Virtual Prototyping of Semiconductor Processing Equipment

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Abstract

There are great expectations for modeling and virtual prototyping in the semiconductor equipment industry. We discuss key areas where modeling and analysis are being used and have met some of these expectations. We identify interdisciplinary analysis as a requisite for virtual prototyping that will continue to meet current and future expectations. Since semiconductor equipment represents a design microcosm, these ideas will also help achieve the full potential of computer aided design and virtual prototyping in many other industries as well.

Introduction

Semiconductor processing equipment presents a design microcosm in many respects. Novellus Systems designs and analyzes equipment that must be safe, accurate, reliable, and cost effective. The science of this equipment spans many disciplines including vacuum technology, chemical processing, plasma physics, fluid flow, thermal, materials, structures, robotics, software and controls. The scale of problems range from nano-mechanics to seismic events.

The expectations for computer aided design and virtual prototyping technologies are very high. These technologies are expected to improve product quality while reducing material costs. At the same time they are to reduce (or preferably eliminate) the need for physical prototyping, reduce development cycle time, provide design guidance that improves reliability, and doing all this while reducing the required engineering resources.

These are great expectations and in theory the technology can support achievement of these goals. We discuss key areas where modeling and analysis have met some of the expectations described above. We identify interdisciplinary analysis as a requisite for virtual prototyping that meets the high expectations describe above. We present what is currently needed and what is anticipated in the future to achieve the full potential of computer aided design and virtual prototyping of semiconductor processing equipment.

Semiconductor Equipment Technology

Numerous processing steps are needed to produce a chip in its final form. Front-end processes include epitaxial growth and doping, forming initial layers of SiO_2 through oxidation, ion implantation and deposition of dielectrics (electrical insulators) and metals (conductors). Chemical mechanical planarization (CMP) is used to planarize the surface after certain steps and photolithography and etching are used to form electrical lines, trenches and interconnects between circuit layers before they are filled with metal.

Typically each step of the process is accomplished by a different system (or module connected to the system). Back end processing includes such aspects as wafer probe testing, packaging and final testing of the chips. Numerous types of test equipment are needed to ensure the quality and performance of the chips during various stages of fabrication. A huge industrial infrastructure is needed to support chip production. At each stage of the wafer processing the wafer and its contents become more and more valuable. For example, a 300mm wafer may hold approximately 300 state-of-the-art computer processor chips, which at a retail value of $800 each equates to a single wafer value of about $240,000. Wafers are typically processed in FOUPS of 25 wafers each and a 300mm fab may produce 1000 finished wafers per day. The cost of building a 300mm wafer fab is said to range from $2B - $4B.

Because of the large wafer volumes and the run-rates involved, reliability of the processing equipment is of great concern. Reliability is typically measured in MWBF (mean wafers between failure). While MWBF are company sensitive metrics it can be said that often those requirements when partitioned out to individual components of the system can equate to the required probabilities of failure (P_f) for individual components that are often less than $1x10^{-5}$. An equipment company that can produce higher reliability systems has an important advantage in the market place. Modeling and analysis are key ingredients to help design high reliability systems.

Figure 1 shows an idealized wafer processing system. A typical system takes a FOUP of wafers, applies one or more steps of the overall process to them, and when done returns the wafers to the FOUP so that it can then be transferred to the next tool needed to complete the next sequence of processes. In the front end processing the FOUP of wafers may be processed by dozens of different tools. A typical wafer processing system can be broken down into several different sub-systems with the following closely associated technologies:

1. Wafer handling subsystem (structures, robotics, controls)
2. Preheat, cooling & load-lock chambers (vacuum, thermal, controls, structures)
3. Processing chambers (chemistry, plasma physics, fluid flow, materials)
4. System frame and operator interface (structures, software, controls)

We now present how modeling and virtual prototyping is currently used to support research and development, design and manufacturing of semiconductor processing equipment.

