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Research Article

EXPERIMENTAL AND NUMERICAL STUDY OF SHAPING ALUMINUM 7075 AND STAINLESS STEEL 316 SHEETS LAMINATED WITH LASER BEAM

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ABSTRACT
One of the most novel methods of shaping materials is forming via laser. In this method, thermal tensions caused by local heating cause transformation. Because of the dependency of this method on thermal properties of materials, it can be used to shape hard metals and delicate complex components. In this paper, this method has been investigated using numerical methods and finite element software packages, and bending formulation has been provided. Finally, lamination properties of sheets on bending angle and changes thereof have been considered.

Keywords: *Laser Forming, Finite Element Analysis, Multi Layered Sheet*

INTRODUCTION
This investigation is primarily concerned with the process of laser forming or laser bending of metal sheet materials with a high power laser beam. Laser forming has become a viable process for shaping metallic components, as a means of rapid prototyping and adjusting and aligning. The laser forming process is of significant value to industries that previously relied on expensive stamping dies and presses for prototype evaluations. Relevant industry sectors include aerospace, automotive, and microelectronics. In contrast to conventional forming techniques this method requires no mechanical contact and hence offers many of the advantages of process flexibility associated with other laser manufacturing techniques such as laser cutting and marking (Magee *et al.,* 1998). Laser forming can produce metallic, predetermined shapes with minimal distortion. The process is similar to the well-established torch flame bending used on large sheet material in the ship building industry but much more control of the final product can be achieved (Moshaiov *et al.,* 1987). Laser forming process is realized by introducing thermal stresses into the surface of a work piece. These internal stresses induce plastic strains, bending or shortening the material, or result in a local elastic plastic buckling of the work piece depending on the mechanism active (Vollertsen,1998). The range of metals that can be laser-formed is considerable. As there is only localized heating involved below the melting temperature the bulk properties are not altered and good metallurgy is retained in the irradiated area (Maher *et al.,* 1998). Materials of particular interest are specialized high strength alloys (Magee *et al.,* 1998). These include titanium and aluminum alloys. These materials are widely used in the aerospace industry, where the implementation of laser bending as are placement of existing manufacturing processes is under investigation (Watkins *et al.,* 1998) as well as other industry areas (Blake *et al.*, 1997).
There are numerous application areas of the laser forming process in use today that are considered cost effective in the design and/or manufacturing process. These include:
• Rapid prototyping of irregular shapes for turbine blade applications
• Non-contact forming for installation and adjustment of non-accessible parts
• Automotive shapes for prototype and validation testing
• Aerospace shapes for precision shaping of tanks and pressure vessels
• Unbending techniques for repairs and alignment applications
• Tube and pipe precision forming
• Final configuration production parts for small quantities of parts.
• Rapid prototyping of parts prior to final production.

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Temperature Gradient Mechanism (TGM)

This mechanism is the most widely reported, and can be used to bend sheet material out of plane towards the laser. The conditions for the temperature gradient mechanism are energy parameters that lead to a steep temperature gradient across the sheet thickness (figure 1). This result in a differential thermal expansion through the thickness. The beam diameter is typically of the same order as the sheet thickness, or slightly less. The path feed rate has to be chosen to be large enough so that a steep temperature gradient can be maintained. The feed rate/temperature gradient has to be increased if materials are used which have a high thermal conductivity. The laser path on the sheet surface is typically a straight line across the whole sheet. This straight line coincides with the bending edge. Initially the sheet bends in the direction away from the laser. This is called counter bending. With continue heating the bending moment of the sheet opposes the counter bending and the mechanical properties of the material are reduced. Once the thermal stress reaches the temperature dependent yield stress any further thermal expansion is converted into plastic compression during cooling the material contracts again in the upper layers, and because it has been compressed, there is a local shortening of the upper layers of the sheet and the sheet bends towards the laser beam. The yield stress and Young's modulus return to a much higher level during this cooling phase and little plastic re-straining occurs. Bends of approximately one degree per pass are achieved with this mechanism (Magee *et al.,* 1999).

