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Development of material law for simulation of ultrasonic welding

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Abstract. It is important to involve influence of manufacturing process of parts and assemblies which are later analysed and developed by using CAE simulations. We are recently able to successfully simulate so many different kinds of manufacturing processes and bring their results as boundary condition for further calculation. Ultrasonic welding is one of commonly used physical technology, but possibilities to simulate this process are currently very limited. The project is about development of viscoelastic material model suitable for ultrasonic welding CAE simulation. It is related to usage of user subroutine in Radioss Solver and programming of user defined material model.

Introduction

New and new manufacturing technologies are implemented into practice. Computational simulations must follow this progress and should be prepared to react on it. Simulations of manufacturing processes can save a lot of expenses and accelerate development of products.

Our team decided to react to expanding use of ultrasonic welding in production of plastic and metal products as well as missing appropriate material law which would be able to simulate this process in explicit solver Altair RADIOSS.

The research's aim is to develop a material law for Altair RADIOSS, which enables to simulate a complete process of ultrasonic welding from contact of parts up to cool down.

CAE Solver

Altair RADIOSS is one of the high-performance world-wide used explicit solvers in the field of structural analysis of nonlinear dynamic load problems. It includes tools for multi-physical simulation and modelling of complex materials such as composites also. RADIOSS is used across industries to increase impact resistance, safety and manufacturability of structural designs. It includes almost 100 material laws and 20 failure material models which define physical behaviour of simulated materials [1]. Unfortunately, up to now no of them can be used for accurate simulation of ultrasonic welding.

Theory

Ultrasonic welding is manufacturing technology which uses ultrasonic waves for connecting parts of assembly. It transforms high-frequency ultrasonic acoustic vibrations into heat that increases temperature of contact layer between two parts up to melting point. Then the material of two parts is blended and the assembly cooled down.

Few different methods which differs in principle of heat production can be used for the welding. Our team focused on a method which uses visco-elasto-plastic properties of materials, which are characteristic for almost all real materials

Viscoelastic behaviour means that when the material is under stress, part of energy is transformed into heat and another part is stored for shape restoration when the stress is lost. This is due to hysteresis in stress strain dependency of the material. This hysteresis behaviour causes that the strain is delayed in comparison with the stress, i.e. stress–strain curve is different during loading and unloading process. A phase shift between stress and strain is significant. These effects are described in Eq. (1) [2].

$$\sigma = E_{RE} \cdot \varepsilon_0 \cdot \cos(\omega \cdot t) + E_{IM} \cdot \varepsilon_0 \cdot \cos\left(\omega \cdot t + \frac{\pi}{2}\right) \tag{1}$$

where σ is stress, ε_0 is strain, E_{RE} is real part of complex Young's modulus and E_{IM} is imaginary part – i.e. loss modulus which determines energy transformed to heat during material deformation.

Then loss factor LF, ratio of transformed and non-transformed energy, is a dimensionless quantity defined as Eq. (2) [3].

$$LF = {}^{E_{IM}}/_{E_{RE}} = \tan\varphi \tag{2}$$

where φ is a phase shift and it is a material characteristic that can be measured. This quantity can describe ability of material to generate the heat as well as damp mechanical vibrations. One can see the value of the phase shift is a crucial factor here.

Visco-elasto-plastic behaviour then means that when elastic limit, i.e. yield stress, is exceeded, the plastic changes are taken into account also. This effect is very important for correct simulation of welding of plastic materials, because part of the heat is also generated by plastic deformation.

Implementation of theory into the material law

It was decided that the implementation of theory into our material law will be sequential. We started with rather great disregards of physical effects which were taken in care only in next following phases of development. One of the simplifications of the solved problem was a linearization of elastic part of stress-strain curve which is shown at Figure 1. The amount of energy transformed into heat is proportional to area of hysteresis loop that characterizes dependency between stress and strain during one cycle of harmonic loading and unloading of the visco-elastic materials, see Figure 1 on the left. As dependency between stress and strain is nonlinear, the Hook's law does not hold for visco-elastic materials.

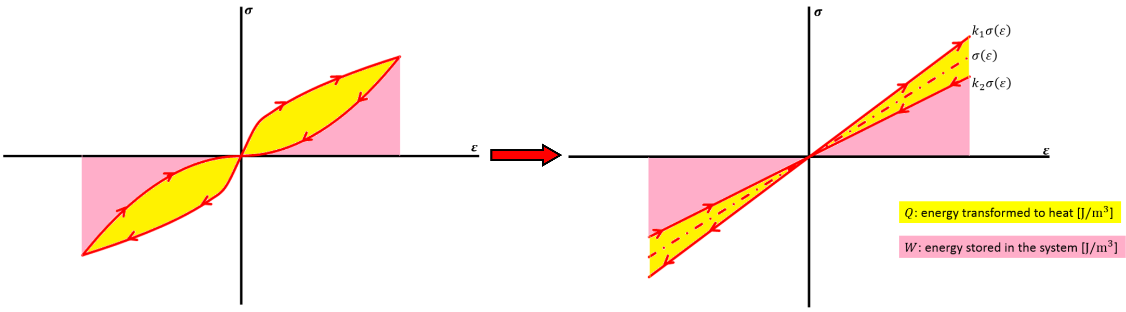

Fig. 1: Linearization of stress-strain curve

The basic relation for the energy is:

$$U = \frac{1}{2} V \sigma \varepsilon \tag{3}$$

where, U is internal energy (of element) and V is volume (of element). During unloading process part of the internal energy W is used for shape restoration and remaining energy Q is dissipated to the heat. The relation (3) holds for all components of stress and strain tensors and overall energy is sum of energy for all of these tensor components. The slopes k_1 and k_2 of ascending (loading) and descending (unloading) line are chosen so that after linearization:

$$\frac{Q}{W} = tan\,\varphi, \tag{4}$$

which corresponds to Eq. (2) and therefore the heat produced by linearized model is in accordance with real material behaviour.

