Some progress in physical simulation of forging operations: replicating thermal-mechanical history and evaluating force components

Bariani, P.F., Berti, G., D'Angelo, L., De Chiffre, L., Guggia, R. and Meneghello, R.
DIMEG - Dipartimento di Innovazione Meccanica e Gestionale; via Venezia, 1; Padova 35131

Marchetti A.
Carraro S.p.A.: via Olmo, 37: Campodarsego (PD) 35011

Summary

New experimental facilities have recently been developed and installed at the DIMEG Lab that are specifically designed for physical simulation experiments both on real and model materials.
This paper illustrates some applications of these facilities and relevant simulative techniques to the analysis of bulk metal forming operations such as hot forging of turbine blades and hot rolling of steel plates. The presentation focuses on the most original aspects of the simulations that concern (i) the evaluation of the force and torque components applied to the dies during forging of complex parts and (ii) complementary aspects of physical and F.E. simulation with particular emphasis on precise replicating, under computer control, of local thermal-mechanical profiles that are predicted by F.E. codes.

Key words: bulk metal forming; physical simulation; thermal-mechanical history

1. Introduction

Depending on the objectives of simulations and phenomena to be analysed, two approaches can be recognised in physical simulation of forming operations [1].
The first approach consists of simulating a production unit process with real materials on a laboratory scale and under practice-oriented operating conditions and monitoring or controlling the important process parameters. These simulations are usually aimed at investigating the effects of working variables on micro-structural changes during and after deformation and properties of the forged part. Most of the experimental techniques available for gathering material data behaviour are sub-scale metal-forming operations and, therefore, fall in this category of simulative activities.

The second approach to physical modelling is to devise laboratory tests that are faster, easier, and less expensive than a sub-scale production process. Model materials and visioplasticity techniques are utilised in this approach for analysing flow behaviour, thanks to relatively low loads for deformation, easy observation of deformation patterns and inexpensive test specimens and die materials [2].

New experimental facilities have recently been developed and installed at the DIMEG Lab that are specifically designed for physical simulation experiments both on real and model materials and based on the two above mentioned approaches. Main facilities include (i) a multi-purpose dynamic thermal-mechanical simulator (a GLEEBLE 2000 system with Hydrawedge) capable of multi-stage forging and heat-treatment experiments and (ii) a lab press of 2000 kN (called "Toy Press") equipped with a multi-direction force transducer.

The paper presents some applications of these facilities and relevant simulative techniques to the analysis of bulk metal forming operations such as hot forging of turbine blades and hot rolling of steel plates. After a short overview of the general simulation system for forging process analysis and design, the presentation focuses on the most original aspects of the simulations that concern (i) the evaluation of the force and torque components applied to the dies during forging of complex parts and (ii) complementary aspects of physical and F.E. simulation with particular emphasis on precise replicating, under computer control, of local thermal-mechanical profiles that are predicted by F.E. codes.

2. The Simulation System for Forging Process Analysis and Design

The System (Fig. 1) collects complementary techniques today available for simulation of forging operations, including:

- Finite Element simulation,
- physical simulation of thermal-mechanical operations, and
- model-material based simulation.

2.1. Finite Element simulation

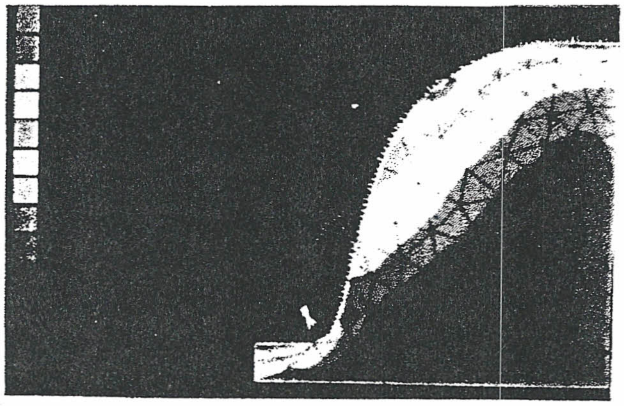
Finite Element simulation is based on commercially available programs, both general purpose and devoted to forming operation analysis. It provides the process designer with detailed information on metal flow and process variables such as strain and strain rates, temperatures of dies and workpiece, deflection of tool surfaces, thermal and mechanical history of metal, textures and load-stroke relationship.