Principles of Forming with the Help Laser Beam and Modeling

In this method, sheet is heated using laser beam in the intended direction and then, according to temperature difference in upper and lower layers and due to expansion and contraction of material, certain forces are created in network structure of the material. Induced by inter network forces, relatively high moments are created leading to warping along heat direction. In this condition the higher level is stretched and the lower ones get compressed (figure 2-a) (Vollersten *et al.,* 1995). After this step, the material is cooled, leading to the contraction of higher levels to their former size. But the lower stretched levels hinder this. Therefore, a moment is created opposite to the heating direction, which causes renewed warping of the sheet in the opposite direction (figure 2-b).

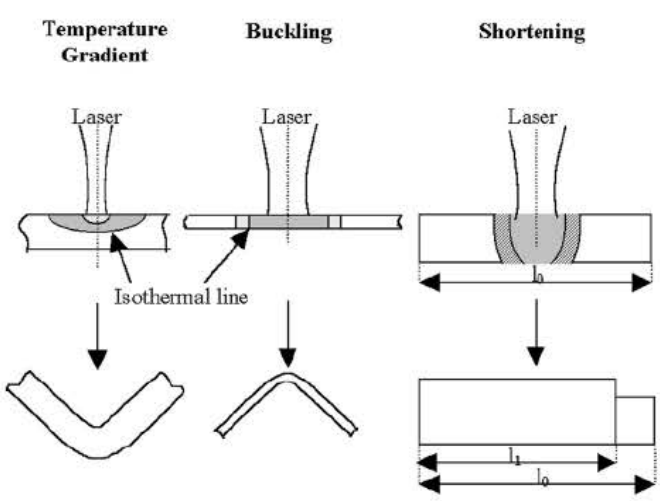

Figure 1: Illustration of the three main laser forming mechanisms (Vollersten *et al.*, 1998).

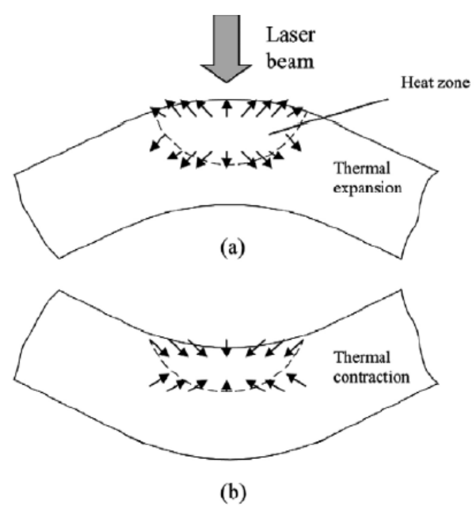

Figure 2: (a) counter - bending during heating, (b) positive bending during cooling

Laser Ray Behavior and Heat Distribution

The heat produced by laser beam has a Gaussian distribution. Heat flow density on a surface is measured with the following equation (Yanjin *et al.,* 2005).

$$I = \frac{2AP}{\pi r^2}\exp(-\frac{2r_1^2}{r^2})$$

Thus, the average value for the heat flux density in laser beam range is calculated by integrating the flux function (equation 1) within the range.

$$I_m = \frac{1}{\pi r^2}\int_0^r I(2\pi r_1)dr_1 = \frac{2\pi}{\pi r^2}\int_0^r \frac{2AP}{\pi r^2}\exp(-\frac{2r_1^2}{r^2})(r_1)dr_1 = \frac{0.865AP}{\pi r^2}$$

Where, A represents surface absorbance coefficient, P is laser power, r_1 is the distance between the point under study and center of the laser, and r is the radius for the laser ray. To improve laser beam absorption by the surface, the work piece is covered with oxide and graphite layers, which provide an absorbance coefficient of 0.5 to 0.7. Absorbance intensity is assumed to be 0.6 in this paper according to conducted experiments (Shi *et al.*, 2006).

