DEVELOPMENT OF A COMPUTER-ASSISTED ENVIRONMENT FOR SEQUENCE DESIGN OF COLD FORGING TECHNOLOGY

P. Bariani*, G. Berti*, L. D'Angelo*, M. Marengo** and A. Rossi*

* Dipartimento di Innovazione Meccanica e Gestionale,
University of Padua, Italy

** Teksid Spa, Turin, Italy

ABSTRACT

Some progress on a research project aimed at designing and developing a computer— assisted environment for the design of preforming sequences for cold forging are presented and discussed.

The main focus is on the "Generate, Test and Rectify" mechanism which controls the sequence design process, as well as on the classification and structure of the rules in the knowledge-based system. Details are given on logic and capabilities of the two modules devoted, respectively, to generate and analyse for suitability the forming sequences for multi-stage cold forging of solid and hollow rotationally symmetric parts. Some application examples end the paper.

Key Words: A.I., expert system, CAPP, cold forging, forging sequence.

1. INTRODUCTION

A remarkable research effort has been recently made to develop process modelling of metal forming, mainly in the area of computer aided techniques. However, in spite of the significant progress in understanding the mechanism of deformation, knowledge of plastic phenomena often is not formalized for practical applications and still presents considerable gaps.

Inadequate knowledge, as well as the inherent complexity in modelling and planning forming operations [1], make process planning for a forged part a domain where knowledge is "expert-like" and comes from experience gained through long practice. Consequently, process planning activities which could take direct advantage from process simulation (such as assessing the feasibility of a funning operation and parametrizing it) are still largely experience based.

The above reasons have substantially retarded the development of process planning systems for forging. Not only CAPP systems for this technology are extremely restricted in number, but the considerable effort to develop CAPP systems in machining and, more recently, to upgrade them to a working industrial tool has not been matched in forming.

Today, the existing prospective tools based on GT classifications of forged parts - a survey is in have not yet formalized for process planning purposes, and the computer driven process planning systems [3-15] - including those based on A.I. techniques - are, at the most, at the experimental prototype stage.

The paper presents some progress on a research project aimed at designing and developing a computer-assisted environment for the design of performing sequences for cold forging [8, 9, 13 and 15], the main focus being on the generative rule-based approach in designing the sequence.

The first part of the paper outlines and justifies the Generate, Test and Rectify (G,T&R) mechanism which controls the sequence design process. The latter part of the paper gives details on logic and capabilities of the two modules devoted, respectively, to the sequence generation and test.

2. THE SEQUENCE DESIGN PROBLEM AND THE "G,T&R" APPROACH

The design of a suitable sequence is one of the most critical responsability in planning a multi-stage cold forging process. It directly influences all the other decisions required before the work planning is completed.

Besides the sequence design, activities pertaining to planning a cold forging process are:

- selecting the machines,
- designing the new set of tools and handling devices,
- estimating tooling and operating costs, and
- determining appropriate machine setting conditions.

According to the criterion of acceptance, an operation sequence can be feasible, realizable, or suitable.

Feasibility of a preforming sequence is an intrinsic feature. It implies that blanks are formed at the different stations without surface or inner defects. Additionally, the sequence does not include unnecessary extra preforming steps.

Realizability pertains to the actual execution of the process by given resources. A realizable forging sequence has to be instantiated for defined presses and handling devices.

Suitability refers to the "goodness" of the sequence design. It matches the technical success and a good economic balance, the latter being dependent, for instance, on tooling and operating costs.

The level of acceptance of a sequence reflects nature and extension of the involved in the design process and determines the design approach as well. While the practicability of a deductive approach in designing a feasible forging sequence is well established [5, 9, 12 and 14], no deductive system is known which is capable of generating suitable sequences. The practice of using a sequence as a basis for improvement when a new suitable forging sequence is required (Figs. 1 and 2) reveals a knowledge of the forging technology that is inadequate to deduce a suitable sequence.