When the elastic behaviour is linearized, then the plastic behaviour can be described by different material laws. As the best one for our purposes the Johnson-Cook model was chosen. It describes the material by Eq. (5).

$$\sigma = \left(a + b\varepsilon_p{}^n\right)\left(1 + c\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\left(1-(T^*)^m\right) \tag{5}$$

where, a, b, c and n are material parameters, ε_p is the plastic strain, $\dot{\varepsilon}$ is the strain rate, $T^* = (T - T_r)/(T_{melt} - T_r)$, T is the temperature, T_r is the ambient temperature, and T_{melt} is the melting temperature. For our current purposes the strain rate and temperature dependency of stress is neglected in this phase of development. Overall heat produced can be expressed as sum of heat due to the loss factor in the elastic region and heat due to the plastic deformation in the plastic region of the stress-strain curve. This is depicted in Figure 2.

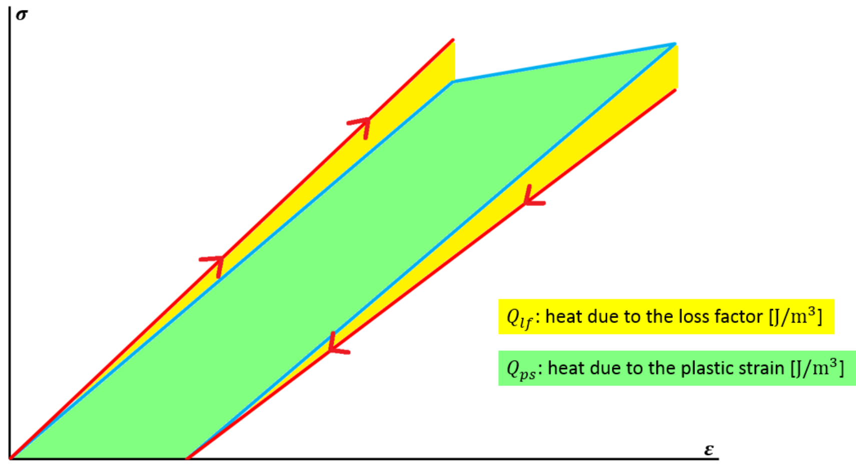

Fig. 2: Linearization of stress-strain curve with plastic behaviour

After few internal tests we decided that in this phase of development a heat transfer by conduction will be disregarded. We can presume that the heat transfer will be minimal, because the welding process is very fast (complete process lasts tenths or maximum seconds) as can be seen in Figure 3. Nevertheless, if there is a need of basic heat transfer, it can be modelled (in very simplified way) in postprocessing by averaging values on elements.

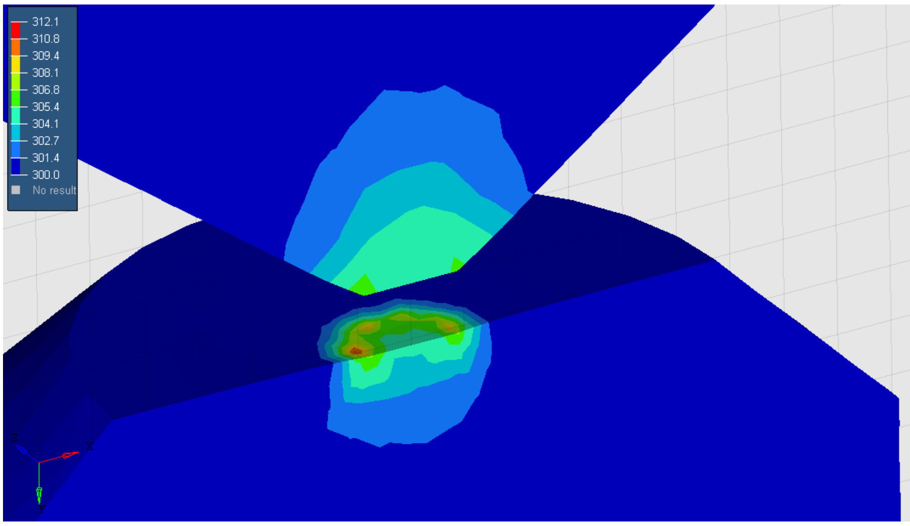

Fig. 3: Thermal distribution at time t = 7 ms

There was found out in benchmarks that mesh size has very great influence on result accuracy. On the other hand, size of the smallest element in mesh determines size of time-step of simulation (and computational time demands too) in RADIOSS solver, or any explicit solver. Due to it, the mesh size must be chosen very prudently and the whole mesh must be result of compromise between accuracy and speed even more than in common structural analysis.

Conclusions

A development of new material law is not ended. There is still a space for enhancing code and implementing other minor physical effects. We will continue in our effort. For example, because of simulation of post welding cooling, we would like to implement heat transfer model which is disregarded at this moment. Nevertheless, the current state looks promisingly enough to be sufficiently accurate to successfully simulate typical process of ultrasonic welding after finishing validation process.

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