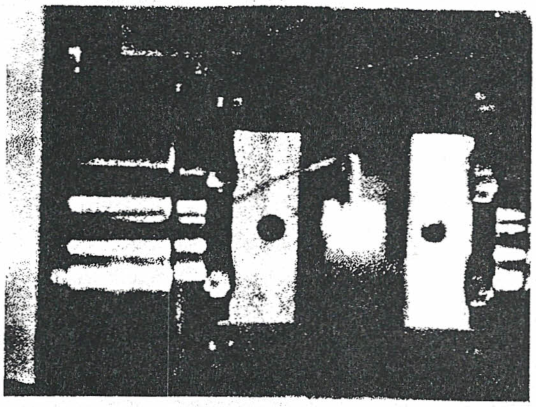
2.2. *Physical simulation of thermal-mechanical operations*

The physical simulation of thermal and mechanical operations is based on the GLEEBLE 2000 Hydrawedge system. The system [3] is a multi-purpose dynamic thermal-mechanical simulator capable of reproducing (under computer control of force, strain, strain rate and temperature) thermal-mechanical phenomena related to several operations and processes, such as multi-stage forging and rolling, welding, heat treatments, casting, powder sintering, etc.

FEM Simulation

prediction of
- metal flow
- temperature (die, workpiece)
- strain and strain rate
- stresses (die, workpiece)
- die deflection
- thermal & mechanical history
- load-stroke relationship
- texture





Thermal-Mechanical Simulation

material data and constitutive model generation

replication in a test sample of thermal and mechanical profiles

selection of appropriate process parameters

Toy-Press Simulation

analysis of
- tool loading system
- cavity filling detects

optimisation of
- billet and preform sequence
- parting line and flash

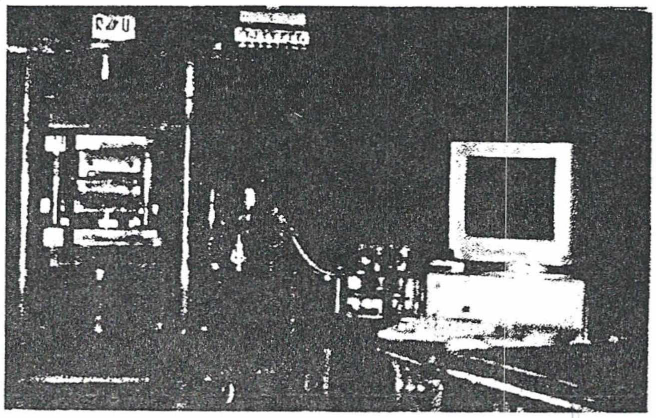


Fig. 1 - The components of the simulation system for forging process analysis and design.

