AN LS-DYNA MATERIAL MODEL FOR THE CONSISTENT SIMULATION OF WELDING, FORMING AND HEAT TREATMENT

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ABSTRACT

Cold and hot forming, welding, heat treatment or post weld heat treatment are well-established production processes in manufacturing industries, but predicting the final state of geometry, residual stresses, microstructure or material properties of the processed parts is still a major issue. The most crucial process parameter in hot forming, welding and heat treatment processes is the thermal loading applied on the part as material properties usually depend on temperature and thermal loading can initiate a transformation within the microstructure of the material.

This microstructure transformation is used in case of for example heat treatment and press hardening with intent to design tailored material properties of a part. On the other hand, microstructure transformation might also occur unintended and uncontrolled in welding. In both cases, it has a significant impact on the shape and properties of the processed part and its effects have to be taken into account in the simulation in order to obtain a quantitatively good agreement between simulation and reality.

Beside the similarities, each of the above mentioned processes shows some individual characteristics and, thus, poses additional, distinctive requirements and challenges on the simulation. For welding simulations, the contribution of filler material (often in multilayered welds), the grinding of welded layers and re-welding have to be accounted for. In contrast, carburization and carbon depending material properties are crucial features for a successful heat treatment or post weld heat treatment simulation. Tempering, stress relieve and creeping behaviour also have to be considered in this case. Finally, when considering forming simulations an accurate description of the strain rate effects are crucial for a predictive simulation.

Recently, researchers described a temperature dependency of the Bauschinger effect [1,2,3], which necessitates a temperature depending parameter for a plasticity model with a mixed isotropic and kinematic hardening. Another important point is to identify damage or cracks in the assembly either initiated by the manufacturing process, in serviceability or ultimate load. Damage models for material at room temperature like GISSMO [4,5] are already available in the Finite-Element software package LS-DYNA and have been successfully employed for crash or forming analysis. For the processes at hand, these models need to be extended for material behaviour at elevated temperatures up to melting point of the material.

In this contribution we introduce a novel elasto-plastic, temperature and strain rate dependent material model in LS-DYNA entitled *MAT_GENERALIZED_PHASECHANGE (*MAT_254) that has been developed and implemented to overcome existing limitations of other models. It is based on a very general implementation and provides a flexible input structure. The number of phases in the microstructure is a user-defined input variable. For the phase transition between the individual phases the user can choose from a set of generic and well-established models. To be applicable in welding simulations, thermal and mechanical activation of the material is included as well as a deactivation functionality to represent grinding and re-welding of certain layers.

INTRODUCTION: MATERIALS AND PROCESSES

Steel and aluminium alloys are the most commonly used materials in today's manufacturing industry. Thus, these two materials, their properties and behaviour are mainly considered for the new LS-DYNA material *MAT_GENERALIZED_PHASECHANGE (*MAT_254), but it is not restricted to those and might be applicable to other materials as well.

Steel is a material the microstructure of which undergoes phase transformations depending on the chemical composition and external temperature loads. Since the macroscopic material properties highly depend on the microstructure, processes like hot forming have been devised to control the phase transformations. Therefore, this state-of-the-art manufacturing techniques allow to obtain parts with tailored material properties.

Aluminium on the other hand is used in heat treated or milled states that have significantly higher strength as compared to the base material. The reason for this superior property is that in case of heating or melting recrystallisation occurs and leads to a change of material properties.

Considering the main applications in manufacturing industries as well as the possibilities already offered by the many material formulations in LS-DYNA, the main focus of the new LS-DYNA material is put on two processes: welding and heat treatment. Naturally, the processes have to be incorporated into a continuous simulation chain including previous or subsequent steps like for example forming or serviceability analysis.

Studying welding in more detail it becomes evident that, locally**,** it consists of the following processes:

- Heating
- Cooling
- Reheating in case of multilayered welds
- Grinding

In general, the cooling rates during welding processes are continuous and do not have holding times. Nevertheless, tempering effects can often be observed in multi-layered welds.

