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Effects of Forced Cooling in Laser Forming

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Abstract*: This paper presents the numerical bending studies of the alloy sheet of Magnesium M1A to achieve the bigger bending angle in a single laser forming process. A three-dimensional model of finite elements was created and different simulations were performed for sheet laser bending. Magnesium alloys are difficult-to-form yet have huge applications in automobile and aerospace industries because of its high strength to weight ratio. To study the sheet bending method and effect of various process parameters including laser scanning velocity, beam diameter and laser power, a three-dimensional numerical model was developed. The developed numerical model was designed with ABAQUS Simulia and validated with the published numerical model. On the validated numerical model, a further number of simulations were performed to understand the effects of forced cooling conditions in single scan laser forming process. This research work concluded that forced cooling conditions in laser forming can be used to increase the bend angle in a single scan.

Keywords: laser forming, forced cooling, bending, magnesium alloy

I. INTRODUCTION

Laser forming is the most promising and advanced non-conventional sheet metal forming method by applying thermal source, i.e. defocused laser beam and material characteristics without using internal mechanical load. [1, 2]. Laser forming process is very much similar to the flame bending process. For accurate and precise bending of sheets and neglect the defects such as wrinkling, thinning, spring-back and cross-sectional distortions that may occur with conventional forming methods, laser forming is recommended. In conventional forming operations, to get a particular shape, same mirror shaped dies are used, and the manufacturing of these dies consumes lots of time, manpower and much costly. In laser forming, sheet bending can be generated without punches or dies being used. On the other hand, different shapes of forming can be achieved with same laser beam by adjusting its scan speed, power and beam diameter, therefore it eliminates the die manufacturing process and thus save lot of cost and time [3-5].

In the multi-pass laser forming method, Edwardson et al. researched the impacts of the mechanism of temperature gradient on mild steel, Ti6Al4V and AA5251.They studied the effects of sheet bending by applications of graphite-coated materials [4]. Watkins et al. studied the laser forming processes of aerospace alloys like AA 2024 T3 aluminium alloy and Ti6Ai4V titanium alloy. They discovered that the symmetricity along the plate's length and width is essential to create a saddle shape from a rectangular flat plate[5].Hu et al. researched experimental and computer simulations to explore laser-forming bending of sheet metal and found that bending angle rises with increased numbers of laser scans. The bend angle is also stated as a function of scanning velocity and laser power [6]. Ramos et al. researched the impacts of laser bent sheet metal Al-2024-T3 on microstructure and micro-hardness. They examined various methods for characterization of material properties, these methods are scanning electron microscopy, light microscopy and Vickers micro-hardness [3]. The process of laser forming occurs primarily through three distinct processes depending on the material characteristics, beam geometry and forming process type required such as: [7].

Temperature Gradient Mechanism (TGM), the energy parameters cause steep variations in the temperature throughout the workpiece thickness (sheet), leading in temperature gradient mechanism. The required condition for TGM is that, beam diameter of laser spot must be greater than sheet thickness, by factor of two to four commonly used. For high thermal conductivity materials, to maintain temperature gradient, scanning speed must be fast. Bend angle 0.3 to 3 degree is obtained in a single scan of laser beam [4], [8].

Buckling Mechanism mainly used for the bending of tubes and thin sheets with a negligible temperatures gradient across the material thickness. The necessary condition for Buckling Mechanism, the diameter of laser spot is much larger than the thickness of workpiece, and for some cases, by factor of ten. To penetrate more energy into the material, and uniformly distribution of temperature, scanning speed should be slower in buckling mechanism. This mechanism is suggested for the production of three dimensional complex shapes profiles.

In the case of Upsetting or Shortening Mechanism (UM), material geometry increases in thickness and its sectional modulus changes [9]. The laser beam diameter is smaller than the thickness of the workpiece and there is no steep temperature gradient across the thickness of the workpiece [10]. The thermal expansion in heated region is not able to generating as much stress to bend the workpiece and the plastic compressive stresses is restricted from the unheated area. The material started to cool after the laser spot moved away, causing the workpiece to shorten owing to the rise in heated region thickness [11]. In the case of multi-scan laser forming, Paramasivan et al. investigated the effects of forced cooling. They observed forced cooling at bottom surface of 304 stainless steel, coaxial to laser scan by which temperature gradient mechanism and bend angle were highly influenced. It was observed that by liquid forced convection bend angle increases 20% compared to natural convection [12].