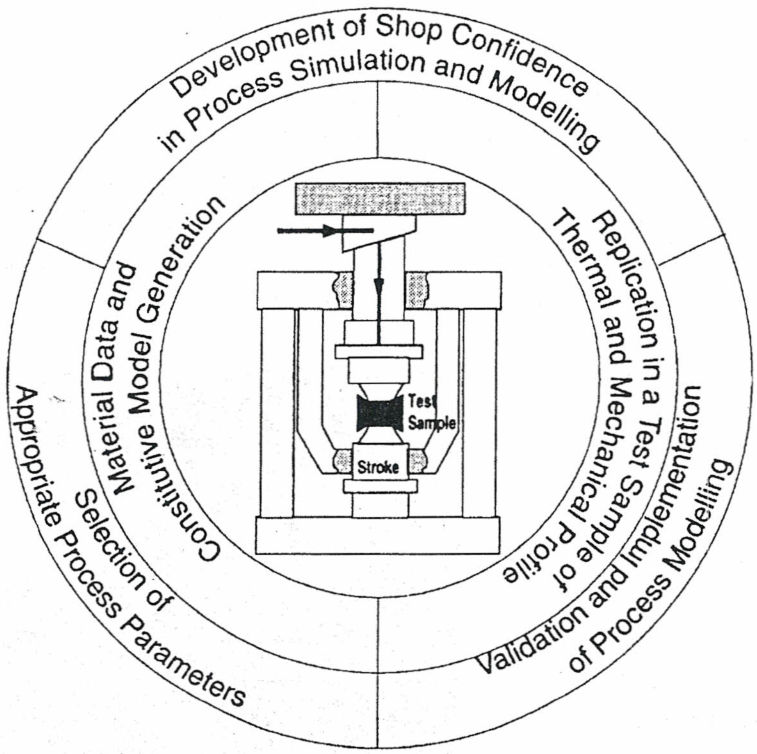


Fig. 2 - Physical simulation of thermal-mechanical operations.

The temperature is measured and controlled by thermocouples or a pyrometer and, during the experiments, compression or tension of samples, heating and heat treatments are all carried out in situ. The system (Fig. 3) characteristics can be summarized as follows:

maximum load	±200 kN
maximum stroke rate	3 m/s
maximum heating rate	10000 °C/s

For the purposes of the projects ongoing at DIMEG in the area of forming processes, main utilizations of theGleeble system are (Fig. 2):

- acquisition of material and interface data and generation of constitutive models, including true stress-true strain curves and workability data,
- replicating in test samples the thermal and mechanical profiles that locally occur in the forgings during the process and that can be predicted by FE codes and
- designing appropriate process parameters through the in situ simulation of the whole thermal-mechanical process.

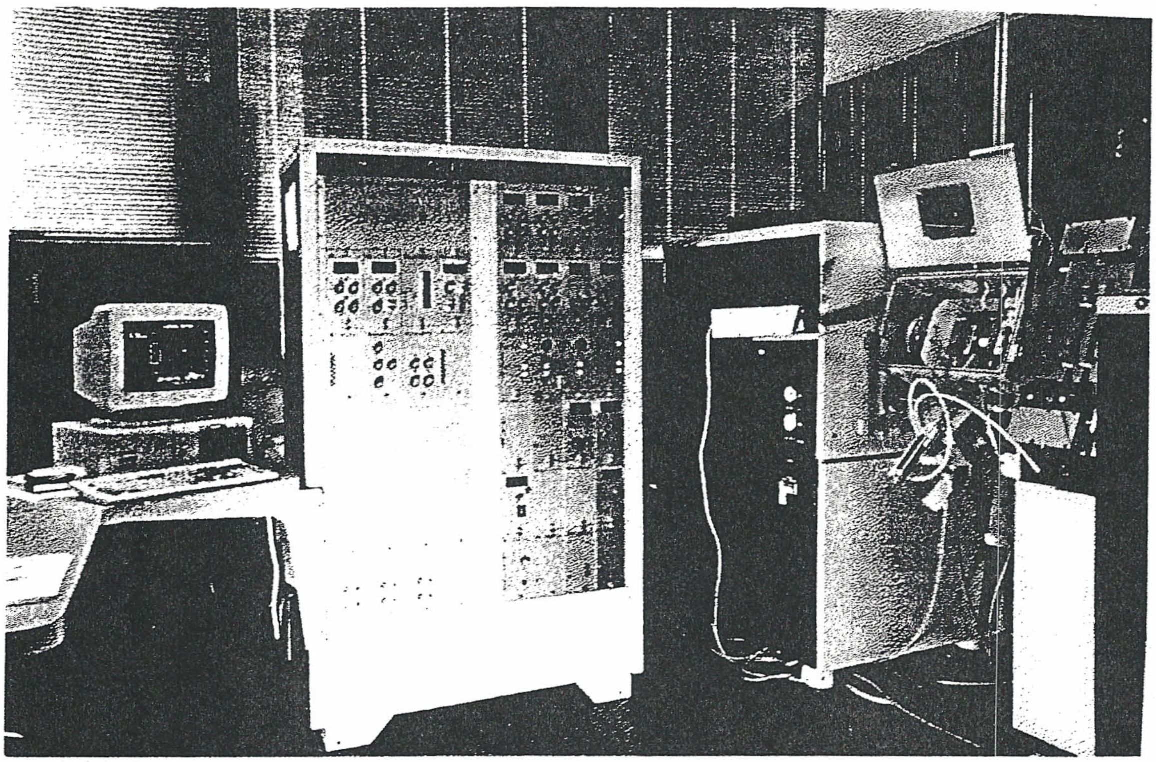


Fig. 3 - Gleeble 2000 system for thermomechanical process simulation.