Modeling and Virtual Prototyping of Semiconductor Equipment

Wafer handling systems consist of end-effectors used to pick up and place wafers, motors, mechanisms and control systems that drive the end-effectors, lift pins, table (z motion) actuators and drives, and index tables (rings) that allow multiple wafers to visit different stations inside the process chamber. Normally there are several different robots driving the end-effectors in different portions of the system. An atmospheric robot picks up wafers from the FOUP, transfer robots may move the wafer from the load-lock to process chamber, then back again. One goal of the system is to have as high of a throughput as possible. This means that we want to move wafers fast, yet, we don’t want

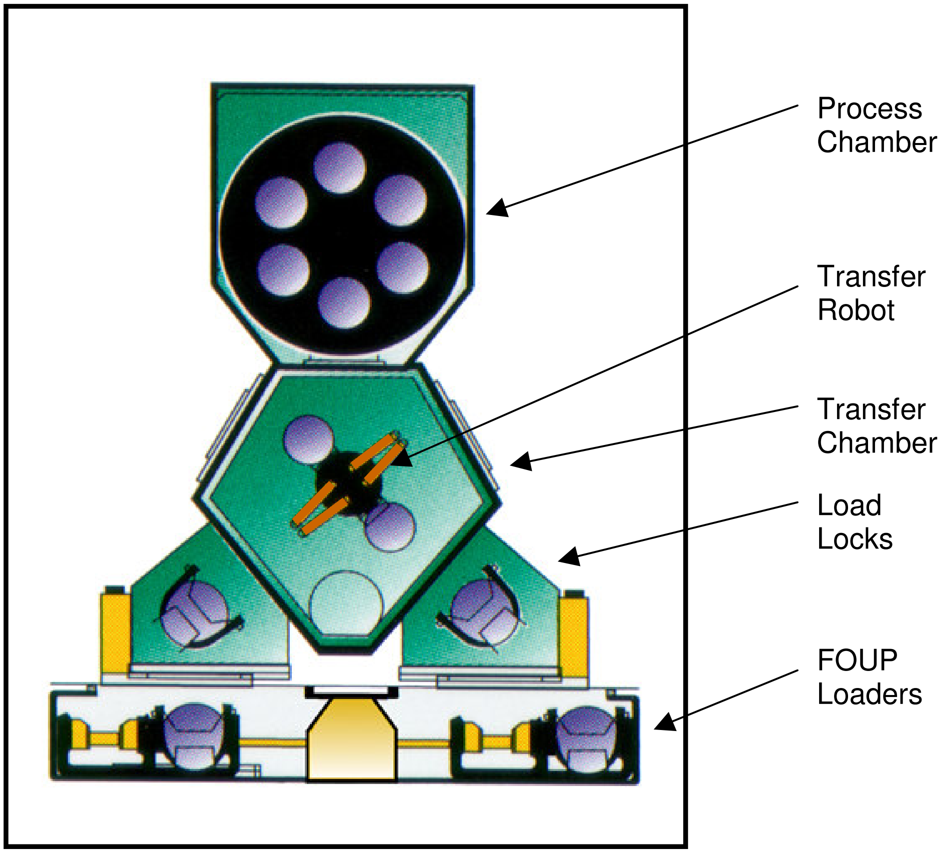

Figure 1 – Idealized Wafer Processing System (Novellus Sequel Express)

to damage or misplace them. Their placement is critical as a misplaced wafer may cause an unsuspecting robot end-effector to crash into it (not to mention process issues). The mechanisms often must reach large distances (1 m or more), yet, are subject to critical vertical deflection requirements. One MSC.Software product that helps in the design, analysis and optimization of such robot arms is Adams. Figure 2 shows an Adams model used to help understand the kinematics of a multiply articulated atmospheric robot in the Novellus Vector tool. We have used both MSC.Adams and MSC.Nastran to study kinematics, vibration and controls-vibration interaction issues in wafer handling systems. In another study, finite element analysis was used to help study the interaction of wafer distortions and end-effector distortions that occur in a vacuum robot end-effector chuck to help properly design the o-ring and groove configuration for that vacuum chuck (Figure 3). This analysis quantified the o-ring compression uniformity in the presence of both wafer and chuck elastic distortions. This determines whether the chuck has sufficient vacuum capability to hold the wafer while minimizing loading on the wafer.