Theoretical Equation of Bending Angle

Geiger and Vollertsen (1993) and Vollertsen (1994) have conducted studies regarding bending angle, resulting in the following equations where physical specification of laser beam and work piece surface are seen.

$$\alpha = \frac{180\sqrt{2}}{5\pi\sqrt{\pi}}\frac{AP}{\sqrt{rv}}\frac{\alpha_{th}\sqrt{a}}{ks_0}$$

$$\alpha = \frac{3\alpha_{th}PA}{\rho c_p v s_0^2}$$

Yan has suggested another theoretical model where, based on this model, bending angle is calculated using the following formula.

$$\alpha = \frac{3\alpha_{th}PA}{\rho c_p v s_0^2}\frac{7}{2} - 36\frac{r}{s_0}\frac{\sigma_s}{E}$$

On the other hand (Yongjun Shi *et al.*, 2007) provided the following formula to calculate the bending angle induced by surface heating via laser.

$$\alpha = \frac{6.92\mathrm{AP}\alpha_{th}\mathrm{B}}{L^2 s_0} \times \sqrt{\frac{2r}{\pi^3 \rho c_p k v}}$$

In the preceding equations, A is absorbance coefficient; V is laser beam velocity; K is heat transfer coefficient; α_{th} is thermal expansion coefficient; S_0 is sheet thickness; ρ is density; C_p is specific heat capacity; σ_s is yield tension; and E is Young's modulus. In Shi's equation, the effect of sheet dimensions (B and L) has also been observed as an effective parameter. This equation applies to sheet bending with small dimensions. Given conducted analyses, physical and thermal properties of materials (such as thermal expansion coefficient, specific heat, heat transfer, density) and their mechanical properties (such as Young's modulus and yield strength) both affect the laser forming process. These parameters all depend on temperature and their changes in different temperatures is two broad (Yanjin *et al.*, 2005). Furthermore, different mechanical properties affect laser forming in different ways.

Simulation of the Process

Using finite element method, processes can be simulated. Therefore, laser forming can easily be considered with a broad application range. The present paper performs a combined analysis of heat and transfer with finite element on a multilayered sheet with ABAQUS software and compares the results with bending angle calculated by analytic methods. For simulation, heat transfer in longitudinal direction is ignored and general deformation is considered. Josephson (1985) showed that these hypotheses are valid under such circumstances that laser motion speed is very high and sheet length is long enough. The sheet is initially tensionless. Elastic material is completely plastic, and in each layer, homogeneous and isotropic. Strain and pressure yield tension is equal in every layer. In the software analysis conducted, beam has been considered to be square.

That is, in preliminary analyses conducted, the effect of circular beam was considered, which resulted in unwanted focus centers as well as unreal deformations because of element distortion induced by circular shape of the heat effect.

The element C3D8T has been used for meshing of the collection, which is an element combination of heat effect and displacement. Software simulation and analysis of the process have shown that lamination, upon appropriate selection of layers and suitable mechanical properties, is practical and even in some cases, deformation of multilayered materials is better than mono-layered materials. Initially, analysis is done on steel sample in two different formation modes.

Next, an aluminum sample is considered. The bending angle produced by simulation is compared with provided formulas and after verifying the simulation integrity, a consideration is done on bending angle of tri-layered mode of Steel 316- Aluminum 7075- Stainless steel 316. Simulation conditions of each model correspond to table 1.

Table 1: Conducted simulation, Laser beam diameter=4 mm; initial temperature=20 degrees Celsius

Sample	Material	Dimensions	Simulation conditions
1	Stainless steel 316	40×20×2 mm	P=0.5 KW,V=0.05 m/s
2	Stainless steel 316	40×60×2 mm	P=0.5 KW,V=0.05 m/s
3	Aluminum 7075	40×20×2 mm	P=0.5 KW,V=0.05 m/s
4	Stainless steel (0.5mm) Aluminum (1 mm) Stainless steel (0.5 mm)	40×20×2 mm	P=1.5 KW,V=0.025 m/s
5	Steel (0.5mm)-Aluminum (1 mm) - Steel (0.5 mm)	40×20×2 mm	P=0.5 KW,V=0.05 m/s
6	Steel (1 mm)-Aluminum (0.5 mm) - Steel (1 mm)	40×20×2 mm	P=1.5 KW,V=0.025 m/s

Mechanical and thermal properties of Steel 316 have been explained in (Zhanga *et al.*, 2004) and those of aluminum 7075 are shown in the following diagrams:

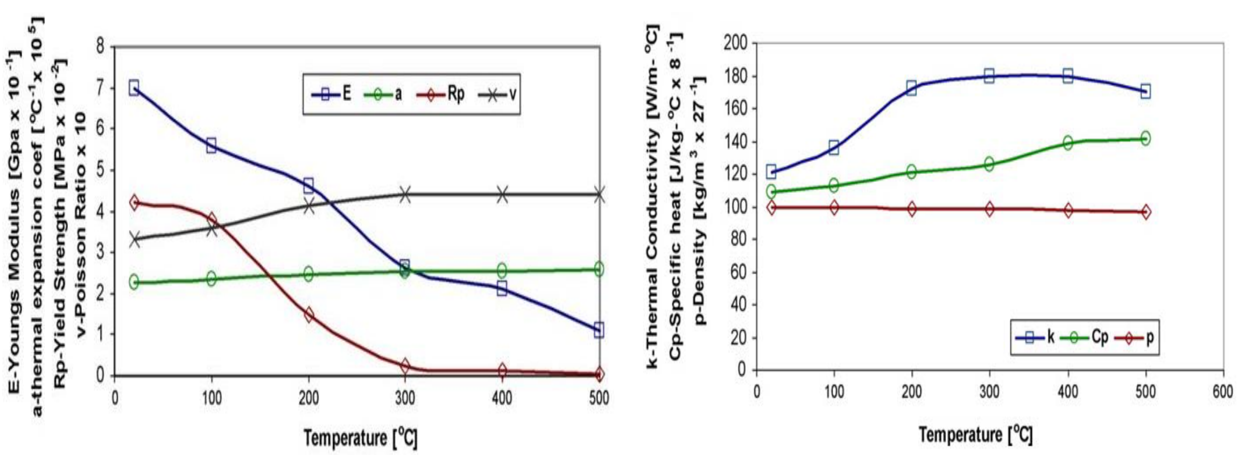

Figure 2: Temperature dependent mechanical (a) and thermal (b) material properties of Aluminum 7075 (Labeas, 2008).

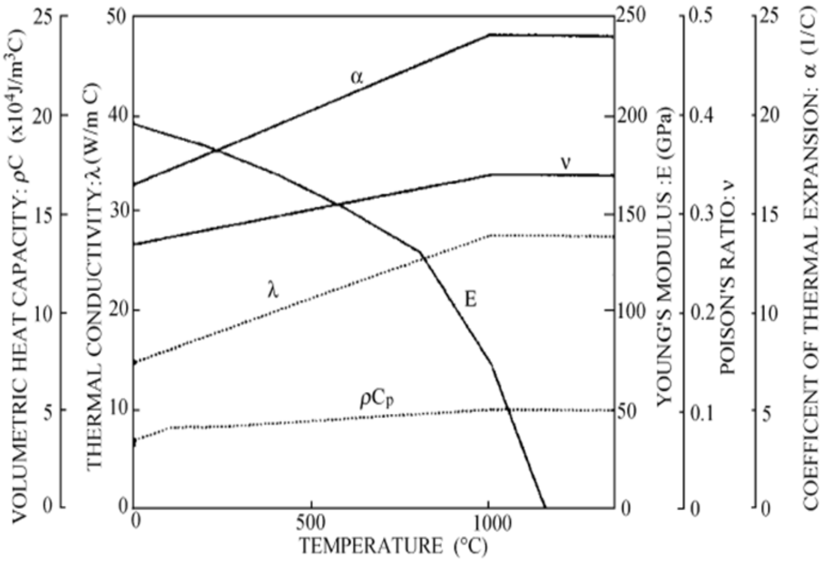

Figure 3: Temperature-dependent material properties of stainless steel 316 (Cheng and Lin, 2001)

Simulation Validation

By comparing the simulation with formulas 3 and 6 it is clear that the conducted simulation is very close to the formulation**.**

Table 2: Comparing the bending angle α° obtained from simulation and experiment with formulation of Geiger, Vollertsen, Yan, and Shi

model	bending angle in experimental test	bending angle in simulation	Geiger	Vollertsen	Yan	Shi
1	2.247	-	3.4640	3.9792	2.5262	2.5785
2	2.9874	2.7765	2.4465	2.6122	2.5312	2.5960
3	1.547	1.3346	1.2391	1.6719	1.2991	1.8877

Model 1 gives two different results in theory and practice. That is because it is assumed in the provided theoretical models that the component has not yielded.

Considering Model Integrity and Solution Method

Models (4, 5, and 6) are simulation of multi layered samples. Models 4 and 5 are similar in terms of work piece material, with the difference only being on laser power and scan speed.