For a successful description of the heat treatment process, the following stages have to be considered:

- Heating
- Carburatisation
- Quenching
- Tempering
- Annealing

It is important to note, that often some of the stages are skipped in industrial applications, such that a heat treatment process may consist of heating and quenching only. During these processes a continuous cooling cannot always be assumed: for longer holding times tempering effects have to be addressed. Post weld heat treatment is considered here as a heat treatment process with tempering or annealing effects.

GENERAL REMARKS ON THE MATERIAL FORMULATION

From a mechanical point of view, welding and heat treatment are multi-physics problems: temperature, structure mechanic and phase transformation have to be considered simultaneously. The FE-package LS-DYNA is already designed to perform coupled analyses. It additionally offers a solver for electro-magnetism, which might be of interest in case of inductive heating, inductive hardening or resistive welding, but those processes are beyond the scope of this publication.

The coupling of a thermal field, structure mechanics and phase transformation has been successfully applied in LS-DYNA for hot forming simulations. The techniques used here are the starting point for the novel development introduced in this contribution.

In the thermal analysis either the specific enthalpy can be considered or the heat capacity in combination with the latent heat at phase transformation points. As it is common for commercial finite element software, the last one is chosen for this material model. Further thermal properties are heat conductivity and density.

Based on the given temperature field the phase transition in the microstructure can be calculated. For hot forming simulations material *MAT_UHS_STEEL (*MAT_244) has been implemented [6]. Recently, it has been extended to be applicable for welding and heat treatment simulations [7]. The model is based on the work of Akerstrom [8]. Its application is restricted to certain steel alloys and can distinguish between five phases (austenite, ferrite, pearlite, bainite and martensite). The main goal of the present development in *MAT_254 is to provide a more general and more flexible microstructure description. Therefore, this important point is discussed in the following section in some detail.

The phase changes have a direct influence on the structure mechanics. The macroscopic mechanical properties depend on the phase composition, as well as on current temperature, grain size and possibly carbon content. In *MAT_254 the elasto-plastic properties (Young's modulus, Poisson's ration, strain-rate dependency, yield stress and strain hardening curves) are defined for the individual phases and have to be combined into a macroscopic behaviour, which is the topic of one of the following sections.

Furthermore, phase transitions induce plastic strains as well as elastic strains within the material. The latter can be identified as jumps in dilatometer curves. The slope of this curves show the thermal expansion of the material, i.e. the thermal strains that also have to be considered for each of the phases in the material formulation.

Besides these effects on the structural mechanics, also the temperature might be locally changed by the latent heat set free in certain phase transformations.

MICROSTRUCTURE REPRESENTATION

As mentioned above, the main reason for developing the new material model are the restriction to five microstructure phases in *MAT_244 and the predefined phase transition laws between the phases. In contrast, the *MAT_254 shall be a multi-phase model with multiple generic laws for the phase transformation the user can choose from for each phase transition. For the current implementation, maximum number of phases is set to.

Following this approach, this material model *MAT_254 can be adapted for a large range of different materials, as many materials in manufacturing industries only differ in the microstructure composition.

PHASE CHANGE MODELLS

In this subsection, the available transformation laws are presented. As the material implementation as well as the parameter input is kept as flexible as possible it the formulation can easily be extended to further laws if needed.

Koinstinen-Marburger: The Koinstinen-Marburger law [9] depends on two parameters: start temperature (MS) and transformation velocity (KM). It is used to describe diffusion-free transformations. The kinetic is not driven by time but by the difference of temperature from transformation start temperature. In *MAT_244, the Koinstinen-Marburger law is used to describe the austenite-martensite transformation.