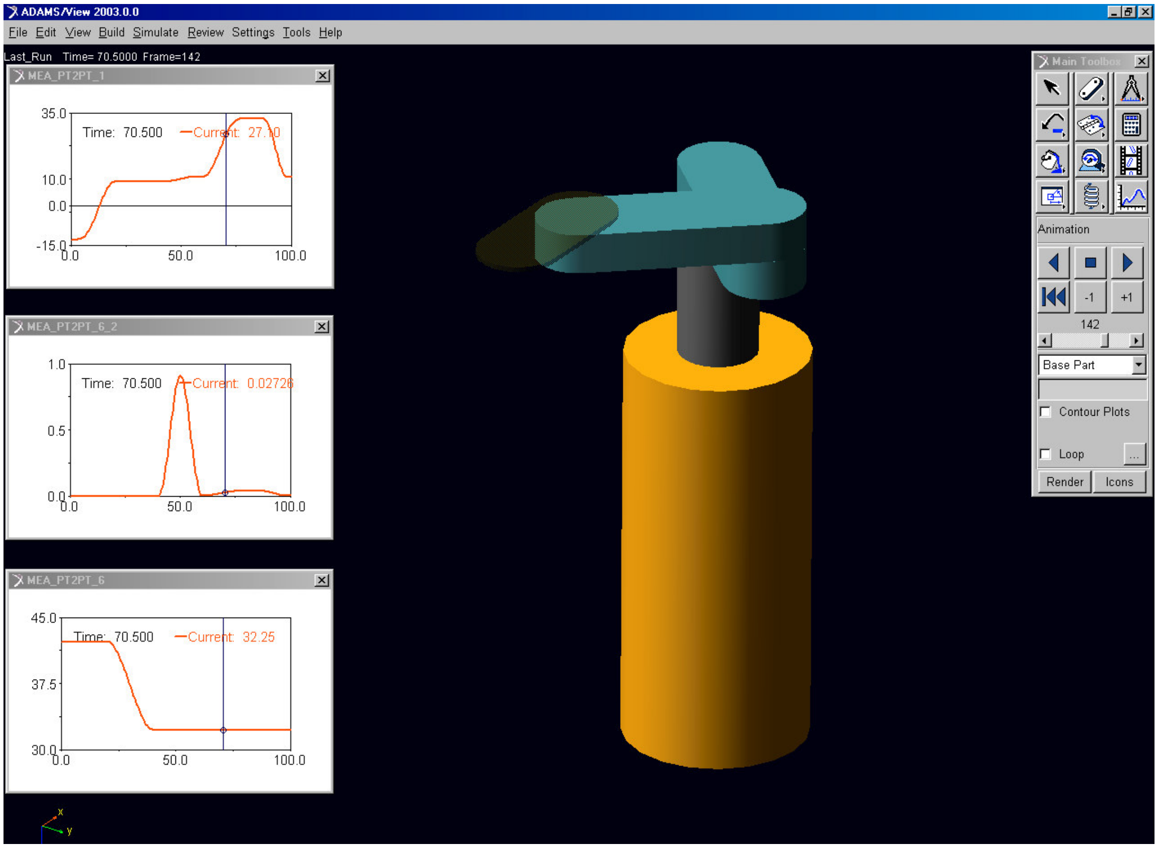

Figure 2 – Adams Model of Typical Atmospheric Robot

Preheating (prior to process) and cooling (after process) may occur inside the actual chambers and/or in separate chambers of the system. The load-lock chamber is normally the interface between the vacuum environment of the transfer chamber and the atmospheric environment of the FOUP. Pedestals are used for cooling and heating of wafers. Spreadsheet type calculations can be used to study ideal conditions such as uniform temperature pedestals and flat wafers. However, often the wafer ends up in a distorted configuration due to a combination of film stresses or non-uniform thermal conditions. The wafer-bow problem can only be generally solved by considering both the structural deformations of the wafer and how these deformations influence the resulting heat transfer to the pedestal. These coupled thermal-structural problems can be solved using nonlinear finite element analysis codes such as MSC.MARC. As semiconductor companies try to increase the number of layers placed on the wafer (to increase the number of circuits for example) wafer bowing will continue to be an issue that needs to be understood and designed for. Figure 4 shows predictions of the wafer temperature distribution and stresses during cooling on a cooling pedestal where the influence of the end-effector can be clearly seen. While the stress levels shown are acceptable, certain designs and conditions can increase these to unacceptable levels.