Table 3: Bending angle obtained from numerical simulation of models 4, 5, and 6.

Model	Experimental bending angle	Simulation bending angle
4	12.934	12.7642
5	4.638	4.1534
6	9.458	9.1212

As expected, under identical circumstances of models 2 and 5 and change of sheet cross-section in model 5, bending angle is more than that of model 2 because of aluminum in the sheet cross-section. In model 5, with increased scan speed and decreased laser power, the bending angle considerably reduces (compared to model 4), but it is more than that of model 2. In model 6, considering the increased cross-section, the bending angle is smaller compared with model 4.

RESULTS AND DISCUSSION

Results

Now, given the conducted analyses, diagrams are given for changes of tension and temperature along the thickness at the center of laser ray irradiation. As predicted, in all diagrams the temperature reduces from the irradiated surface toward the inner surface. This temperature reduction is the main cause of deformation in a sheet. By the way, in models (1, 2, and 3) where work piece has a mono-layered cross-section, tension changes have a decreasing trend corresponding to temperature changes. But in the models (4, 5, and 6), due to changes in the material of the work piece, the diagram has fractures across the diagram thickness (figures 4 and 5). In model 1 work piece does not achieve its yield tension. Thus in cooling stage, it returns to its initial mode. Under identical conditions, in model 4, the increase in bending angle from initial angle of steel to middle layer of aluminum is more than that of model 6, and bending angle increase from the middle aluminum layer to last steel layer is greater in model 4 compared to model 6. In model 5, the increase of bending angle is less than that of models 4 and 6 because of decreased laser power and increased scan speed. Therefore, bending angle in model 4 is higher than that in model 6, and it is higher in model 6 than model 5. Since in model 2 laser beam absorbance in steel cross-section is higher than that of aluminum, it has a greater bending angle increase compared to model 3. In model 4, tension increase is relative near layer material's changing point and after that, tension drops suddenly. The reason for this increase is the forces applied between different layers. Because of layer material's change, however, and aluminum's low tension yield, tension reduces considerably. Nonetheless, at the point of transition from aluminum layer to steel, tension difference is bigger due to greater form change. Model 5 has different conditions. Because of increased scan speed and reduced laser power, it had lower tensions. So, tension is low in steel. But the force created through interaction on aluminum layer leads to a greater tension and causes it to deform. Model 6 has circumstances similar to those of model 4, with the only difference being in layers thickness. This difference leads to a different more consistent tension distribution.