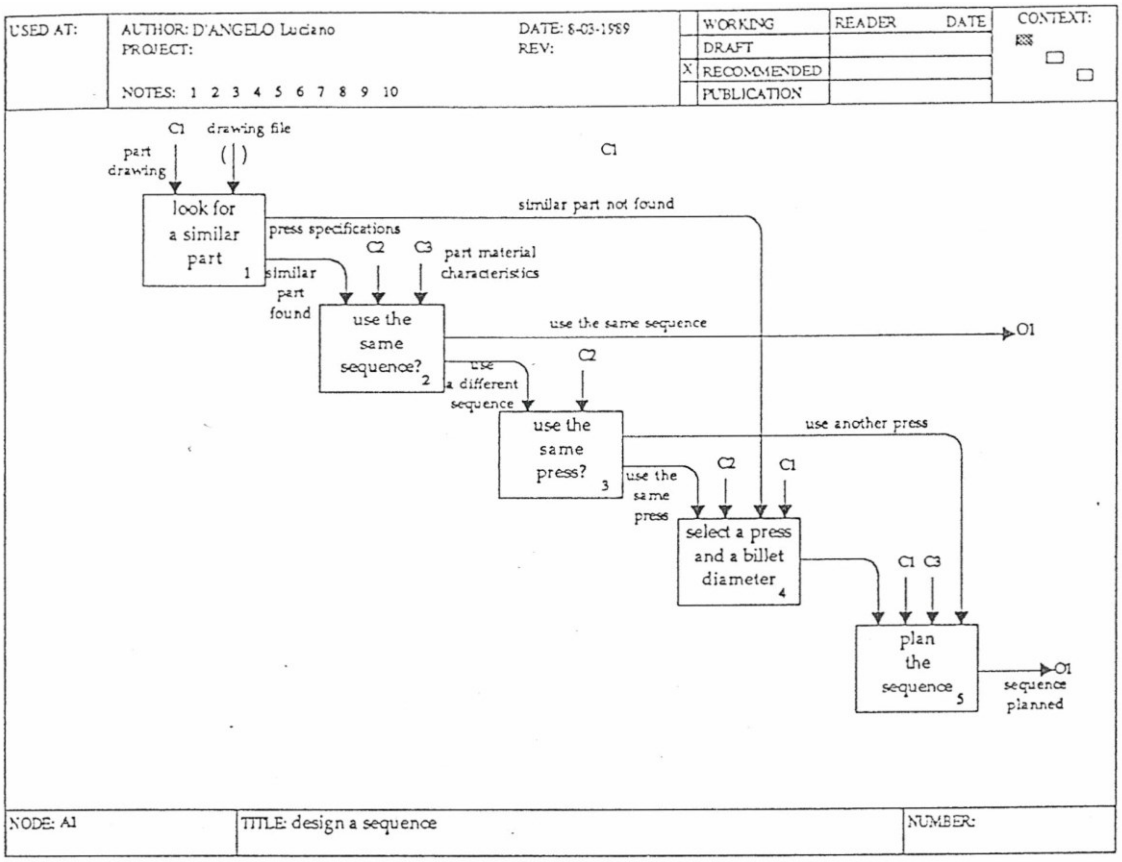


Fig. 1 The design of a cold forging sequence

The G,T&R strategy [16], as other recoursive strategies such as H&T (Hypothesize and Test) [17], provides a non-deductive current-practice based approach for the domain of planning and designing and, specifically, for the problem of designing suitable forging sequences.

As in other guessing methods, the basic idea of the strategy is fairly simple: "Generate an initial solution (hypothesis) and Test it. If the test produces failure, try first to Rectify the solution, and Regenerate it only if rectification is not possible". An automatic sequence design based on the G,T&R approach requires that the fest as well as the rectify subsystem be automatic too.

When applied to the specific domain of the forging sequence design, the hypotheses are the generated feasible sequences; the tests assess realizability and suitability of the hypotheses while the rectification procedure, when invoked, modifies unsatisfactory features of the generated sequence revealed by the testing. Rectification measures are concerned with ordering and grouping forging operations in a different way, modifying operation capabilities, etc. Any rectified sequence mantains the main features of the unrealizable or unsuitable sequence, such as material and geometry of the forged part, billet diameter and, to some extent, mechanical characteristics of the finished part. On the other hand, number of forging stages and load peaks at the different stations usually change. Regeneration implies a more substantial change of the sequence, involving modification of geometry and mechanical characteristics of the forged component.