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Shen et al. studied various cooling effects in multiscan laser bending of sheets to reduce the waiting time in two adjacent scans [13].

II. FEM NUMERICAL MODELING

A. Three Dimensional Model

A three-dimensional model of finite elements is created using ABAQUS Simulink to explore the impact of forced cooling in the process of laser formation. The model consists of 7728 components, with 8 node hexahedral components including fine and coarse meshes. A C3D8T element type mesh is applied to the model for coupled temperature displacement, as shown in figure 1. Model consists of fine mesh, where laser heat is applied to get the accurate results and coarse mesh is applied at the rest of body to reduce the simulation time. The simulation is done for 4-6 seconds for single pass of laser beam, which takes 3-16 hours to complete the simulation. Boundary conditions are applied to fix the one free end of model, i.e.

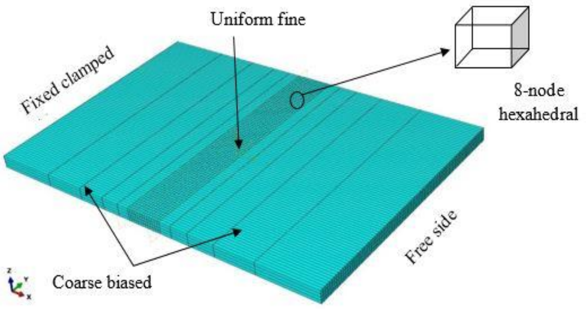

Figure 1: Workpiece mesh model

$$U1 = U2 = U3 = 0 \text{ and } UR1 = UR2 = UR3 = 0 \quad (1)$$

Where, U1, U2, U3 are the restricted displacements of fixed side of workpiece in x-directional, y-directional and z-directional respectively and UR1, UR2 and UR3 are the restricted rotational movements of fixed side of workpiece along x-directional, y-directional and z-directional respectively. Step time is taken as 0.001 and 0.01, for minimum and maximum respectively and maximum temperature change for each increment is taken as 50-100 (degree). In the middle of the workpiece, surface thermal flux (load) is applied and laser beam heat source is assumed to be Gaussian heat flux, as it provides very accurate heat value.

The laser beam displays a pattern of transverse spot modes, referred to as transverse electromagnetic (TEM modes).For Gaussian distribution, TEM_00, denotes the zero-order mode and have distribution of intensity of laser throughout the beam is given by;

$$I(r) = I_p e^{\left(-\frac{2r^2}{w^2}\right)} \quad (2)$$

Where I(r) is the intensity of the laser beam at any radial position, r (W/cm^2), I_p, r and w are the intensity of the peak beam (W/cm^2), the radial coordinate (cm) and the radius at which the intensity of the beam is (1/e^2) equivalent to I_p or 0.14 equivalent to I_p, i.e. 86% of the total energy is contained in a radius w (cm) spot.

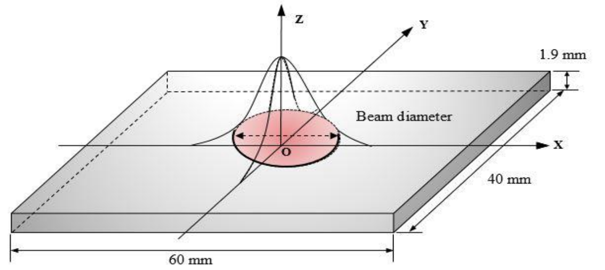

Figure 2: Model of the laser beam scanning of the workpiece [6]

To apply the moving heat source of Gaussian heat flux, DFLUX subroutine was applied on the model, by the compatibility of ABAQUS Simulink with Intel FORTRAN.

