APPLICATION OF FINITE ELEMENT SIMULATION IN METAL FORMING TRIBOLOGY

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KEYWORDS

Finite element simulations, Tribology, Metal forming, Tribology variables

ABSTRACT

The impact of numerical methods, particularly, the Finite Element Method (FEM), in providing tribological information relevant for lubricant formulations and general study of tribological variables is discussed. FEA was used to study surface evolution at the tool-workpiece interface for tube hydroforming and forging processes. The study has demonstrated that material properties, geometric complexity, and loading paths have significant influence on surface evolution, which ultimately predetermines lubrication mechanisms.

A tribo-module that can output relevant tribovariables from finite element simulations has been developed. Using this module, surface evolution history of a deforming part can be traced. The tribo-module can be used by a tribologist to study and gather tribological information for a specific metal forming process. The surface evolution data also help in determining plausible lubrication mechanisms and possible lubricant candidates, and can play a significant role in the development of new lubricants.

INTRODUCTION

The main goals of numerical simulation in manufacturing process are to reduce manufacturing costs and increase quality and productivity. For instance, process simulation can be used to develop forming dies and establish process parameters by a) predicting metal flow and final dimensions of the part, b) preventing flow induced defects such as laps (forging) and excessive thinning and wrinkling (sheet forming), c) predicting temperatures (warm forming operations) so that part properties, and die life can be controlled, and d) predicting and improving grain flow and microstructure.

Tribology is another area where the application of numerical modeling through Finite Element Analysis (FEA) and Molecular Dynamic (MD) Simulation are steadily gaining wide acceptance. Substantial tribological studies involving numerical simulations on metal forming have mainly focused on the development of friction models which can accurately characterize friction at the tool-workpiece interface [Wilson 1979]. Coulomb's and constant shear friction models commonly used in process modeling are unrealistic, thus various attempts to develop nonlinear friction models using internal variables have been developed [Wilson 1979]. Theoretical models that involve simultaneous solutions of the equations governing the flow of lubricant and plastic deformation of the workpiece have been developed, and implemented in FE codes [Meng 1993]. The models are, however, limited to simple processes. In order to improve FE modeling of hot forging processes, Schmid, [2007] developed friction and heat transfer modules which take into account lubricant film thickness and real area of contact. Groche [2007] developed an FE scheme to study the influence of grain size and crystallographic texture on surface evolution. To accurately describe boundary lubrication, researchers have attempted to use molecular dynamic (MD) simulations coupled with FEA [Ham 1997]. Practical predictive ability of MD for application in areas such as nano and micro manufacturing tribology is, however, far away due to highly idealized nature of MD simulations, and also the method is computationally intensive.

Despite the advancements in numerical methods and computer technology, lubricant developers have not benefited much from these tools. This may be due to the fact that the science pertaining to tribochemistry and tribomechanics have been studied separately. Presently lubricant developers are facing great challenges; there has been increasing demand for the development of environmentally friendly lubricants, self lubrication surface systems through die coatings, and effective lubricants for net shape forming of complex parts and emerging processes such as micro and nano manufacturing.

This paper addresses some potential applications of numerical modeling in establishing tribodata via finite element analysis for enhancement of tribological performance and development of metal forming lubricants.

NUMERICAL MODELING IN METAL FORMING TRIBOLOGY

One of the major factors that can benefit tribo-chemists in lubricant development is to be able to describe quantitatively the evolution of boundary surfaces of the deforming part and their tribological derivatives. Though this is extremely a difficult task, the advancement in numerical computational capabilities, has paved a way toward better and efficient examination of the boundary surfaces. A typical metal forming discretization problem used in finite element formulations is represented by the functional,

$$\Pi = I_1 + I_2 - I_3 = \int_V \bar{\sigma}\delta\dot{\bar{\varepsilon}}\,dV + k\int_V \dot{\varepsilon}_V\, k\delta\dot{\varepsilon}_V\,dV - \int_{SF} F_i \delta u_i\,ds \qquad (1)$$

Where k is a penalty constant and $\dot{\varepsilon}_V$ is the volumetric strain rate, $\bar{\sigma}$, effective stress, $\bar{\varepsilon}$, effective strain, $\dot{\bar{\varepsilon}}$ effective strain rate $F_{i,}$ traction. The $\mathbf{I_3}$ term mathematically represents the boundary interactions. Most FE studies have focused on determining realistic frictional models. It should, however, be noted that for a realistic solution to a lubrication problem, the three terms ($\mathbf{I_1}$, $\mathbf{I_2}$, $\mathbf{I_3}$) should not be considered in isolation of one another. Lubrication problem in metal forming is a coupled problem with which the tribological aspects are related to variables such as, material properties of the deforming body, surface topographies, lubricant, process geometry, etc.

