A staggered coupling strategy for the finite element analysis of warm deep drawing process

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Abstract. The thermomechanical finite element analysis of warm forming processes enables an improved comprehension of the process parameters affecting the material formability. However, the thermal and mechanical coupling problem is still a challenge from the computational standpoint. A staggered strategy for the thermomechanical coupling problem is presented in this study, which is based on an isothermal split approach and allows the treatment of the two problems separately. The exchange of information between the mechanical and the thermal problem is performed to achieve a compromise between computational cost and accuracy. The proposed algorithm was implemented in DD3IMP in-house finite element code. Its performance is analysed and compared with a classical strategy commonly employed for solving thermomechanical problems.

1. Introduction

Warm forming is one of the most promising technologies and it has been studied for many years, with increasing attention of the scientific community over recent years. This is a consequence of its advantages, namely the increase of the ductility and decrease of the springback effect in the sheet metal forming of aluminium alloys [1].

The finite element analysis has been playing an important role in the understanding of the deformation mechanism and a great effort has been done to improve the confidence on its results, particularly in the material modelling. Another important aspect, for a successful analysis, is the coupling strategy chosen to handle the dependence of the mechanical behaviour on the thermal behaviour and *vice-versa*. The resultant coupled thermomechanical problem can be approached by monolithic or by staggered algorithms. The monolithic approach treats both problems (thermal and mechanical) in a single system of equations. Despite its unconditional stability, it leads to a large and non-symmetric system of equations and requires a high computational cost for the resolution phase [2]. The staggered approach was designed to reduce the computational costs via partitioning the thermomechanical problem into two sub-problems, thermal and mechanical. Thus, this strategy yields two smaller systems of equations. Within the staggered approach, two methodologies can be applied, the isothermal split and the adiabatic split [3]. The last one has been proposed to circumvent the conditional stability of the isothermal

split. However, in case of metal forming processes, this unstable performance is not expected, since it only occurs for values of the thermal expansion coefficient which are non-physical for metalic materials [4].

In this paper, a new coupling strategy is proposed based on the isothermal split. The mechanical problem is solved at constant temperature and the thermal problem is solved for a fixed configuration. This algorithm was designed with the objective of enhancing the computational performance of the classical algorithms based on isothermal split, without compromising the accuracy.

2. Thermomechanical coupling

A brief description of a classical algorithm based on isothermal split and the proposed algorithm is presented. Both were implemented in the in-house finite element code DD3IMP. Concerning the formulation and solution strategy used for each problem (mechanical and thermal), a detailed description can be founded in [5, 6].

2.1. Implicit algorithm

The classical algorithm presented here, is the so-called iterative or implicit one [7, 8], which was designed to attempt an higher accuracy [7]. It consists of an iterative procedure for the mechanical and thermal problems, in each time increment. Thus, the information between problems is interchanged in each iteration until attaining the convergence criterion. This algorithm may be summarized as follows: for each increment, it starts with the resolution of the mechanical problem for a fixed temperature field from the last increment. After that, the thermal problem is solved and subsequently the temperature-dependent material properties are updated. This procedure is repeated until attaining the convergence criterion.

2.2. Proposed algorithm

The proposed algorithm can be divided into two phases for each time increment. The first phase is a predictor one, where an explicit trial solution for the temperature and displacement fields is determined. The second is a corrector phase, where the trial solution is improved by an implicit method. Therefore, first the thermal problem is solved based on an explicit approach and assuming the boundary conditions of the last increment. After that, the temperature-dependent material properties are updated with the trial temperature field, and the mechanical problem is solved, based on an explicit approach. Then, the corrector phase is performed, where the mechanical problem is solved first using the previously obtained displacement field, which corresponds to the initial solution for the Newton-Raphson method. This is corrected until the equilibrium state is attained. Finally, the thermal problem is solved using an implicit approach, for the current mechanical equilibrium configuration.