Kirkaldy et.al.: The transformation law from Kirkaldy et.al. [8], also discussed by Watt et.al. [10], considers temperature, temperature gradient, grain size, activation energy and kinetic parameter depending on the chemical composition. The transformation law can be used for alloyed or low alloyed non stainless steels. One of its advantages is that the transformation parameters can be derived from the chemical composition. Therefore this model is applicable even if no CCT Diagram is available. In *MAT_244 this model is implemented for the austenite decomposition into ferrite, pearlite and bainite.

Oddy et.al.: The transformation rule by Oddy et.al. [11] describes a diffusion driven transformation with a temperature dependent transformation velocity. It is implemented in *MAT_244 to model the austenite composition in the heating case.

Generalized Johnson-Mehl-Avrami-Kolmogorov (JMAK): The generalized JMAK-law is used for transformations by diffusion. The parameter TAU represents the reciprocal value of the transformation velocity and the Parameter N describes the curvature of the transformation function. Both parameters depend on temperature. This law enables the empiric description of any CCT- or TT-Diagram. In some cases the cooling rate influences the transformation kinetic. This influence is covered by the extension of Leblond, the correction factor F, which is a function of the temperature rate and scales the velocity TAU. With the generalized JMAK-law the transformation of steel can be described as well as the transformation of aluminium.

Time Transformation Law: The time transformation law defines the transformation between to phases at a fixed time point. It has not physical representation, but is implemented to be used to activate or deactivate the material. In this case the material is assumed “deactivated”, if a phase with almost negligible mechanical and thermal properties is predominant in the microstructure composition.

From this little survey it becomes clear that results obtained with *MAT_244 can be reproduced with *MAT_254. It is important to note, that by design of the formulations the input differs: whereas *MAT_244 expects the input of the chemical composition, the parameters necessary for the transformation can be given directly to *MAT_254.

METALLURGICAL EFFECTS

As mentioned above, the phase transformations affect the mechanical and the thermal solution in several ways. The new material model considers the most significant metallurgical effects which can occur during the thermal cycles:

- Phase transformation strain
- Transformation induced plasticity (TRIP)
- Reset of plastic strain at melting point.
- Keep or reset of plastic strain during phase transformation

Phase transformation strain occurs due to a volume change during the transformation. It can be identified and quantified with dilatometer experiments, which for example show this important effect for steel alloys, whenever the alpha-phases transform to the austenitic phase or vice versa. The dilatometer curves show characteristic jumps.

Transformation induced plasticity are induced when a transformation takes place under external tensile or compressive loading. In those cases, the transformation releases additionally movement of dislocations corresponding to additional plastic strain. The model of Leblond [12] has proven to be an accurate description for this behaviour. As this transformation induced plasticity is not present at each transformation, a flag enables or disables transformation induced plasticity for the each transformation separately.

The solidification after melting rebuilds the material, i.e. the history of the material is erased. In particular, the accumulated strain hardening erased, which is to be considered by deleting the plastic strain at melting point and prevent the formation of any new plastic strain till the temperature falls below the solidus temperature. In the numerical model, a temperature range is defined for the reset of plastic strains. This is primarily done for numerical reasons, but the limit values of the range can be interpreted as solidus and liquidus temperature.

Any phase transformation theoretically can result in a reset of plastic strain. To take this into account for each phase transformation a parameter defines the relative amount of plastic strain that remains after the phase transformation.

GRAIN SIZE

The phase transformation kinetic is not only driven by temperatures but also by the grain size, especially by the grain size of the austenite. The austenitic grain size depends on the austenitisation process. The grain growth mainly depends on temperature rate during the heating, peak temperature and holding time.

As the conditions of austenitisation cannot be assumed to be homogenous within the work piece and process parameter, i.e. heating conditions, are not constant, a numerical model is required to determine the grain size distribution within the processed part at any given time during the process. In the current implementation of *MAT_254, the relatively simple evolution equation from *MAT_244 is used. Here the growth rate is assumed to be inversely

proportional to current grain size and to show an exponential dependency on the temperature.