2.3. Model-material based simulation

This experiment consists in forging model-materials (waxes, plasticine, aluminium and lead) components in a lab press (named "Toy Press" and shown in Fig. 4) equipped with a load cell consisting of a three-plates die-set and a CA multi-component force measuring system [4].

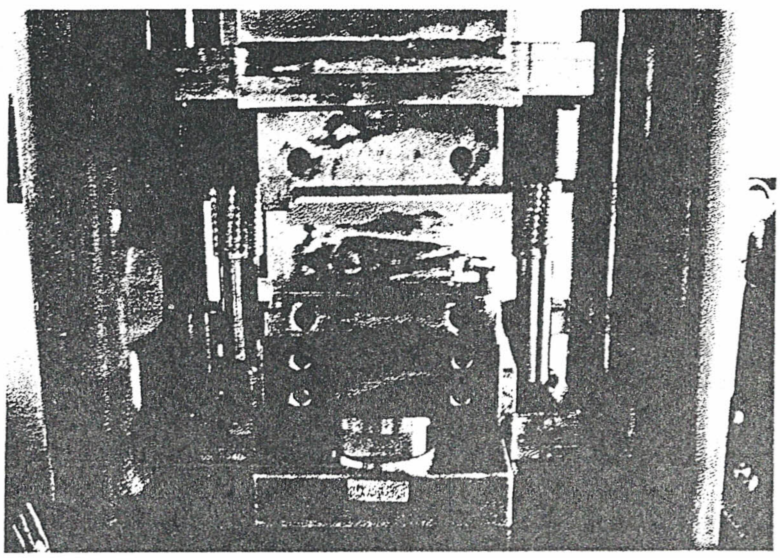


Fig. 4 - The lab press equipped to evaluate the tool-loading system.

The X, Y and Z components of force and moment vector, in a given co-ordinate system, are measured by three force transducers based on piezoelectric sensors. Measuring ranges of the load cell vary with the preload conditions that depend on the load horizontal components to be measured. With preloads of 160 and 0 KN, measuring ranges along the vertical axis are ±40 and ±200 KN, respectively.

The Toy Press is connected to an acquisition system allowing the recording versus time (or die stroke) of the three components (in X-, Y- and Z-direction) of the force acting on each transducer. The acquisition system is able to reconstruct resulting force in X-, Y- and Z-direction, the application point of the resulting force, as well as the moment due to the torque in the X-Y plane and the moment due to the movement of the application point of the resulting force far away from the geometric center of the die set.

The main utilisation of the Toy Press is systematic study of part forging using physical modelling techniques aimed at reconstructing the force system acting in the die set and analysing the flow of the material in order to detect defects in cavity filling and effects of process parameter (such as billet geometry, preforms parting line location and flash design). Different materials can be formed both metallic (e.g. lead, aluminium, etc.) and non-metallic (e.g. wax, plasticine, etc.).

In order to compare results of experiments on model material with industrial forming conditions, the characterization of model material and tribosystem should be preliminary performed. The behaviour of the model material (stress-strain curve, elastic modulus, Poisson ratio) should reproduce, in reduced scale, the behaviour of real material, as well as the chosen lubricant (petrolatum, oil, solid lubricants, soaps, etc.) should approximate the tribological conditions at the die surfaces of the experiment to the real conditions.
The fitting between model experiments and real conditions is performed on the basis of the comparison of results of characterization of model material/model lubricant with results of characterization of real material/lubricant at forming conditions (temperature, strain, strain rate). A geometry factor for dies and preforms, as well as a force factor are determined which allow to perform a scaled test and to make an estimation from results of modelled process to real process.