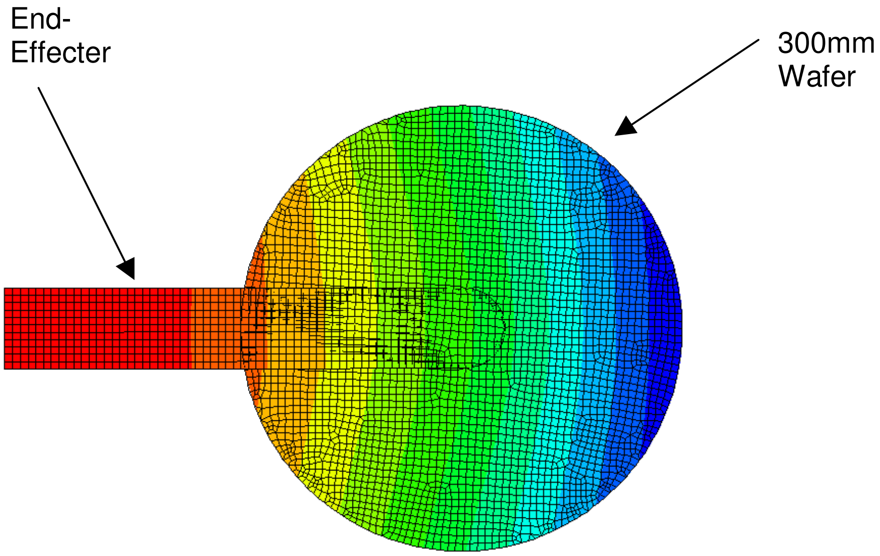

Figure 3 – Wafer/End-Effecter Displacements Vary from 0. (red) to –1.43 mm (dark blue), Outline of Wafer Chuck Can be Seen in Wafer Center

Probably the most important aspect of the process chamber is the understanding of interactions of fluid flows, chemistry and plasma. Different systems use different type of chemical processes. For example, CVD systems (chemical vapor deposition) rely on a uniform flow of reactants, proper activation energy (heating) all while carefully minimizing the use of the reactants. Physical vapor deposition (PVD) systems rely on high vacuum, current and plasma effects to dislodge individual atoms from a target (such as a Cu target) and cause the Cu atoms to deposit on the surface of the wafer. Novellus uses commercial CFD codes (such as Fluent) to perform CFD analyses (including chemistry) of proposed chamber designs and gas delivery concepts. Novellus also uses some commercial as well as specialized Plasma analysis codes to help understand the physics and control of PVD processes. While some commercial codes have attempted to integrate the CFD, plasma, thermal (and even structural) analyses, in practice the codes seem to do better at different aspects of the problems and leave other aspects as second thoughts. The resulting models are technically complex and computationally expensive and hence these overall combined analyses at this time are not currently practical on a regular basis. Structural aspects of process chambers include the prediction of chamber displacements and distortions due to vacuum loading. Figure 5 shows the Novellus WTS (wafer transfer station) structural distortions under vacuum loading. Despite chamber thicknesses on the order of 2 inches measurable displacements are predicted and measured. One use of such displaced plots is to ensure that robots mounted to the chamber to not differentially rotate during depressurization, which would affect the precise alignment and hand-off geometry. Additionally, fatigue issues may exist due to the cyclic stresses imposed and detailed design must include such considerations.