3. Warm deep drawing example

In order to compare the two algorithms previously described, the warm deep drawing of circular AA5754-O aluminium alloy blank was chosen, which is inspired by the work of Laurent et al. [9]. In this work, the deep drawing tools were assumed as rigid and at constant temperature. Regarding the mechanical behaviour of the aluminium alloy, the Hockett-Sherby hardening law and the Hill'48 anisotropic yield criterion were adopted. However, the strain rate dependency was neglected. The mechanical and thermal material parameters, as well as the friction coefficient, are the ones described in [9].

One fourth of the model was simulated, with a total of 9068 tri-linear hexahedron finite elements (2 layers through the thickness) for the blank. Selective reduced integration was adopted for the mechanical problem and full integration for the thermal one. The initial

temperature of the blank, the blank holder and the die was 200°C, whereas the temperature of the punch was 145°C. These thermal conditions imposed a non-homogeneous temperature distribution on the blank, which affects the mechanical behaviour of the material.

3.1. Results and discussion

The punch force/displacement curves are presented in Figure 1 a), for both algorithms. The punch force attains a maximum value for 11.6 kN, for a punch displacement of 10.6 mm. The two algorithms attain the same value and an identical evolution for the curve. The plastic strain distribution is also presented in Figure 1 b) and c) and once again identical results were attained for the two algorithms.

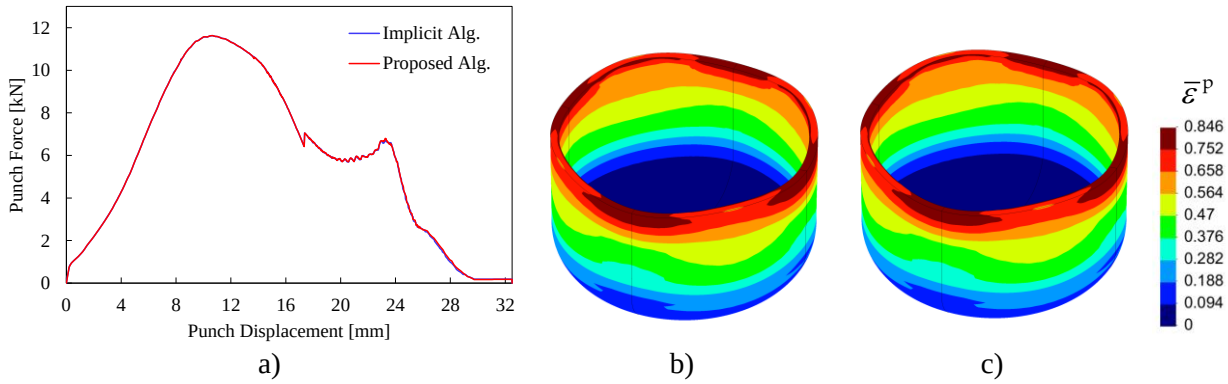

Figure 1. Comparison between the proposed and the implicit algorithms: a) punch force evolution, equivalent plastic strain distribution for the b) proposed and c) implicit algorithm.

Figure 2 a) shows the temperature evolution for two different nodes: the first is located under the blank holder in the beginning of the process, while the other is located under the punch. The