The continuum mechanics employed in numerical modeling through FE can accurately capture the deformation of billet subsurface. We can associate the subsurface deformation with changes in the surface evolution. The surface evolution is defined here as time dependent function of a multitude of mechanical variables, thermal variables, and lubricant/chemical variables. These variables include; surface expansion, surface contraction, surface strain, surface stress state, surface temperature, surface geometry, tribochemical/ lubricant variables, and other process dependent variables. A global optimization of a metal forming process therefore should consider enhancement of tribological performance as one of the objective functions. Many of the variables discussed above can be obtained via the finite element method.

IMPACT OF NUMERICAL MODELING IN LUBRICANT DEVELOPMENT

Lubricants play a key role in metalworking processes as they reduce machine power requirements and the high friction forces occurring at the tool-workpiece interface. Other major roles of lubricants include; control of metal pickup, reduction of tool wear, provide thermal insulation, cooling, and control the surface finish. The development of lubricants represent a substantial effort involving; chemical formulation, laboratory evaluation of candidate lubricants and additives, testing for toxicity and other non-tribological properties, field testing and establishing a lubricant manufacturing process. The great challenge facing lubricant developers is the development of additives/chemicals which upon mixing with the base stocks results in a compound that will meet environmental regulations, toxicity levels, and still maintain desired lubricant functional needs.

There is a need to assimilate process dependent tribomechanical/thermal variables during the early stage of lubricant development. This can be achieved by studying the surface evolution of a metal forming process in question. Numerical modeling via FEA provides an opportunity to tailor lubrication problem such that the process sequence can be designed to match the performance characteristics of the lubricant. This may be achieved by monitoring the surface evolution as the part is being formed and accordingly, minimize local peak values pertaining to surface expansion, surface contraction, surface temperature, surface strain, and other tribological variables. Furthermore, by incorporating tribovariables in the metal forming optimization problem, one may ultimately avoid the use of high quality lubricants and expensive lubricants. A tribo-module that can output surface variables relevant for tribological study from FE processor is discussed in the next section.

TRIBO-MODULE

A tribo-module which computes surface variables from the FEA simulation results is presented. The surface variables included in this module are: Surface expansion/contraction, surface strain, surface pressure, surface temperature, surface velocity, surface sliding length, and surface contact time. These variables are given in Figure 1. It should be noted that most commercial FEA do not directly output field variables shown in Figure 1. The Tribo-module has been developed to output field variables relating to the boundary of the deforming material.

The manner in which surface variables are determined in the module will be demonstrated by focusing on the surface expansion. Figure 2 (a) shows a deformed object surface with tangent plane ABCD and a unit block which represent a material point at the surface. Figure 2(b) shows the strain tensor [ε] of the unit block in Global Coordinate System xyz. Figure 2(c) shows the surface strain [ε'] in the tangent plane in the Local Coordinate System x' y' z' where z' axis is normal to the surface.