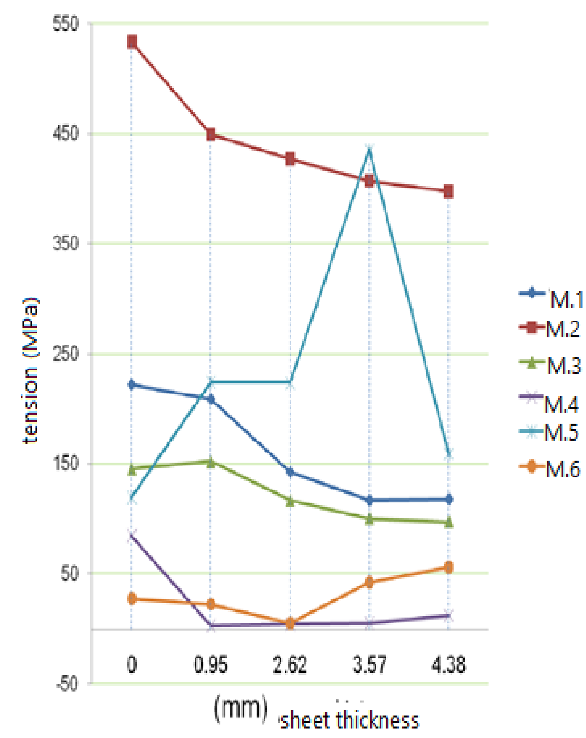

Figure 4: comparison of tension for models under consideration

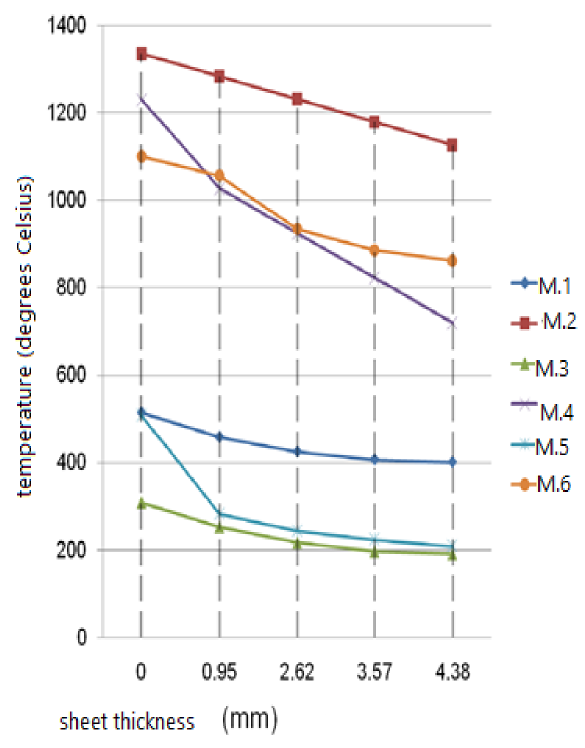

Figure 5: temperature comparison for models considered

Conclusion

Tension distribution on sheet surface has a local form (figure 6-a and 7-a). Also, isothermal points are well discernible in thermal distribution (figure 6-b and 7-b). This is an endorsement on correctness of the devised hypotheses (hypothesis of a beam's square shape). Results of conducted analyses show that by accurately adjusting parameters for this process, multi layered sheets can also be shaped. In identical conditions, in model 4, the increase of bend angle from the first steel layer to the middle aluminum layer is more than that of model 6, and bend angle's increase from the middle aluminum layer to the last steel layer is higher in model 4 compared to model 6. In model 5, bend angle increase is less compared to models 4 and 6 because of reduced laser power and increased scan speed. Thus, bend angle in model 4 is higher than that in model 6, and it is higher in model 6 than that in model 5. Since laser absorbance coefficient is higher in model 2 for steel cross-section compared to that for aluminum, this model has more bending than model 3. Models 4 and 6 showed that with identical conditions and similar surfaces of two materials due to difference of materials in cross-sections, a better forming can be achieved.

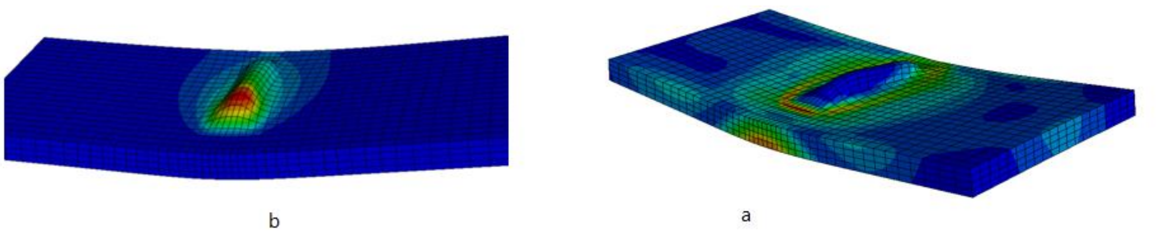

Figure 6: distribution of tension (a) and heat (b) obtained from model 4's simulation

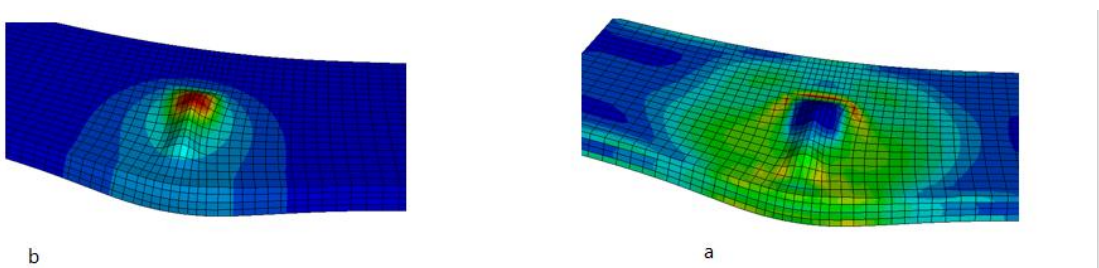

Figure 7: distribution of tension (a) and heat (b) obtained from model 6's simulation

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