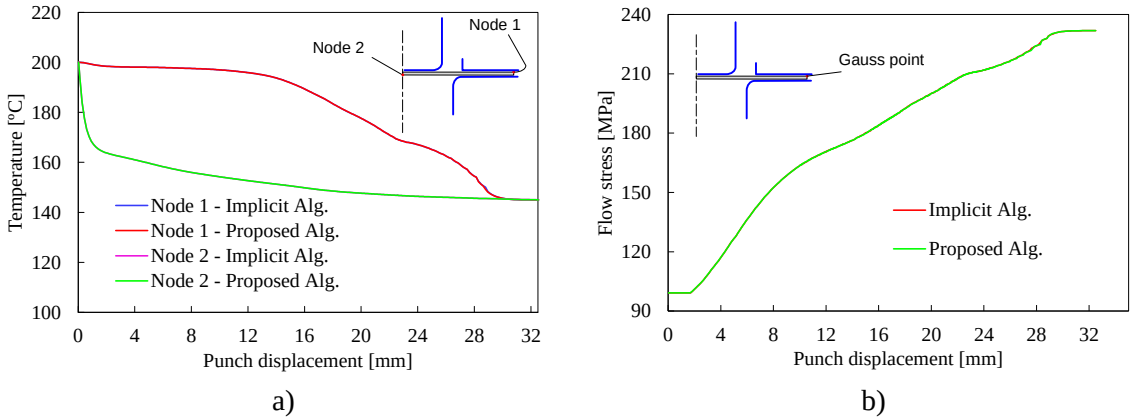

Figure 2. Comparison between the proposed and the implicit algorithms: a) temperature evolution for two nodes and b) flow stress evolution for a gauss point.

second node attains lower values of temperature quicker than the first one, due to the contact with the punch, although both nodes achieved the punch temperature at the end of the process. Figure 2 b) presents the flow stress evolution for a gauss point located under the blank holder in

the beginning of the process. The temperature and the flow stress evolution are equal for both algorithms, revealing a good accuracy of the proposed algorithm.

The numerical simulations were carried out on a computer machine equipped with an Intel Core i74700HQ Quad-Core processor (2.6 GHz). The computational performance of both algorithms is presented in Table 1. The simulation required 536 and 524 increments for the implicit and the proposed algorithms, respectively. Although both algorithms present identical results in terms of accuracy, the computational cost was 32% lower for the proposed algorithm.

Table 1. Computational performance of both algorithms.

	Implicit algorithm	Proposed algorithm
N° increments	536	524
Computational Time [s]	8538	5731

4. Conclusions

In this article, a new staggered algorithm for thermomechanical coupling, based on an isothermal split methodology was presented. This algorithm was designed to achieve a better compromise between computational cost and accuracy. For the sake of comparison and to demonstrate the main advantage of the proposed algorithm, a classical algorithm based on isothermal split was also presented. This classical algorithm, in contrary to the proposed one, is only focused on the accuracy of the results. Both algorithms have been tested on a warm deep drawing example, for which the temperature distribution have a strong effect on the material behaviour. The results show good accuracy of the proposed algorithm and a significant decrease of the computational time, when compared with the classical algorithm.

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References

[1] Ghosh M, Miroux A, Werkhoven R J, Bolt P J and Kestens L A I 2014 Warm deep-drawing and post drawing analysis of two Al-Mg-Si alloys *J. Mater. Process. Technol.* **214** 756-766

[2] Adam L, Ponthot J P 2002 Numerical simulation of viscoplastic and frictional heating during finite deformation of metal. Part I: Theory *J. Eng. Mech.* **128** 1215-1221

[3] Armero F and Simo J C 1992 A new unconditionally stable fractional step method for non-linear coupled thermomechanical problems *Int. J. Numer. Meth. Eng.* **35** 737766

[4] Armero F and Simo J C 1993 A priori stability estimates and unconditionally stable product formula algorithms for nonlinear coupled thermoplasticity *Int. J. Plasticity* **9** 749-782

[5] Oliveira M C , Alves J L and Menezes L F 2008 Algorithms and strategies for treatment of large deformation frictional contact in the numerical simulation of deep drawing process *Arch. Comput. Meth. Eng.* **15** 113162

[6] Martins J M P, Alves J L, Neto D M, Oliveira M C and Menezes L F 2016 Numerical analysis of different heating systems for warm sheet metal forming *Int. J. Adv. Manuf. Technol.* **83** 897909

[7] Vaz Jr M, Muoz-Rojas P A and Lange M R 2011 Damage evolution and thermal coupled effects in inelastic solids *Int. J. Mech Sci.* **53** 387-398

[8] Erbts P and Dster A 2012 Accelerated staggered coupling schemes for problems of thermoelasticity at finite strains *Comput. Math. Appl.* **64** 2408-2430

[9] Laurent H, Coër J, Manach P Y, Oliveira M C and Menezes L F 2015 Experimental and numerical studies on the warm deep drawing of an AlMg alloy *Int. J. Mech Sci.* **93** 59-72