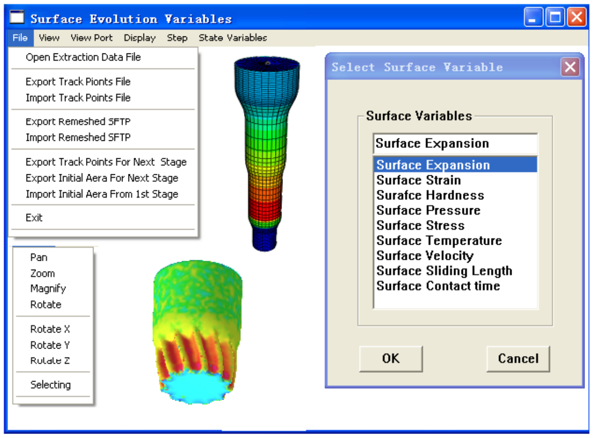

FIGURE 1. SURFACE EVOLUTION VARIABLES

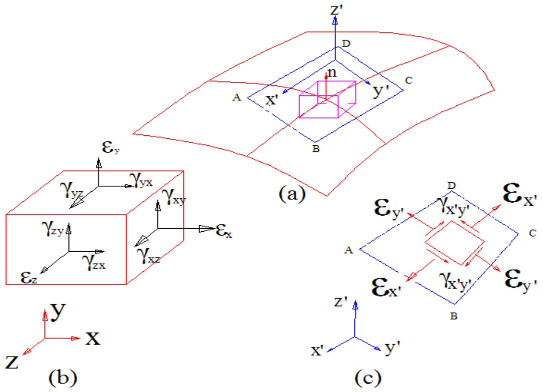

FIGURE 2. SCHEMATIC FOR SURFACE STRAIN AND SURFACE EXPANSION DETERMINATION

The transformation matrix, Λ , between system x' y' z' and system x y z is given in equation (2).

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \Lambda \begin{bmatrix} x \\ y \\ z \end{bmatrix}; \qquad \Lambda = \begin{bmatrix} \Lambda_{11} & \Lambda_{12} & \Lambda_{13} \\ \Lambda_{21} & \Lambda_{22} & \Lambda_{23} \\ \Lambda_{31} & \Lambda_{32} & \Lambda_{33} \end{bmatrix} \qquad (2)$$

$$[\varepsilon] = \begin{bmatrix} \varepsilon_x & \frac{\gamma_{xy}}{2} & \frac{\gamma_{xz}}{2} \\ \frac{\gamma_{yx}}{2} & \varepsilon_y & \frac{\gamma_{yz}}{2} \\ \frac{\gamma_{zx}}{2} & \frac{\gamma_{zy}}{2} & \varepsilon_z \end{bmatrix} \qquad [\varepsilon'] = \begin{bmatrix} \varepsilon_{x'} & \frac{\gamma_{x'y'}}{2} & \frac{\gamma_{x'z'}}{2} \\ \frac{\gamma_{y'x'}}{2} & \varepsilon_{y'} & \frac{\gamma_{y'z'}}{2} \\ \frac{\gamma_{z'x'}}{2} & \frac{\gamma_{z'y'}}{2} & \varepsilon_{z'} \end{bmatrix} \qquad (3)$$

The strain tensor in the Local Coordinate System x' y' z' can be computed by equation (4). Thus, the surface strain $\varepsilon_{x'},\varepsilon_{y'},\gamma_{x'y'}$ can be computed based on the global strain tensor, $[\varepsilon]$, as shown in equation 4.

$$[\varepsilon']=\Lambda[\varepsilon]\Lambda^{T} \qquad (4)$$

The surface expansion SE can be define as

$$SE=\begin{cases} \dfrac{A'}{A_0}=\dfrac{A_0+dA}{A_0} & dA>0 \\ -\dfrac{A_0}{A'}=-\dfrac{A_0}{A_0+dA} & dA<0 \end{cases} \qquad (5)$$

Where A_0 is the un-deformed area, A' is the deformed area, and dA is the area increment. dA >0, implies that surface expansion will occur, while dA<0, means surface contraction will occur. If the principal strains in the tangent planes are $\varepsilon_1{'}$ and $\varepsilon_2{'}$ respectively, the deformed area A' is then given by equation (6). Substituting equation (6) into equation (5), the equation for surface expansion can be obtained as given in equation (7) where $\varepsilon_1{'}$ and $\varepsilon_2{'}$ can be computed by equation (8)

$$A'=A_0e^{\varepsilon_2'+\varepsilon_1'} \qquad (6)$$

$$SE=\begin{cases} e^{(\varepsilon_1'+\varepsilon_2')} & dA>0 \\ -\dfrac{1}{e^{(\varepsilon_1'+\varepsilon_2')}} & dA<0 \end{cases} \qquad (7)$$

$$\begin{cases} \varepsilon_1'=\dfrac{\varepsilon_{x'}+\varepsilon_{y'}}{2}+\dfrac{1}{2}\sqrt{(\varepsilon_{x'}-\varepsilon_{y'})^2+\gamma_{x'y'}{}^2} \\ \varepsilon_2'=\dfrac{\varepsilon_{x'}+\varepsilon_{y'}}{2}-\dfrac{1}{2}\sqrt{(\varepsilon_{x'}-\varepsilon_{y'})^2+\gamma_{x'y'}{}^2} \end{cases} \qquad (8)$$