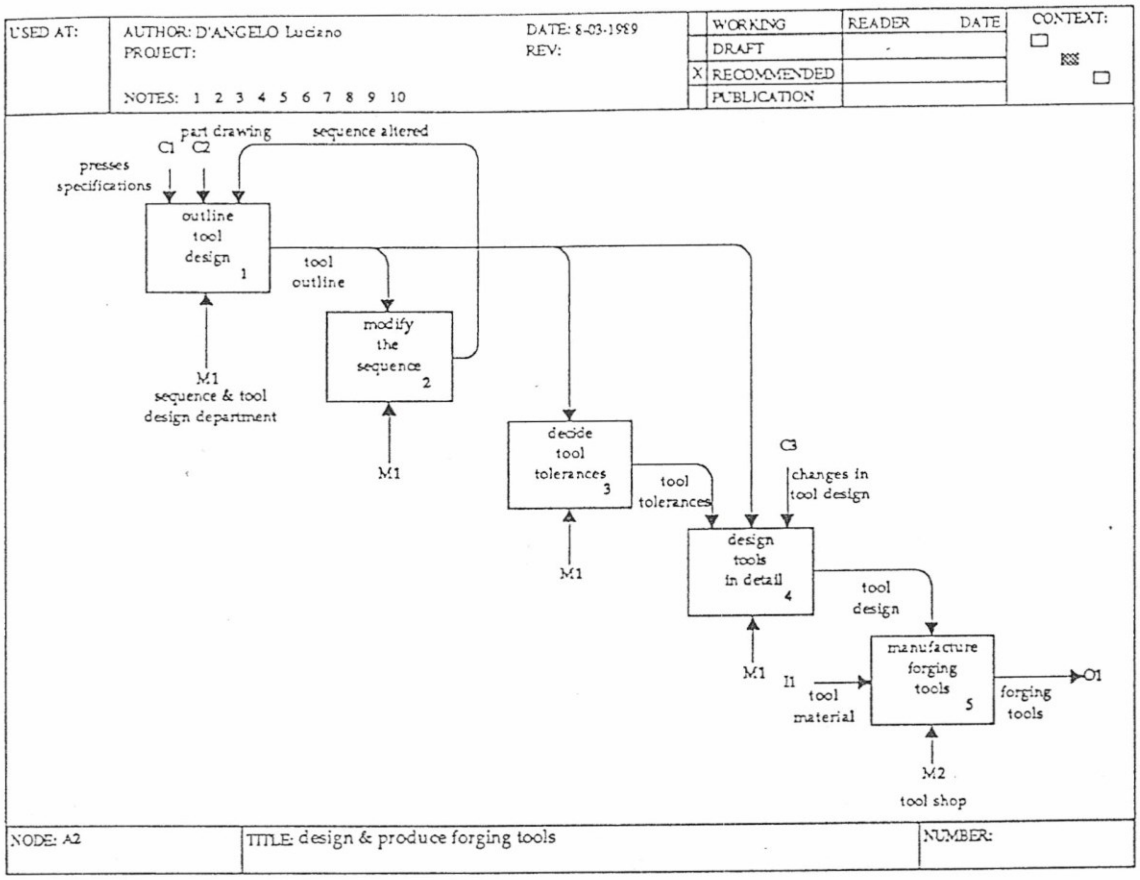


Fig.2 The design and preparation of forging tools

One important result of the approach is that it is possible to keep separate the knowledge domains pertaining to generation, testing and rectification. This separation reflects nature and organization of current knowledge of cold forging and, additionally, permits the three functionalities to be developed independently.

At the time of writing, an experimental system consisting of the generation and test components of the G,T&R system have been developed and related procedures formalized in a rule-based representation. The system is capable of generating feasible sequences for solid and hollow rotational parts, as well as testing sequences for suitability on the basis of load-peak and energy consumption distribution at the different stages and effective strain accumulated in the forged product.