B. Process assumptions

There are some assumptions, which were considered in this research work for the laser bending of sheet:

- The material of the worksheet is isotropic and homogeneous.
- The material of worksheet is elastic-perfect plastic.
- The impacts of Bauschinger's and Strain hardening are overlooked due to the high temperature in the deformation region.
- Dissipation of energy is neglected because of plastic deformation.
- The worksheet is regarded to be flat and residual stress-free.
- Above the melting temperature, mechanical properties (stiffness) are lost.
- Laser beam has properties of Gaussian heat distribution within the geometry of the beam spot diameter.

C. Material Properties

The material of this workpiece is Magnesium M1A alloy with geometry 60mm length, 40mm width and 1.9mm thickness.

Table I: Mechanical characteristics of M1A alloy depending on temperature

S. No.	T (°C)	Tensile yield strength per minute at strain rate (MPa)				E (GPa)
		0.005	*0.05*	*0.5*	*5*	
1.	24	171	181	191	201	44
2.	93	137	137	163	177	
3.	149	82	82	133	163	
4.	204	52	52	86	86	
5.	260	33	33	58	58	
6.	316	26	26	40	40	
7.	371	18	18	29	29	
8.	427	15	15	21	21	
9.	482	10	12	14	14	
10.	650	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}

T= Temperature, E= Elastic Modulus
Data source: R. Kant and S. N. Joshi [8]

Magnesium M1A alloy composition contains 98.07% magnesium and 1.93% manganese. The Poisson's ratio of material is 0.35.

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Table II: Physical and thermal properties of magnesium M1A alloy.

S. no.	T (°C)	Th (µm/m°C)	S (kJ/kg °C)	k (W/m °C)	Dn (kg/m³)
1.	20	25.4	1.04		
2.	100	26.9	1.042		
3.	300	30.6	1.148	138	1730
4.	550	35.3	1.338		
5.	650	35.3	1.414		

T= Temperature, Th= Thermal Expansion coefficient, S= Specific heat, k= thermal conductivity, Dn= Density
Data source: R. Kant and S. N. Joshi [8]

The magnesium alloys are hard and difficult to deform their shapes at room temperature due to their poor ductility, yet they have huge applications in automobiles and aerospace industries like; steering wheel, intake manifolds, automobile seat chassis etc.

The thermal and mechanical properties dependent on the model were applied to the temperature and strain rate, these properties are shown in Table I and II. The M1A alloy solidus temperature is 648°C and the liquidus temperature is 649 ° C. Because the simulation process destabilized by a short-range of latent heat of melting temperatures, it is perceived to be distributed between 645°C and 655°C. Magnesium alloy M1A has latent heat of 370 kJ/kg°C.

The simulation was done by considering the environmental temperature Te = 20°C and convective heat transfer coefficient of the material h = 25 W/m^2.The radiation heat loss (q_r) was determined by:

$$q_r = \varepsilon\sigma(T_s^4 - T_e^4) \quad (3)$$

Where, σ = 5.67x10^{-8} W/m^2.°C^4 is the value of Stefan-Boltzmann constant and ε = 0.2 is the worksheet material's surface emissivity. Heat flows into the workpiece by thermal conductivity mode and flows into the atmosphere by modes of convection and radiation. The q(r) thermal flux applied to the model is an exponential laser spot radius function;

$$q(r) = \frac{2\eta P}{\pi R^2}\, exp\left(\frac{-2(x^2+(y-Vt)^2)}{R^2}\right) \quad (4)$$

Where η, t, V, R and P are the absorptivity, time period of laser scan, scan speed, laser beam radius and laser power respectively. Laser heating produces thermal stress owing to thermal expansion in the heated region, resulting in plastic strains and further distortions in the workpiece. This distortion happens in a comparatively short time and can therefore be ignored to make a creeping contribution. The sum of elastic strain, plastic strain and thermal strain rates is the total stain rate in a material as:

$$\dot{\varepsilon}_{total} = \dot{\varepsilon}_{elastic} + \dot{\varepsilon}_{plastic} + \dot{\varepsilon}_{thermal} \quad (5)$$

D. Validating 3D Model

A 3D FEM model was developed in this research work to study the published work.[i.e. S.N. Joshi and R. Kant [14].They developed a three dimensional model to study the thermo-mechanical behavior of Magnesium M1 alloy, under different parameters of laser forming and validate their research experimentally. To validate this research work, the data of this model was compared with the experimental results published by Kant and Joshi and can be observed in the Table III, that the developed 3-D model shows accurate values with minimum or negligible error. As, it was validated, thereafter any further change in load or interactions in that model would provide accurate results.