When a shell element is used, equation (7) can be expressed by the thickness strain ε_t as given in equation (9)

$$SE=\begin{cases} \dfrac{1}{\varepsilon_t+1} & dA>0 \\ -(\varepsilon_t+1) & dA<0 \end{cases} \qquad (9)$$

The surface sliding length between the tool and the deforming material can be computed by taking an integral of relative velocity v_r, as given in equation 10, where t is the contact time.

$$\text{Surface sliding length}=\int v_r dt \qquad (10)$$

SURFACE EVOLUTION STUDY FOR FORGING AND TUBE HYDROFORMING

To demonstrate the function of the tribo-module, case studies for forging/extrusion and tube hydroforming were carried out. Forging simulations included helical gear, tripod, and a pinion gear shaft. For tube hydroforming a Y-Shape part was studied.

It should be noted that in studying the surface evolution, the tribo-chemist should first know the surface quality needed for the part to be formed and assume corresponding friction coefficient levels to attain this surface quality. The assumed friction value will be used in the FE simulations to establish the surface evolution. By observing the local boundary variables such as surface expansion distribution, interface pressure distribution, surface strain distribution, etc., the tribo-chemist will be able to determine the tribological severity of the process. This information will facilitate the tribo-chemist to decide potential lubricant candidates or provide recommendations to manufacturing engineers for possible redesign of the forming process sequence to optimize tribological conditions.

Helical Gear Forging

The FE simulations were carried out by commercial FE software DEFORM 3D. AISI-1060 billet of 40mm in diameter and 50mm height was discretized by 306067 tetrahedral solid elements. A friction shear factor of 0.15 was used. The maximum punch stroke was 40mm. Thus, the input data to the tribo-module were all from DEFORM 3D.

Figure 3 shows initial billet and surface expansion distribution map. The variation on surface expansion at a cross section A-B is shown in Figure 4. It can be seen that higher surface expansion (150%) is exhibited at the ridge of the gear teeth. At the valley (root of the teeth) a surface contraction (-140%) is observed. From the tribological stand point, the surface expansion variation could be associated with lubricant thinning, particularly, if a coating based lubricant is used.

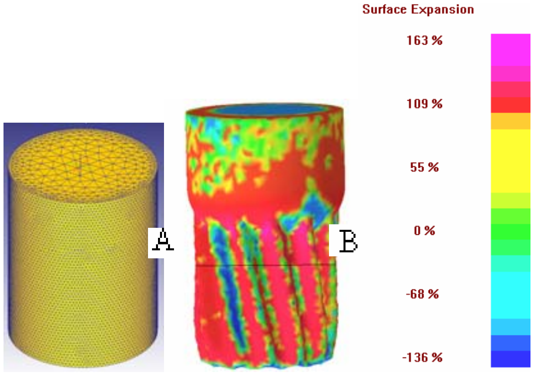

FIGURE 3. SURFACE EXPANSION OFHELICAL GEAR WITH CUTLINE

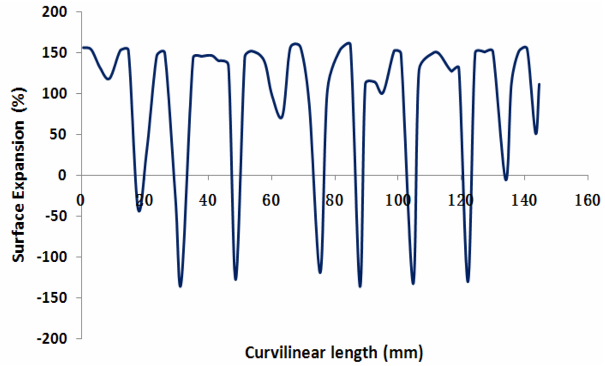

FIGURE 4. SURFACE EXPANSION ON AB CROSS SECTION

The research work carried out by Bay, et al [1995], on tribological characteristic of a backward can extrusion showed that the surface expansion distribution determined through numerical modeling agrees well with experimental measurements of lubricant thinning distribution along the inside of the extruded cup (Figure 5). The use of the surface evolution variables such as surface expansion provides an opportunity to develop relationships by which coating based lubricants could be formulated based on quantifiable variables obtainable from numerical simulations.