3. Replicating thermal-mechanical history in multi-stage hot rolling

The aim of this investigation is to physically replicate the entire rolling process, from heat-up, through multiple-stand rolling, to cool-down, on a laboratory scale. The test was performed on specimen (1018 SAE steel) which has an initial height chosen as 25 mm and the final height as 13 mm. The total reduction should be obtained in 3 steps with a constant true strain rate of 20 s^{-1} in the first step and 30 s^{-1} in the second and in the third step. At the corresponding travelling speeds the stroke stops istantaneously at the desired specimen height hitting against the mechanical stop frame.

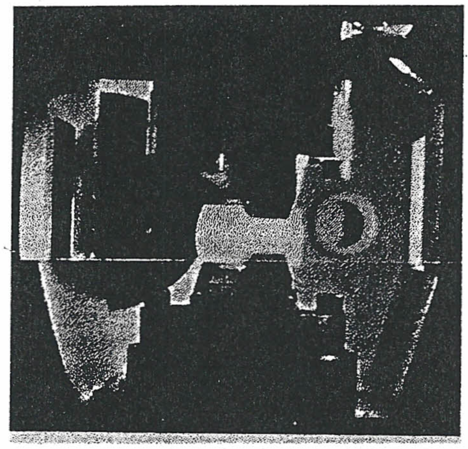


Fig. 5 - Plane strain deformation at 1050 °C in the simulation of multi-stage hot rolling.

The anvils are wedge-shaped (see Fig. 5) in order to establish plane strain conditions in the deformation of square-section specimens.