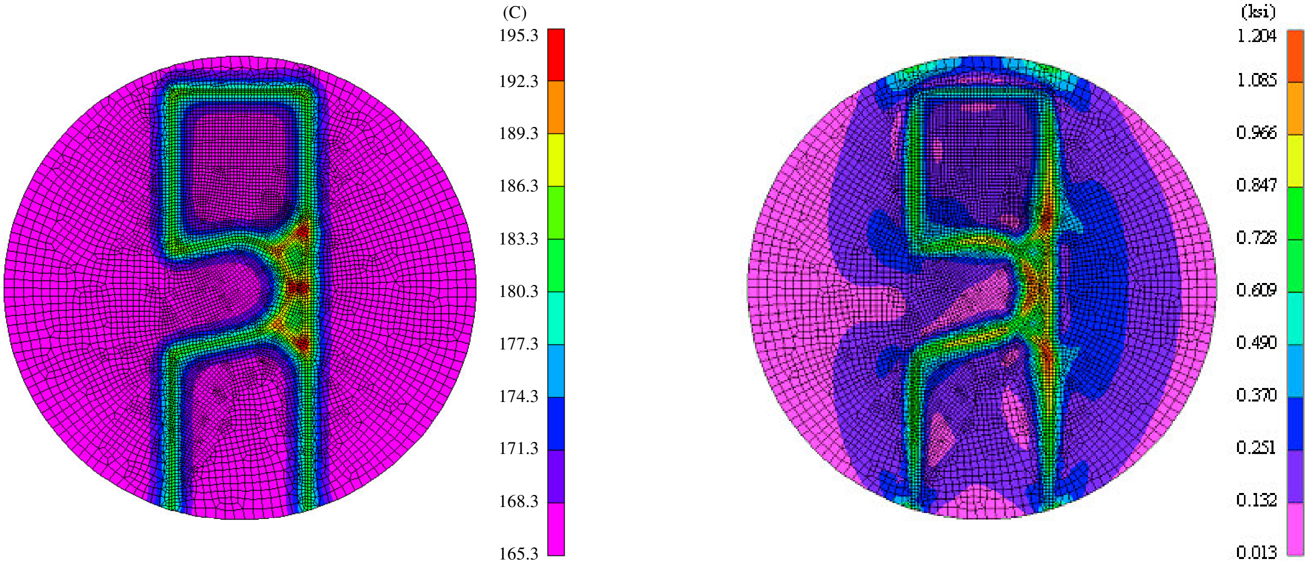

Figure 4 – Wafer Temperatures and Stresses during Wafer Cool. Pedestal Cut-Out Effects Can be Clearly Seen (MSC.Nastran for Windows)

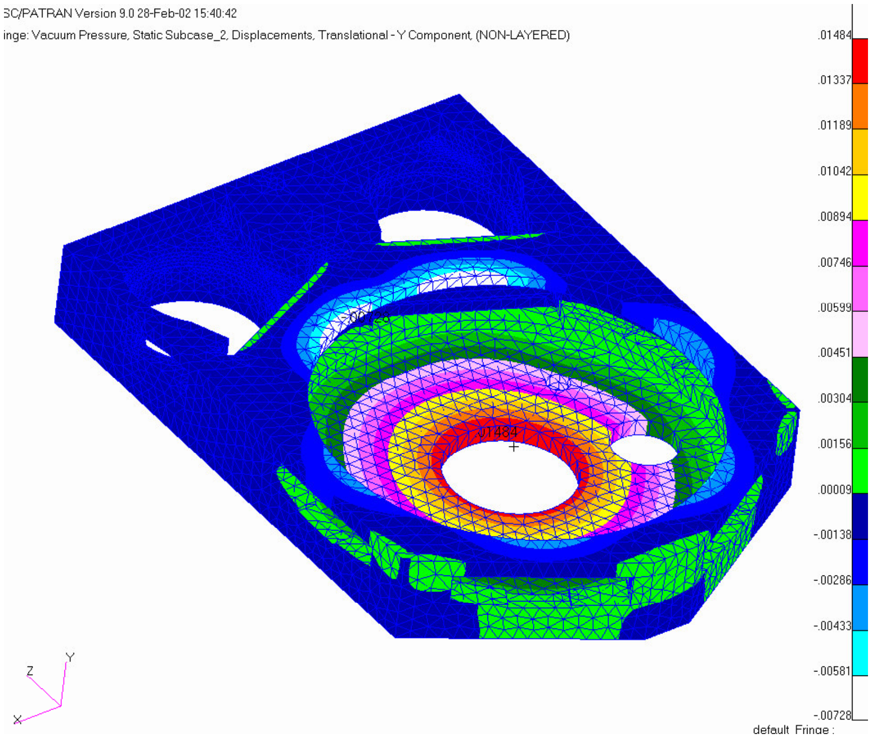

Figure 5 – Vertical Displacement Under Vacuum Loading Conditions, Novellus WTS Chamber (MSC.Patran & MSC.Nastran)