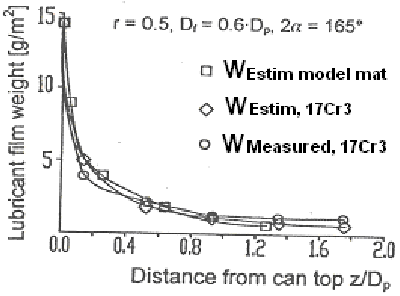

FIGURE 5. COMPARISON BETWEEN MEASURED AND ESTIMATED LUBRICANT FILM WEIGH DISTRIBUTION [Bay 1995].

Tripod Forging

An AISI-1010 billet of 30mm in diameter and a height of 126 was discretized by 20969 tetrahedral elements. Friction shear factor of 0.15 was prescribed in the simulation. A punch stroke of 100 mm was used. Figure 6 shows the strain distribution map and Figure 7 shows the surface strain distribution for the top and bottom regions of the tripod. The two regions exhibit different strain levels. The effective strain could be associated with hardness distribution, implying that the tripod exhibit significant hardness gradient during the deformation process. This information provides insight to a tribologist to determine plausible lubrication mechanism and appropriate lubricant families that could sustain such a scenario. Figure 8 shows that the maximum surface expansion at the top region is 200 % while the bottom region exhibit surface expansion of over 400 %. It is apparent that the bottom region of the tripod presents a severe triblogical condition as compared to the top region.

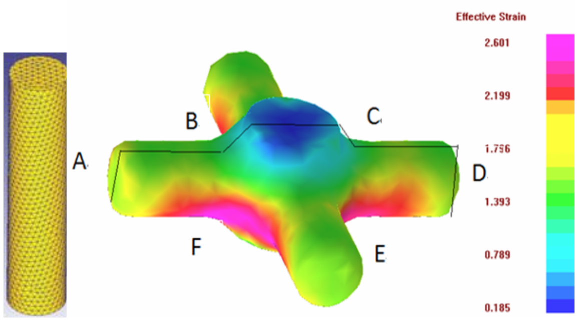

FIGURE 6. EFFECTIVE STRAIN DISTRIBUTION OF TRIPOD

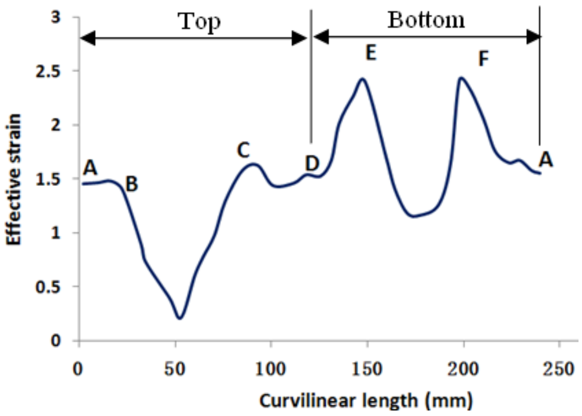

FIGURE 7. EFFECTIVE STRAIN DISTRIBUTION FOR TOP AND BOTTOM PART OF THE CUT PLANE AD (TRIPOD)