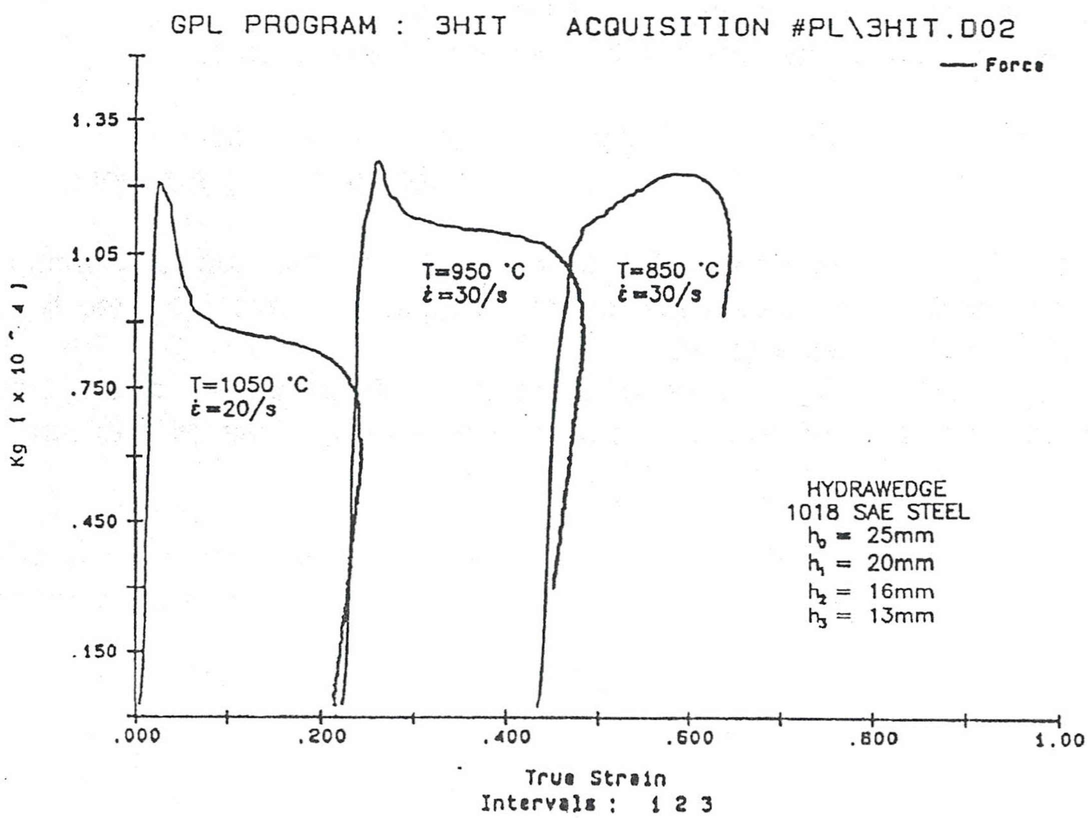


Fig. 6 - Force versus True Strain in the simulation of multi-stage hot rolling.

The temperatures of the specimen before the first-, second- and third-deformation are 1050 °C, 950 °C and 850 °C respectively; the system provides a computer controlled heating of the specimen at the prescribed heating rate during the process simulation using as feedback a Cromel-Alumel thermocouple located at the midspan of the specimen.

Before the next reduction the stroke anvil-deformed specimen-wedge anvil are moved downward of an amount equal to the next reduction. Despite the high travelling speed the amount of strain in each forming step is fine controlled by the mechanical stop of the forming anvil.

The force (or stress), as well as controlled parameters are recorded during the simulation and can be plotted after the simulation is completed (Fig. 6).
Following this approach, it is possible to optimize rolling mill operations without putting expensive production equipment at risk.

4. Evaluating force and torque components during hot forging

The simulation experiments of hot hammer forging of turbine-blades, are aimed at analysing the forces acting in the dies and force application point with the respect to the center of the dies, as well as the influence of the positioning of preforms between the dies on cavity filling and product accuracy.
The model material is plasticine with the following characteristics:

C	=	0.0604	N/mm^2	Strength coefficient
n	=	0.3381		Strain hardening exponent

Solid soap is sprayed on die surfaces in order to replicate lubrication conditions. The geometry factor for dies and preforms is equal to 1 and the force factor has been estimated to be equal to 2800.
In the upper part of Fig. 7 three different steps of the forming of the blade are shown; the diagrams of resulting force components vs. time (or die stroke) are shown in the lower part of the same figure.

Other data available from the test are the moment due to the torque in the X-Y plane as well as the moment due to the deviation of application point of resulting force from the geometric center of the dies.
From the test a movement of this point has been recognized along a direction normal to the axis of the blade; in details the application point is located at 0.5 mm, 14 mm and 20 mm from the center of dies when the die stroke is 16.5 mm, 22.5 mm and 28.5 mm respectively.