Table III: Validation of basic three dimensional model

S. no	P	V	H	D	Ex. (°)	Nu. (°)	S. Nu. (°)	E. (%)
1	300	1000	20	3.870	1.069	1.095	1.070	0.558
2	300	1000	30	5.810	0.731	0.718	0.726	0.683
3	300	1000	40	7.740	0.490	0.369	0.423	13.67
4	300	2000	20	3.870	0.836	0.932	0.907	7.82
5	300	2000	30	5.810	0.312	0.334	0.333	6.306
6	300	2000	40	7.740	0.119	0.083	0.097	18.48
7	300	3000	20	3.870	0.604	0.550	0.588	2.64
8	300	3000	30	5.810	0.139	0.105	0.121	12.94
9	300	3000	40	7.740	*	0.011	0.024	*
10	400	1000	20	3.870	1.281	1.250	1.256	1.951
11	400	1000	30	5.810	0.836	0.974	0.858	2.56
12	400	1000	40	7.740	0.771	0.739	0.759	1.55
13	400	2000	20	3.870	1.305	1.465	1.460	10.58
14	400	2000	30	5.810	0.766	0.860	0.767	0.130
15	400	2000	40	7.740	0.437	0.404	0.412	5.72
16	400	3000	20	3.870	1.113	1.158	1.157	3.802
17	400	3000	30	5.810	0.418	0.399	0.405	3.110
18	400	3000	40	7.740	0.107	0.098	0.099	7.47
19	500	1000	20	3.870	0.993	1.113	1.208	17.79
20	500	1000	30	5.810	0.940	1.053	0.973	3.39
21	500	1000	40	7.740	0.753	0.872	0.821	8.28
22	500	2000	20	3.870	1.425	1.591	1.571	9.293
23	500	2000	30	5.810	1.003	1.161	1.026	2.24
24	500	2000	40	7.740	0.721	0.709	0.706	2.08
25	500	3000	20	3.870	1.268	1.571	1.547	18.03
26	500	3000	30	5.810	0.838	0.771	0.801	4.415
27	500	3000	40	7.740	0.345	0.272	0.312	9.565
Average absolute error = 6.73								

P= Laser power (W), *V= Scan speed* (mm/min), *H= Stand-off distance* (mm), *D= Beam diameter* (mm), *Ex. = Published Experimental Bend angle, Nu= Published Numerical Bend angle, S. Nu.= Simulation angle, E = Absolute Error*
Data source: R. Kant and S. N. Joshi [14]

III. RESULTS AND DISCUSSION

A. Forced Cooling

As, the simulation model is validated, it is assumed that further cooling interactions applied on this model will also give the accurate results. Therefore, cooling conditions applied to only validated simulations parameters, i.e. laser power 300 W, 400 W and 500 W, scan speed 1000 m/min, 2000 m/min and 3000 m/min and laser beam diameters 3.87 mm. The bottom side of the workpiece, opposite to the laser scan path, is considered for the cooling simulations, causes steep temperature difference along the thickness.

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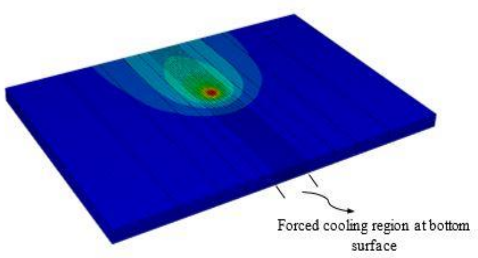

Figure 3: Three dimensional model showing cooling region

In this research work, temperature gradient mechanism is dominated for bending of sheet, and to achieve maximum bend in single scan, multiple simulations are carried out to get the optimum value of forced cooling i.e. convective heat transfer coefficient (h) W/m^2 .K.