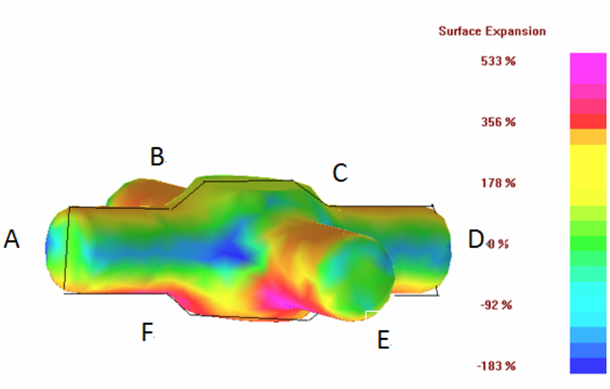

FIGURE 8. SURFACE EXPANSION DISTRIBUTION OF THE CUT PLANE AD

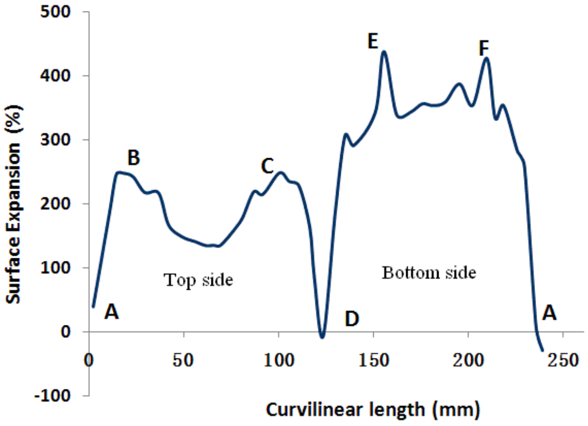

FIGURE 9. SURFACE EXPANSION DISTRIBUTION ON THE CUT PLANE

Pinion Gear Shaft Forging

An AISI-1010 billet of 66mm in diameter and 158mm height was discretized with 1680 elements and simulated using ABAQUS. A punch stroke of 70mm was used. A friction coefficient of 0.1 was prescribed in the simulations. This part required 3 forming stages as shown in Figure 10. Figure 11(a, b) shows the surface sliding length and pressure distributions for the second stage forming.

The evolution of sliding length and pressure can be used to study wear characteristic of the die and the respective locations on the die or punch where maximum pressure is exhibited. The sliding length and the maximum contact time may play a significant role in non-isothermal forming where material-die contact time may need to be minimized to offset effects on lubrication and formed part characteristics.

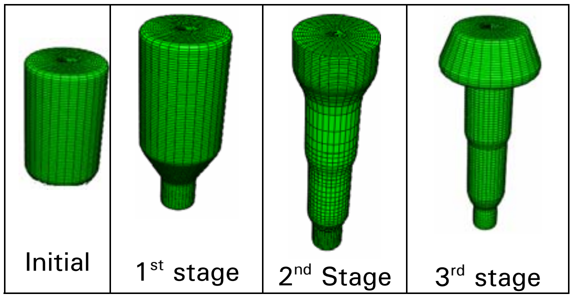

FIGURE 10. FORGING SEQUENCE

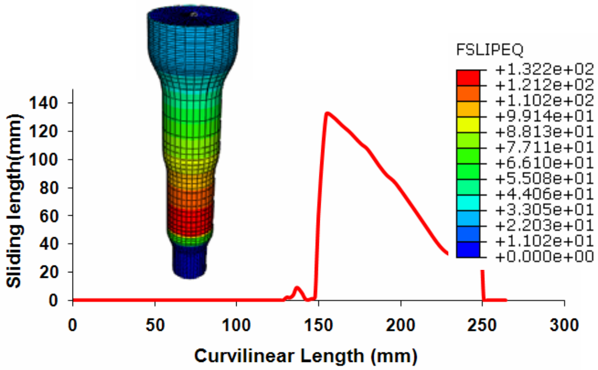

FIGURE11A. SLIDING LENGTH DISTRIBUTION OF PINION GEAR SHAFT

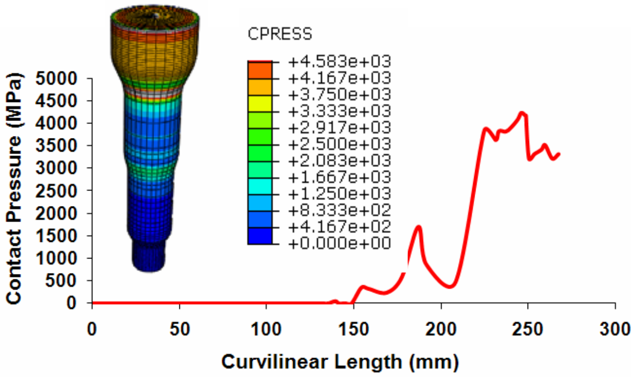

FIGURE 11B. CONTACT PRESSURE DISTRIBUTION OF PINION GEAR SHAFT

Tube Hydroforming of a Y- Shape

The tube hydroforming process was simulated using ABAQUS. Stainless steel (SS 304) tubing, 28mm in diameter was discretized with 1800 shell elements. The strength coefficient K for this material was 1450MPa and strain hardening exponent n was 0.52. The FE model was prescribed with a friction coefficient of 0.1.