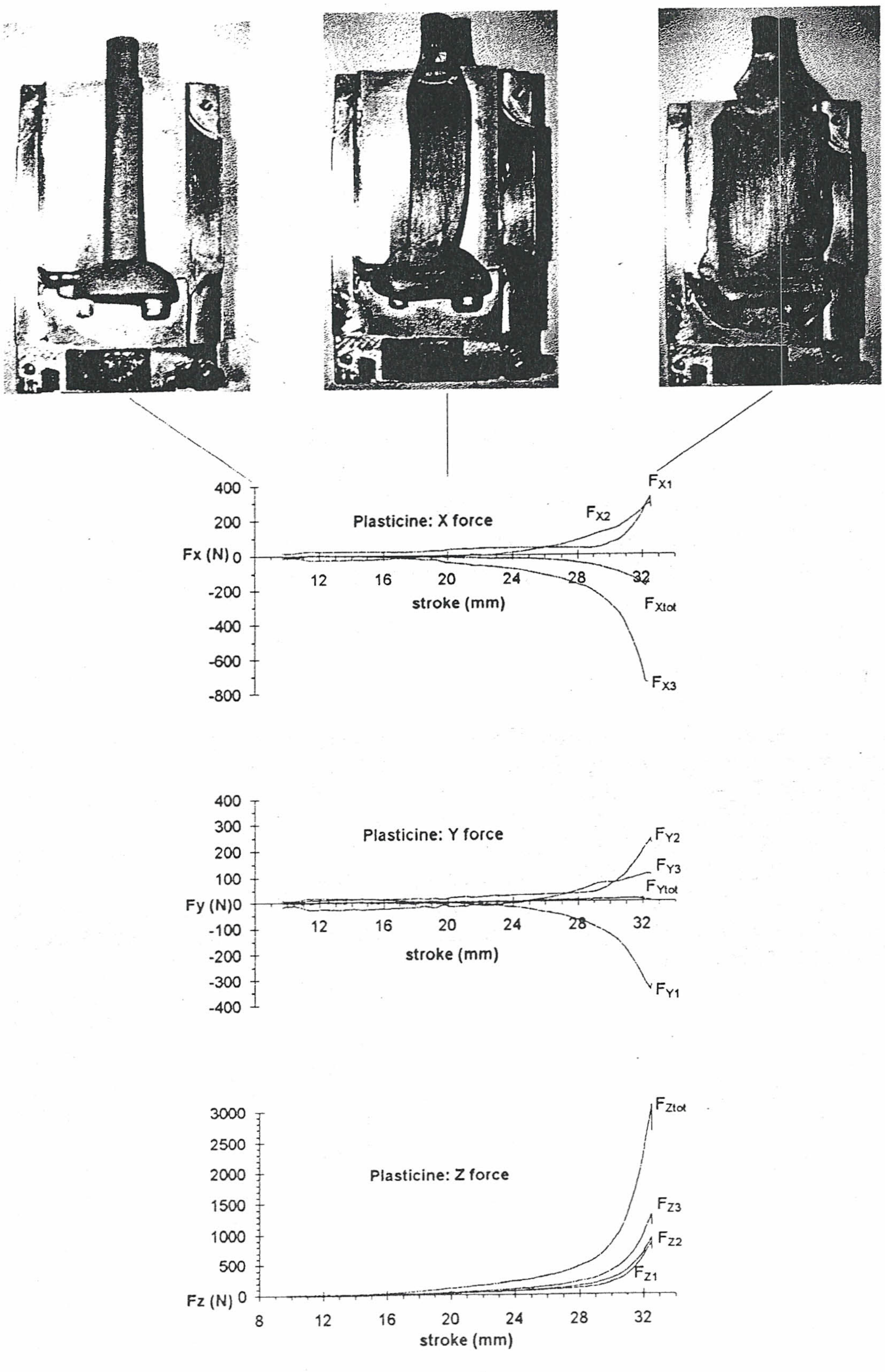


Fig. 7 - Three different steps of the forming of turbine blade using plasticine and the corresponding diagrams of resulting force (X-, Y- and Z-component) versus time (or die stroke).

5. Conclusions

Some recent progress in physical simulation of forging operations has been presented. The paper has illustrated some applications of these techniques in the analysis of bulk forming operations such as hot forging of turbine blades and hot rolling of steel plates. These techniques should be complementary to other ones, such as Finite Element simulation, and they provide powerful tools to investigate forming processes in order to optimize them, improving the quality of the products and saving energy.

Acknowledgements

The work described in this paper is part of the EUREKA research project No. EU-668 "E.F.FOR.T." sponsored by the European Union.
The authors wish to thank Messrs. M. Zanzo and P. Manfredi for the contribution given during the thesis project. The M.U.R.S.T. Ministry of Science and Technology and M.I.C.R.A. Ministry of Industry are gratefully acknowledged for the financial support.

References

[1] Boër, C.,*et al.*; 1986, Process Modelling of Metal Forming and Thermomechanical Treatment, Springer Verlag, Berlin.

[2] Wanheim, T.. *et al.*; 1984, The Physical Modelling of Plastic Working Processes , Proc. of the Int. Conf. on the Technology of Plasticity, II: 1003.

[3] Mandziej, S.T.; 1993, Cold Forging and Related Micro-Mechanisms of Quasi-Brittle Fracture, Proc. 26th ICFG Plenary Meeting, Osaka, Japan.

[4] Meneghello, R.; 1993, Progetto di un sistema di celle di carico per il rilievo di forze e momenti nel processo di stampaggio (in Italian), Thesis Dissertation, DIMEG, University of Padova.