Cooling simulations made using conventional values of forced air, water, lubricating oils, coolants, etc. convective-heat-transfer coefficients range from 50-10,000 W / m^2.K.Also in some cases this value exceeded to 35,000 - 40,000 W/m^2.K; which is too difficult to achieve with normal working conditions. These values can only be possible either by cryogenic conditions or additional laser cooling setup. Although some adverse cooling conditions are not yet feasible to perform experiments, but this research theoretically finds the optimum cooling value using simulations. Figure 4, shows the actual image of moving laser beam spot during simulation, which indicates Gaussian heat flux distribution. In this figure, the inner most circle shows the laser beam spot and outside rings of this circle indicates heat transfer during conduction and convection.

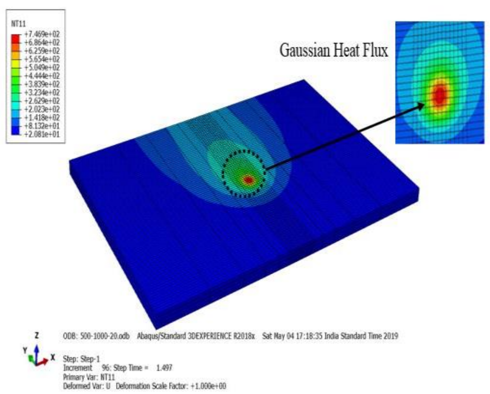

Figure 4: Gaussian heat flux distribution during simulation

B. Bend Angle

As, it is known from simulations and literature survey that increase in laser beam diameter will decrease the bend angle, in a single pass laser forming. So, to study the cooling effects for higher bend angle, simulations were done only with smaller beam diameter i.e. 3.87 mm and it observed that bend angle increase with increases in forced cooling conditions up to a certain limit than it decreases.

In case of 500 W power and 1000 m/min speed with 3.87 mm beam diameter gives positive response with increase in bend angle. The bend angle obtained without cooling conditions is 1.208° increases to 2.313° (maximum) with cooling conditions (h = 25,000 W/m^2.K), as shown in Figure 5 and subsequently reduces as forced cooling continues to raise. The bend angle at value of convective heat transfer of 20,000 (W/m^2.K) is 2.29° and at 30,000 (W/m^2.K) is 2.302°, which shows that from 20,000 - 30,000 (W/m^2.K), only negligible increase is achieved in bend angle. Therefore, cooling condition ranging from 20,000 - 30,000 (W/m^2.K) is known as the optimum range for theses parameters.

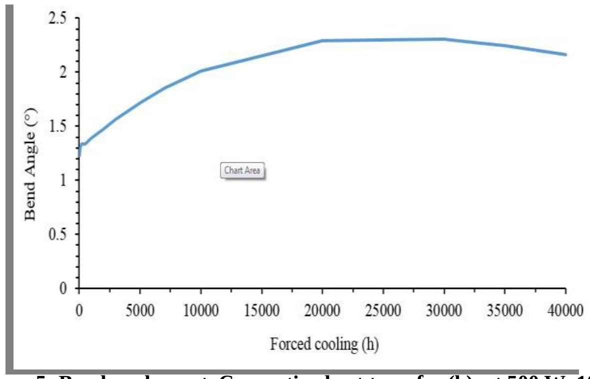

Figure 5: Bend angle w.r.t. Convective heat transfer (h), at 500 W, 1000 m/min and 3.87 mm beam diameter

Similar trends were seen with parameters 300 W and 400 W, bend angle increases from 1.070° to 1.174° (maximum at 1000 W/m^2.K) and 1.256° to 1.91° (maximum at 12,000 W/m^2.K) respectively with scan speed of 1000 m/min. At higher scan speeds, i.e. 2000 m/min and 3000 m/min, forced cooling conditions cause negligible increase in bend angle but reasonable decrease in bend angle at higher values of h, because at faster scan, lesser heat penetration will occur, resulting lesser steep temperature gradient.

