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ЧИСЕЛЬНЕ МОДЕЛЮВАННЯ ЗАЛИШКОВИХ НАПРУЖЕНЬ В ПРОЦЕСАХ РІЗАННЯ МЕТАЛІВ

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NUMERICAL MODELLING OF RESIDUAL STRESSES IN METAL CUTTING PROCESSES

Residual stresses in machined surfaces have been investigated since the early 1960s, leading to handbook data (experimental approach). More recently, finite element methods of machining have been used to predict residual stresses from computed stress and temperature distributions. However, such methods are highly time consuming and very costly. As a consequence, new approaches combining experimental, analytical and numerical models appeared recently in order to enable a rapid prediction of the residual stresses within a few minutes, making this approach usable for industrial applications.

The large majority of these researches are interested in predicting the residual stress state after orthogonal turning (or grinding), which is a 2D problem far from realistic cutting processes (3D turning, milling, drilling, etc.). The main limitation to moving towards complex cutting processes is central processing unit (CPU) time. Only few investigations dealt with 3D turning operation but with many more assumptions and uncertainties in order to limit the CPU time. Moreover such models do not consider microstructural modifications, which limit their applications. From this point of view, the cutting scientific community is behind the welding scientific community which has investigated the coupling of metallurgical–mechanical–thermal effects in 3D configurations for a long time. This section aims to provide some trends and references in residual stresses modelling in orthogonal cutting without considering metallurgical changes.

Numerical models necessitate the application of standard finite element codes such as SYSWELD, ABAQUS, DEFORM, etc. In such approaches, two major types of parameters are strategic (Figure 1):

1. The input data: mechanical properties of the metal, thermal properties of the working material and cutting tool, friction model at the tool – work material interface, etc.
2. The numerical model: Lagrangian, Eulerian or ALE techniques, Adaptative remeshing or none, Implicit or explicit formulation, Element type and size.

The cutting tool geometry is provided by the tool manufacturer (rake and clearance angles, cutting edge radius, chip breaker geometry). Most of the time, researchers consider a plane-strain configuration since they consider that the depth of cut is much larger than the feed. The Lagrangian technique consists of tracking a discrete material point. A predetermined line of separation at the tool tip is usually present, propagating a fictitious crack ahead of the tool in order to avoid severe mesh distortions. In this case, a failure criterion is required.

The criterion is either based on a distance between the tool tip and the node, or based on a parameter depending on the stress state, on the strain rate and on the temperature at a certain distance ahead of the tool tip. In both cases, the separation occurs when a critical value is reached. However only sharp cutting tools can be modelled. Other kinds of Lagrangian techniques prefer the use of adaptive remeshing techniques to bypass the problem, which enables the modelling of blunt tools. Of course, the CPU time becomes very high since a fine mesh is required around the cutting edge radius.

Eulerian techniques consist of tracking volumes and do not induce problems of mesh distortion or require failure criterion. However the determination of free surfaces is critical, which necessitates some assumptions about the chip geometry. Finally, the avoidance of elastic behavior does not enable the estimation of residual stresses. The arbitrary Lagrangian–Eulerian (ALE) technique is a relatively new modelling technique that represents a combination of the Lagrangian and Eulerian techniques without their drawbacks.

In metal cutting simulations, usually apply explicit integration methods; although some works are available with implicit methods [1]. In explicit integration, a system of decoupled differential equations is solved on an element-byelement basis, in which only the element stiffness matrix is formulated and saved without the need for the global stiffness matrix. On the other hand, the global stiffness matrix has to be formulated and saved in implicit integration, and the whole system of differential equations has to be solved simultaneously. Therefore, explicit methods are computationally more efficient, especially when non-linearity is encountered. This becomes more evident in thermally coupled analysis, as in metal cutting, because structural and thermal variables are solved simultaneously. Explicit integration is conditionally stable because the critical time step depends on the minimum element size and the speed of wave propagation, while implicit integration is unconditionally stable.

Concerning the input data of numerical models, the identification of the constitutive equations for the work material (flow stress model and damage model) remains an issue, since it requires the determination of material properties at high strain rates, large strains, high temperatures and high heating rates. The main problem originates from the strain rate achievable in standard mechanical tests (for example, Hopkinson's bar), which are about 100 times too slow compared to classical strain rates in metal cutting ~105–106 s^{-1}. A common practice consists of using the Johnson–Cook model, including deformation hardening, thermal softening and rate sensitivity. Another major problem originates from the identification of the coefficients independently from each other, i.e., the strain rate effect is identified at low temperature, the temperature effect is identified under low strain rates, etc. As a consequence, there is no way to validate that such models remain meaningful under the combination of high strain rates and high temperatures. It is important to underline the sensitivity of Johnson–Cook parameters on the residual stresses predicted to prove the necessity of improvement of the identification methodology and of the constitutive models.

The objective of analytical models is to predict residual stresses based on equations coming from mechanical and thermal properties of materials. Such models are very efficient in terms of speed compared to experimental approaches, it is necessary for its optimization.

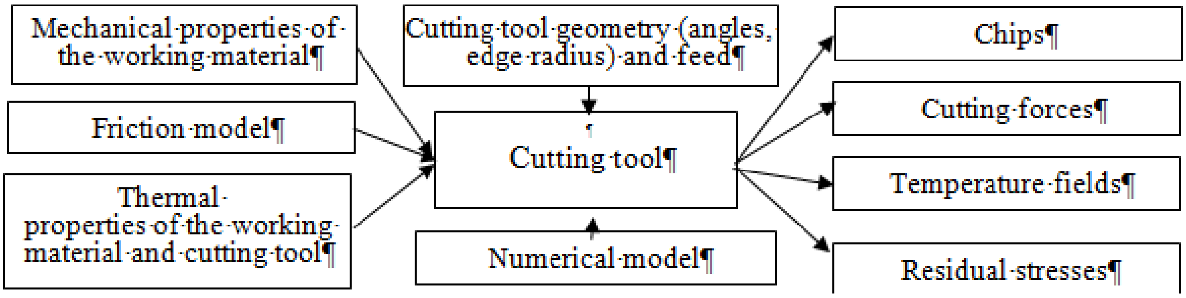

Figure 1 - Data involved in the numerical modelling of residual stresses

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