To form a Y-shape, the tube is fed from both ends and at the same time pressurized inside the tube. The axial feed and pressure paths need to be synchronized such that there is an optimal flow of material that will ensure a non-defective hydroformed part. A linear pressure loading varying from 0 to 120MPa was used. The axial feeding was 60mm. Figure 12 shows the local surface expansion distribution maps. The Figure also shows surface expansion on a cut plane ABCDE. The surface expansion shows two distinct regions. Region BCD exhibits surface expansion while regions AB and DC exhibit surface contraction.

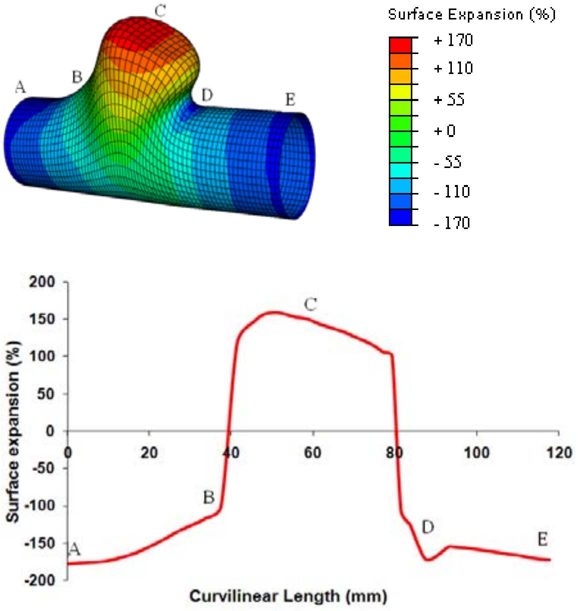

FIGURE 12. SURFACE EXPANSION DISTRIBUTON Y-SHAPE

Figure 13 shows the effective stress distribution along the Y-Shape. Similar to the surface expansion, two distinct regions are observed. Regions AB and DE exhibit compressive stresses, whereas region BCD exhibits tensile stresses. If we assume that atomic opening on the surface is proportional to surface tensile loading and inversely proportional to compressive loading, then diffusion of lubricant chemicals may be influenced by the state of stress, thus changing the lubrication mechanisms.

Depending on the level of the compressive stressed in regions AB and DE, the lubricant captured in the surface asperity pockets can be compressed leading to hydrodynamic or hydrostatic lubrication mechanisms. It should be noted that earlier work by Bay et al [1995] and Ngaile, et al [2004; 2006] have shown that material flow characteristics changes with change in strain hardening exponent and can have substantial influence on the surface evolution history.

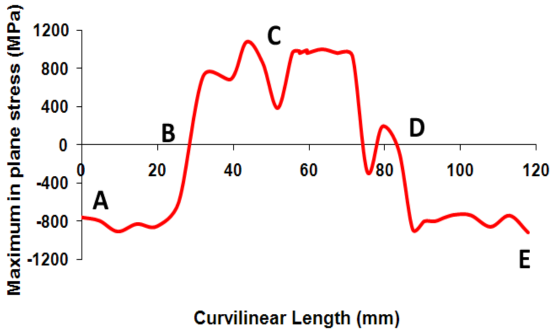

FIGURE 13. MAXIMUM INPLANE STRESS ON CUT PLANE ABCDE

Figure 14 (a & b) shows the surface strain distribution across longitudinal and radial sections. The effective strain various proportionally to the hardness of the material. Though the simulation shows variation of effective strain/hardness in the whole part, an interest to the tribologist may be the transformation of hardness as the tube deforms. The increase in surface hardness suggests changes in the lubrication mechanisms.