Again, the input structure and the material implementation exhibit enough flexibility to easily incorporate more involved evolution equations if needed.

MACROSCOPIC DESCRIPTION

For a structure mechanics analysis the macroscopic properties are needed. For the material formulation at hand, these have to be derived from the microstructure composition. Therefore, a complete structure mechanics description of the individual phases is to be given by the user, i.e. elastic properties, yield curves and coefficients of thermal expansion.

MIXTURE RULE

The simplest approach of the mixture of properties between different phases is a linear mixture according the phase proportion. This approach can for example be found in *MAT_244. In case of volume dependent properties like heat capacity, thermal expansion coefficient this approach is commonly seen to be physically correct. For other properties like heat conductivity or the flow curves nonlinearity may occur. These nonlinearities may depend on the temperature.

To enable arbitrary mixture rules the method weighting functions is chosen. For each phase a function depending on temperature is defined to determine a weight of the particular phase in the mixture rule. The weights might have to be normalized to sum up to one. In order to compute a mechanical parameter, a weighted sum is then evaluated. The individual weights are multiplied with the corresponding mechanical parameter and the phase concentration.

MECHANICAL PROPERTIES

At the time being, the novel material model features an elasto-plastic material model with isotropic strain hardening. The elastic parameters for each phase are naturally temperature. An isotropic plasticity model based on the standard von-Mises yield criterion has been implemented.

Nevertheless, the material can be used in wide range of application. This is ensured by the definition of the yield stress as a function of temperature, rate of the equivalent plastic strain and the equivalent plastic strain itself. Thus, nonlinear strain hardening effects can be captured and the input can easily be generated from the experimental data.

For welding, heat treatment and forming the temperature dependence of the yield stress is crucial for the accuracy of the model. For a subsequent serviceability or crash analysis are usually performed at constant temperatures and strain rate effects become predominant.

Thermal Properties

For the thermal analysis, any thermal material model in LS-DYNA can be coupled with the new material *MAT_254. The thermal materials provide the thermal conductivity and thermal capacity, both possibly again temperature dependent, for the thermal solver. For welding analysis, *MAT_THERMAL_CWM (*MAT_T07) has been developed that additionally offers an activation strategy based on simulation time and temperature that is important for modelling multi-layered welds.

As stated above the temperature influences the mechanical properties of the material. Furthermore, heating and cooling induce a thermal expansion and shrinkage, respectively. It is numerically represented by thermal strains that are subtracted from the mechanical strain tensor before stress evaluation.

SOME TAILORED PROPERTIES

Filler and Grinding

The continuous adding of material during welding processes like arc welding, gas metal arc welding or submerged arc welding requires a simulation method for the activation of elements, as the complete weld seams are discretized within the pre-processing phase. Initially, the elements stay in a deactivated state and switch to active state if a certain criterion is fulfilled. This criterion may be the temperature, the time or a geometric criterion.

The LS-DYNA material *MAT_244 employs a ghosting approach, i.e. an additional state of the material with given macroscopic material properties. In the new material the deactivated material is represented by an additional phase of the microstructure and mechanical activation, consequently modelled by phase transformation from this deactivated phase to an activated phase. For the activation any of the available transformation laws can be used. The thermal activation is realized by time criterion.

In multi-layered welds the groove weld is often grinded out and re-welded since the first welded groove in general contains welding errors. With the proposed approach, grinding is a phase transformation to the deactivated phase. The transformation law is the time transformation law defining the point of process time when deactivation has to occur. To represent the physics correctly, deactivation has to go along with the re-set of plastic strains in the material. The option for reset plastic strain at phase transformation is used for this item.

Special History Variables

For the evaluation the simulation quality for the processes at hand, it is often useful to have access to material data that is not necessary for the simulation itself. Nevertheless, they are

stored as history variables for the material formulation and can be accessed by standard post-processing tools.