C. Effect on Stresses distribution

Laser forming mechanism is essential for enhancing this process's effectiveness and enhancing product quality. The adjacent cooler region restricts the growth of the irradiated region and the forced cooling conditions that affect steep gradient temperature at the bottom of the worksheet during laser heating. This creates compressive stresses in the adjacent areas in the warm area and tensile stresses. Figure 6 shows the variations in the Maximum principal stresses for the maximum bend angle (i.e. 500 W, 1000 m/min and 3.87 mm dia.) with the effects of forced cooling.

It is observed that initially maximum principal stress increases with increase in the convective heat transfer, i.e. curve increases till h = 20,000 W/m^2.K. In the maximum bend angle range, its value fluctuates in a small region and forms peaks and hills in the graph and then it regains the previous trend. Figure 7 shows the principal stress history in x-direction at point A and B under the effect of forced cooling conditions at maximum bend angle.

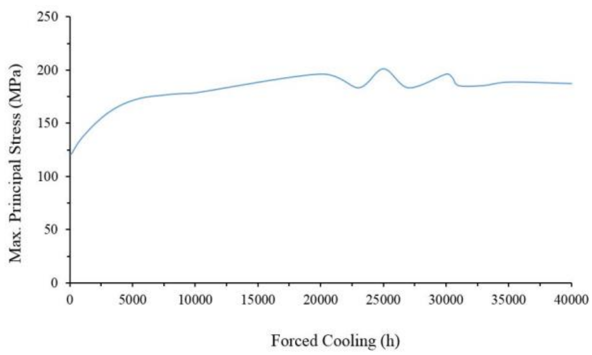

Figure 6: Maximum Principal Stress w.r.t. Convective heat transfer

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It is observed that when laser source is moving towards point A, the heated region of upper surface starts to expand but the cooler surrounding material resists the expansion and compressive stress arises in the heated area and tensile stress occurs in the cooler regions. Forced cooling at the bottom surface increases heat transfer frequency and creates steep temperature gradient, and compressive stress size at the bottom surface is greater compared to the top surface. Figure 7 shows the x-directional stresses along with the scanning time of simulation.

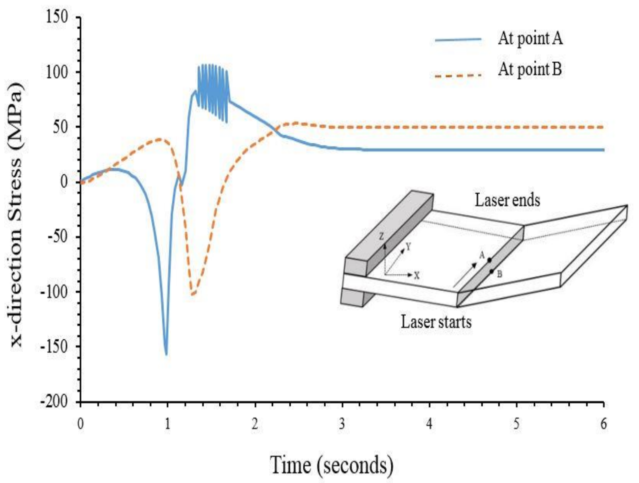

Figure 7: x-directional stress with respect to scanning time

Figure 8 indicates the thermal profile of the worksheet's top and bottom surfaces. The simulation start with boundary conditions of room temperature 20°C and it is observed that when laser source moving towards the point A, temperature of top surface increases to maximum of 603°C and temperature of bottom surface reaches to 230°C, for 500 W laser power at 1000 m/min. the peak of thermal profile at the top surface is much higher, when compared to the temperature peak of bottom surface, this change in variation of temperature profiles shows the presence of temperature gradient. As, the laser source reaches to the end of worksheet, the temperature starts decreases to 22°C. This rapid decrease in temperature is possible due to higher values of forced cooling conditions and this fast cooling down of the workpiece temperature has many great applications in multi-pass laser forming of sheets. In that case, material will not heated up high, and it also removes the idle time of laser forming process for multi-pass.