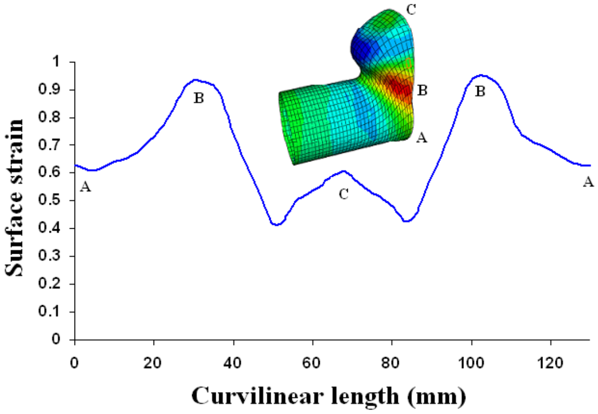

FIGURE 14A. SURFACE STRAIN DISTRIBUTON, Y-SHAPE

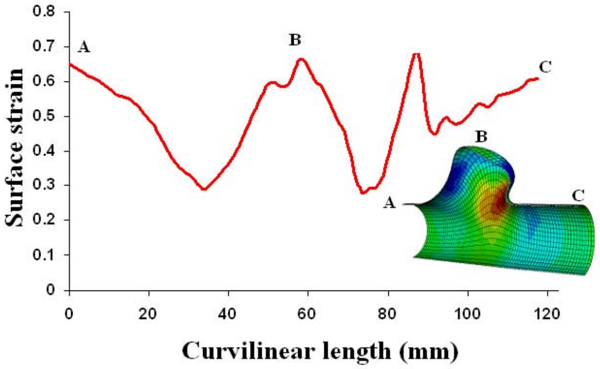

FIGURE 14B. SURFACE STRAIN DISTRIBUTON, Y-SHAPE

CONCLUDING REMARKS

Potential applications of the finite element methods in metal forming tribology have been discussed with a focus on the capabilities of FEM to provide tribomechanical/thermal variables that can be used in lubricant development and other tribological studies.

A tribo-module that can output surface variables relevant for tribological studies has been presented. The functions of the module were demonstrated through four case studies. This work has shown that studying surface evolution history of a specific forming operation in question provide tribological information that can allow tribologists to determine whether the tribological severity can be sustained using the available lubricants or not.

The tribological information gathered from the surface evolution history can also guide tribochemists to determine suitable chemicals for lubricant formulation. Of equal importance, capturing of these surface field variables will enable tribo-chemists to determine which forming processes may require lubricants with less demanding chemical compositions, hence lowering the cost of lubricants and promoting environmentally friendly products.

REFERENCES

Bay, N. (1995). “Aspects of lubrication in cold forging of aluminum and steel,” *Proc. Of the 9th International cold forging congress, UK, pp. 135-145*

Geiger, M. (1995). “Towards Clean Forming Technologies”, *Annals of the CIRP Vol. 44/2/ pp. 581-592*

Groche, P., R. Shafer., and M. Henning. (2007).” Finite element calculation of surface evolution considering grain size and crystallographic texture effect” *International conference on Tribology in Manufacturing Processes, ICTMP, Yokohama Japan, pp. 219-226*

Ham, T. L., J. Tichy, (1997). ”A scheme for hybrid molecular dynamics/finite element analysis of thin film lubrication,” *Wear 207 pp. 100-106*

Meng. Y., S. Wen, (1993). “A finite element approach to plasto hydrodynamic lubrication in cold forging),” *Wear, 160, pp. 163-170.*

Ngaile, G., (2004). “Application of Numerical Methods in Metal Forming Tribology”, *8th International conference on numerical methods for industrial forming processes, Columbus OH, USA*

Ngaile, G., J. Cochran, and D. Stark (2006). “Development of Polymeric Lubricant for Cold Forging Processes.” *Transactions of NAMRI/SME, Vol. 34 34, pp. 563-570*

Schmid, S.R., W. R.D. Wilson (2007). “Friction and Heat transfer Modules for Computer Simulation of Metal Forming” *International conference on Tribology in Manufacturing Processes, ICTMP, Yokohama Japan, pp. 55-62*

Wilson, W.R.D., (1979). ”Friction and lubrication in Bulk Metal Forming processes,” J*ournal of Applied Metalworking , Vol, 1, No. 1, pp.7-19*