The peak temperature, i.e. maximum temperature was reached in the element during the simulation history, is needed to visualize the molten areas and, thus, to verify the correct parameterization of the heat sources and thermal properties.

The macroscopic yield stress is a scalar value that depends of the phase proportion and the mixture of the yield strain of the single phases according the mixture rule and the strain hardening. Its visualization allows for an effective first evaluation of the simulation and the phase transformation behaviour.

DATA TRANSFER FOR FURTHER ANALYSES

It is today state-of-the-art to initialize material parameters with respect to previous process stages. Only by considering pre-straining and pre-damage it is possible to close the virtual process chain for manufacturing industries. LS-DYNA allows including history variables from previous simulations using the so-called dynain-file.

This strategy has already been used to simulate multi-stage hot-forming processes, but also for the forming of welded parts [13].

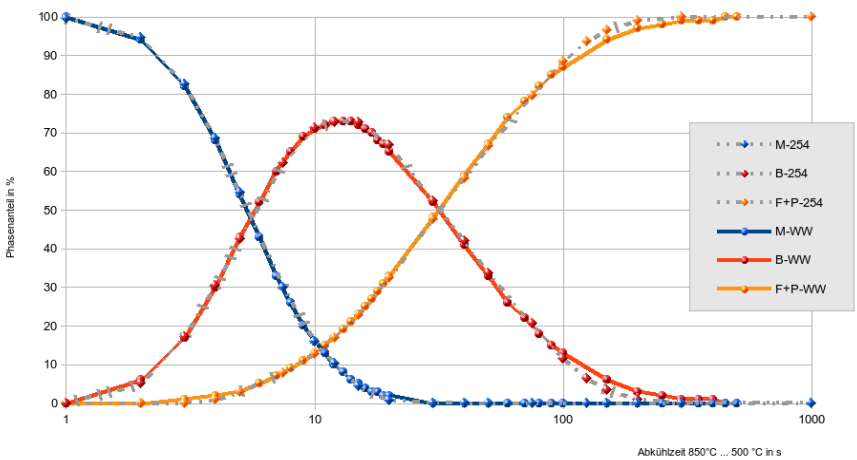

Fig 1: S420 Phase Proportion calculated with *MAT_254 compared with given data

FIRST NUMERICAL EXAMPLE

One of the first tests is performed for S420. Fig 1 shows the result of phase calculation with the new LS-DYNA material model. The calculated results are compared with the given

CCT-data from WeldWare. The generalized JMAK law is used for the dekompositon of austenit to ferite-perlite and bainite phase the Koinstinen Marburger law is used for the dekompositon of austenite to martensite phase.

FURTHER DEVELOPMENT

Although the novel material model already contains a large variety of features to model complex manufacturing processes, there are additional features to be implemented in *MAT_254 to further widen the range of applications.

First of all, the plasticity algorithm within the material only considers isotropic hardening. For many materials of interest a mixed hardening rule provides a better description. Here kinematic hardening is also considered to model the Bauschinger effect.

Recently, researches showed that some materials behave not only according to a constant mixture between both hardening types, but temperature dependence has been proved [2,3x]. The Bauschinger effect disappeared above a specific temperature limit. Thus, in future releases the material will feature a mixed harding rule with a varying hardening parameter beta.

So far, viscosity of the material has been included by the strain rate effects for the yield stress criterion. In many processes creeping, i.e. a time depended decrease of stress, is observed, in particular for steel at higher temperature. The current formulation will be tested with respect to this behaviour and if necessary an additional visco-elastic formulation for the material will be implemented.

The case hardening process results in non-homogeneous material properties, because of non-homogeneous carbon content distributions within the work piece. To cover this situation in the simulation correctly, the carbon distribution needs to be analysed first. The results have to be transferred to subsequent analysis steps. Naturally, this only enhances the quality further simulation if the material formulation can translate the carbon content into material properties. Thus, a future version of the material will allow defining the influence of the carbon on the phase transformation laws as well as on the material properties themselves.

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