The system frame is used to support the heavy process chambers and the complex system of vacuum pumps, RF generators, power supplies, etc. In addition, hoists are often built into the frame to aid in preventive maintenance and the (hopefully rare) removal of major components. The frame must be seismically restrained to the fab floor using anchors. The SEMI [1] standard provides recommended seismic design guidelines, which equate to approximately 1g lateral loads being applied as static load cases. The frame and structure must be able to withstand this loading condition. In addition transportation and hoisting loads must be considered to ensure safety of the service engineers. A typical Novellus system weights 3000-4000 lbs, however, one of Novellus' heaviest tools weighs approximately 16,000 lbs. This tool is a CMP system, which uses a combination of chemical and mechanical polishing to remove extremely thin layers of material from the wafer surface. The required high precision dictates extremely low allowable structural distortions during processing which has a major impact on frame and structural design of the system. Additionally, vibratory loads due to the rotation of the planarization heads must not excite natural structural frequencies of the system. The most desirable design ensures that the lowest structural frequencies exceed the operational frequency of the heads. Figure 6 shows the first fundamental vibration mode of a recently designed Novellus Xceda CMP system. The MSC.Nastran structural analysis code was indispensable for it's design and optimization of the structural layout.

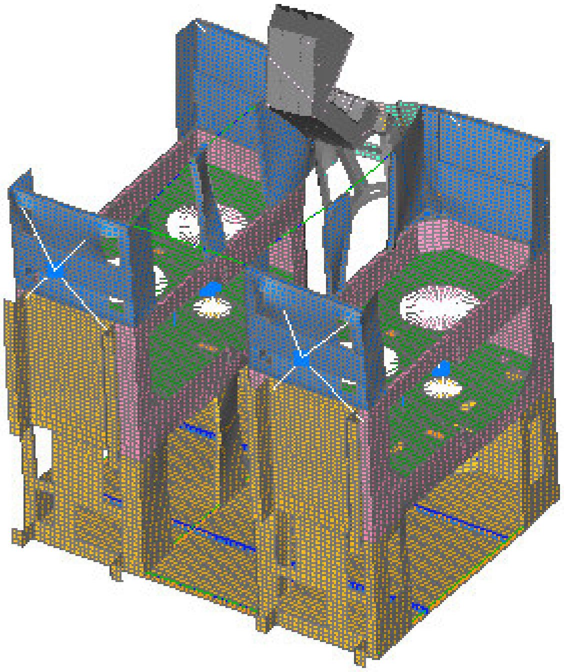

Figure 6 – Vibration Analysis of Novellus Xceda System, First Mode = 21.3 Hz (MSC.Nastran for Windows)

The Future of Virtual Prototyping in Semiconductor Equipment Manufacturing

Virtual prototyping and modeling have provided valuable design guidance for proposed, existing and in-progress Novellus tools. As shown previously, it is being successfully used to help understand issues with installed systems as well as to support continuous improvement (CIP) activities. What more can be expected from a virtual prototyping environment? How can virtual prototyping be used to achieve higher engineering productivity and lower design and manufacturing costs? The following are proposed as key requirements:

- Improving product quality (addresses safety, accuracy and reliability)
- Reducing material, manufacturing and engineering costs (achieves a more cost effective design)
- Reducing development cycle time (can reduce engineering design costs, and, provide critical "first to market" advantage)

In a nutshell, how can virtual prototyping be used to improve product quality, reduce costs and development cycle time?

