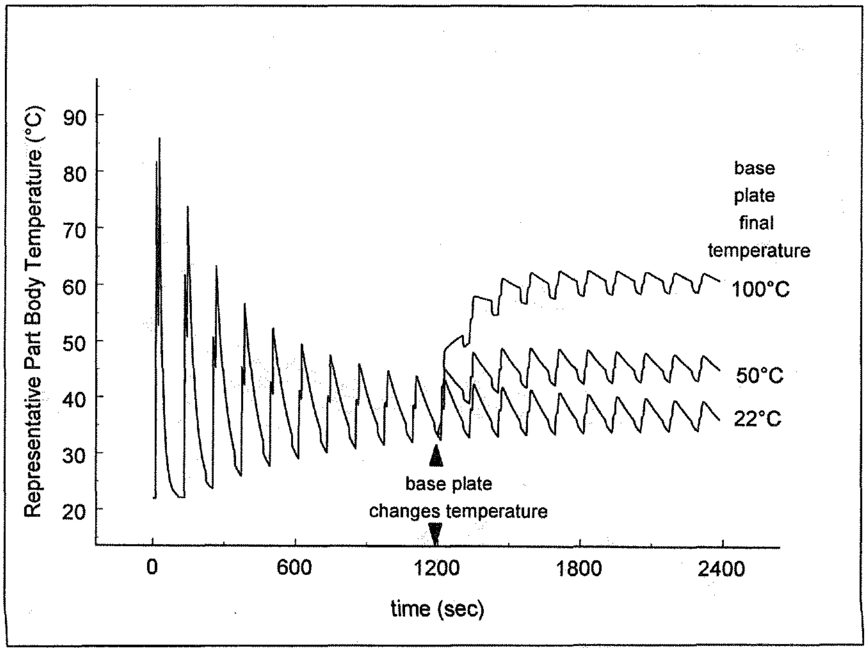

Figure 5: Effect of changing base plate temperature halfway through a run: simulated, dynamic temperature profiles inside a 20-layer SiC LOM part during the building process (120 seconds per layer) using the parameters given in Table 2 (trials 15, 16).

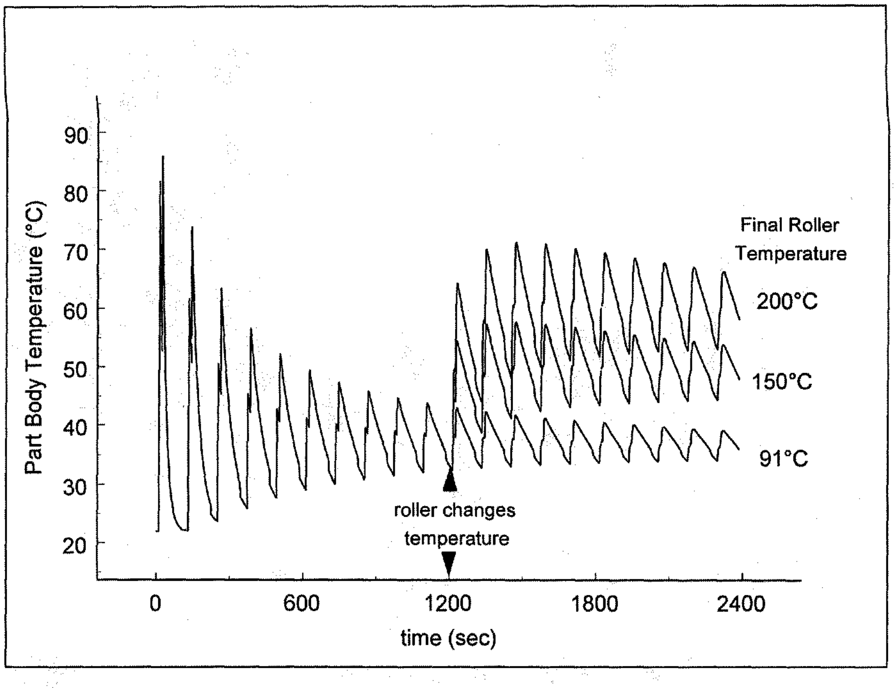

Figure 6: Effect of changing the roller temperature (from 91°C) halfway through a run: simulated, dynamic temperature profiles inside a 20-layer SiC LOM part during the building process (120 seconds per layer) using the parameters given in Table 2 (trials 17, 18).