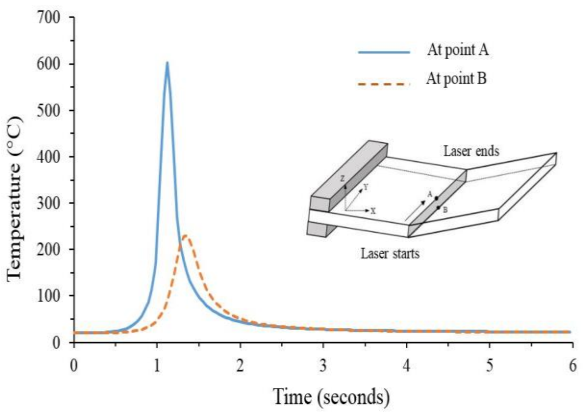

Figure 8: Temperature w.r.t. simulation time

D. Effects on Strain

In this section, the occurrence of strain behavior mechanism is discussed in the laser bending of Mg M1A alloy sheet. Plastic strains developed with thermal stresses becomes greater than temperature dependent flow stresses. Figure 9 displays point A and point B of the x-directional plastic strain. It can be observed that on both top bottom surfaces of the sheet, plastic strain deformations are compressive in x-direction. At bottom surface, the magnitude of deformation is more while compared to top surface. This variation in deformation of upper and bottom surfaces cause bending of sheet.

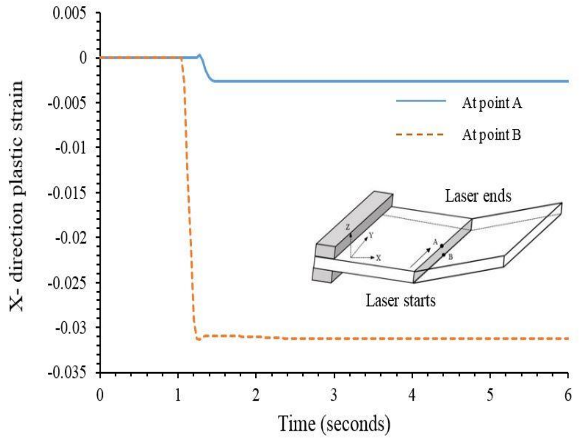

Figure 9: x-directional plastic strain with time

The rise in temperature results in a heated zone thermal expansion. Figure 10, shows that bend angle history along the laser scan. It can be seen that at the beginning of the scan, the top surface temperature is more than the low surface temperature, leading in more thermal expansion on the top side of the worksheet. Therefore, workpiece slightly bends opposite to the direction of heat source (i.e. away from the laser scan), this term is known as counter-bending. At the end of laser scan, as in shown in Figure 10, it is observed that the elasticity recovery of material is not enough to dominate the bend angle, hence constant bend angle can be achieved.

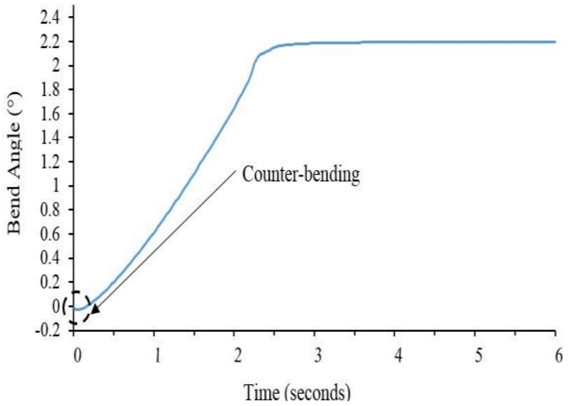

Figure 10: Bend angle history with respect to simulation time

IV. CONCLUSION

In this work, a 3-D numerical model of magnesium M1A alloy is developed to investigate the forced cooling conditions and effects of cooling on bend angle, induced stress and strains in laser forming process.

Without forced cooling, it can be observed that with enhanced laser energy, reduced beam diameter and slower scanning velocity the laser bend angle of the material rises. Forced cooling conditions are applied to the model by taking minimum beam diameter, i.e. 3.870 mm. Similar trends can be seen with forced cooling conditions, with increase in forced cooling, bend angle initially increases until it achieves the maximum value. After the peak value is gained, the bend angle decreases with the cooling condition being further increased.

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