The following are considered key ingredients needed in virtual prototyping software in order to improve product quality, reduce costs and development cycle time. To improve the analysis quality more attention must be paid to coupling between different physical events. For example, in the wafer bow problem, there is an extremely strong coupling between the structural deflections and the gap conduction that occurs between the pedestal and wafer. The problem is nonlinear and time dependent and after each structural solution time step a thermal solution must be performed. Another strong coupling exists in CMP systems where a fluid-film develops between the wafer and polishing pad. In order to ensure minimum usage of slurry the pressure distribution should be well understood. Virtual prototyping should allow for better development of pad geometry, materials and fluid delivery systems. A rudimentary coupling exists in the MSC.MARC software (fluid bearing analysis), however, it is currently cumbersome to use and not conveniently coupled to the structural solver.

The use of convenient user routines and flexible post-processing capability is extremely important when trying to push the envelope in terms of analysis capability. All virtual prototyping software must allow for easy custom processing of standard results so that the analysis can be tailored to different industries needs. Some of these needs are highly proprietary and the engineers involved are not always at liberty to disclose what is needed to the code developers. Also, continual development of basic capability, improvement in heat transfer capabilities such as radiation (view factor & specular radiation considerations), continued development in constitutive modeling (such as unified creep-plasticity models) will also improve the quality, reliability and safety of virtually prototypes systems.

Increased knowledge through accurate simulation provides the ability to design with reduced factors of safety, knowledge of the design robustness (through multiple what-if simulations) and improved reliability due to the fact that stresses, strains and deflections can be accurately predicted, all lead to reducing material and manufacturing costs. This effort will reduce warranty costs since the design robustness and expected life will be better known. (The expected life will be better known through the ability to perform fatigue life predictions.) The MSC.Fatigue software addresses this issue. While we have not yet utilized it, it is on our list of items to investigate (we currently post process results to predict lifetimes). Another important technology that is part of the MSC.Nastran capability is design optimization. We have investigated this capability in a cursory fashion and hope to utilize it on future projects. Design optimization must be straightforward to use, and, must be robust and capable of multiple physics. Further development of this area is considered an important part of reducing the manufacturing and material costs in a virtually prototyped design.

The reduction of engineering time and costs, development time and the ability to be first to market are all interconnected. If engineering and development costs were not an issue we could simply increase the number of engineers performing virtual prototyping activities. This unfortunately drives up engineering costs and does not allow for rapid ramping of development efforts unless a high overhead of qualified analysts are waiting to be utilized. A preferred solution is to make the software more productive so that a single skilled engineering analyst can produce more high quality simulations in shorter amounts of time. Part of the solution is better computer hardware, however, often it is not the hardware that limits the overall productivity of an analyst, it is often the software. Development of more user intuitive interfaces with ergonomic hardware interfacing is a serious challenge. As software increases in capability, the difficulty to rapidly use it seems to increase as well. For example, the ability to automatically mesh complex solids is currently available in MSC.Patran (see Figure 5). However, development of more complicated, topologically heterogeneous models (such as those best represented as combinations of beams, plates and possibly solids) are still time consuming if you want to make certain that all connections are appropriate and element geometry is optimal (see Figure 6). It seems that some type of artificial intelligence could be utilized to better perform these functions that currently require very time consuming operations by human operations. Most of the rules used in modeling can be captured, thus, it seems that artificial intelligence maybe a way to help improve the speed with which complex meshes, loads, boundary conditions and material properties can be defined. Another possibility would be to provide, simple to use, user templates that would pre-define many rules that a particular analysts uses, so, the software can be better customized (in a quick & easy fashion) to suit the needs of a particular analyst or analysis task.

Conclusions

Virtual prototyping and modeling have been used for some time in the semi-conductor equipment industry. In order to continually improve product quality, reduce costs and increase development speed more attention must be paid to physically coupled phenomena that in the past were either unsolvable, or, required tedious and drawn out analyses. Additionally, while adding capability to the software, we should strive to continuously make it easier to use. This will allow more virtual prototyping to occur, and, at the same time reduce engineering costs and development time. Virtual prototyping software vendors who meet these challenges will continue to have strong positions in the market.

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References

[1] Semi S2-0200; "Environmental Health and Safety Guidelines For Semiconductor Manufacturing Equipment" 2000.