A description of the approach to generate feasible sequences and test them automatically is given in the following. The main focus is on the classification and structure of the generation and testing rules, rather than on an overview of these rules and their representation. Some application examples illustrate the capabilities of the system at the present stage of development.

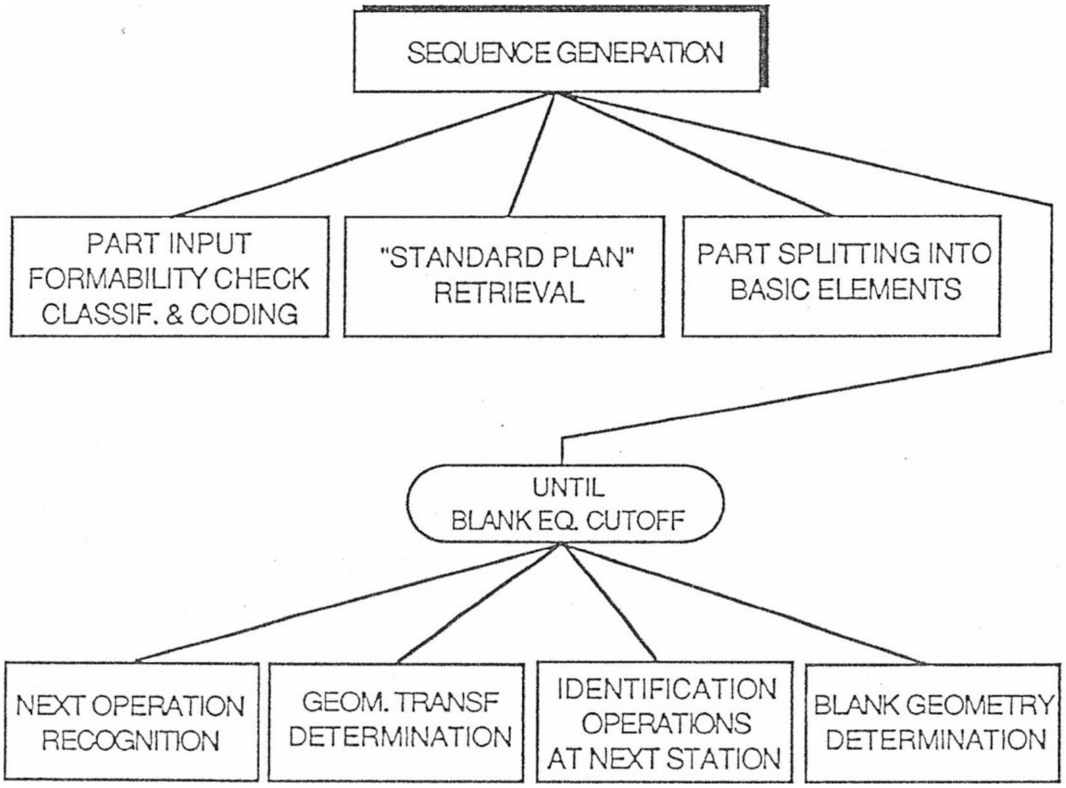


Fig. 3. Basic structure of the sequence generation procedure.

3. GENERATION OF THE SEQUENCE

The basic structure of the sequence generation procedure is shown in the diagram of Fig. 3 which represents the steps (hereafter called subtasks) to be processed when a complete preforming sequence is generated. Each subtask involves a number of decisions to be made before the next subtask is undertaken. Since the decision logic is formalized in terms of rules, the diagram indicates the criterion in grouping the rules, as well as the order in which the groups of rules are consulted.

The activities pertaining to the first subtask are the input of the material and geometry of the forged component, checking it for formability, and then classifying and coding of the shape features of the part.

Currently, the method of describing the part geometry is that proposed in [5]. The workpiece is considered as made up of a combination of simple volumetric primitives axially positioned. The two basic primitives -the chamfered cylinder and the convex/ concave curve- can be either positive or negative, thus permitting the geometry of all solid and hollow rotationally symmetric components to be accurately represented, at least in respect of the sequence design problem. Afterwards, the input geometry is checked for unformable form features, such as outside and inside undercuts, too thin or too long holes, etc (see for instance [18]).

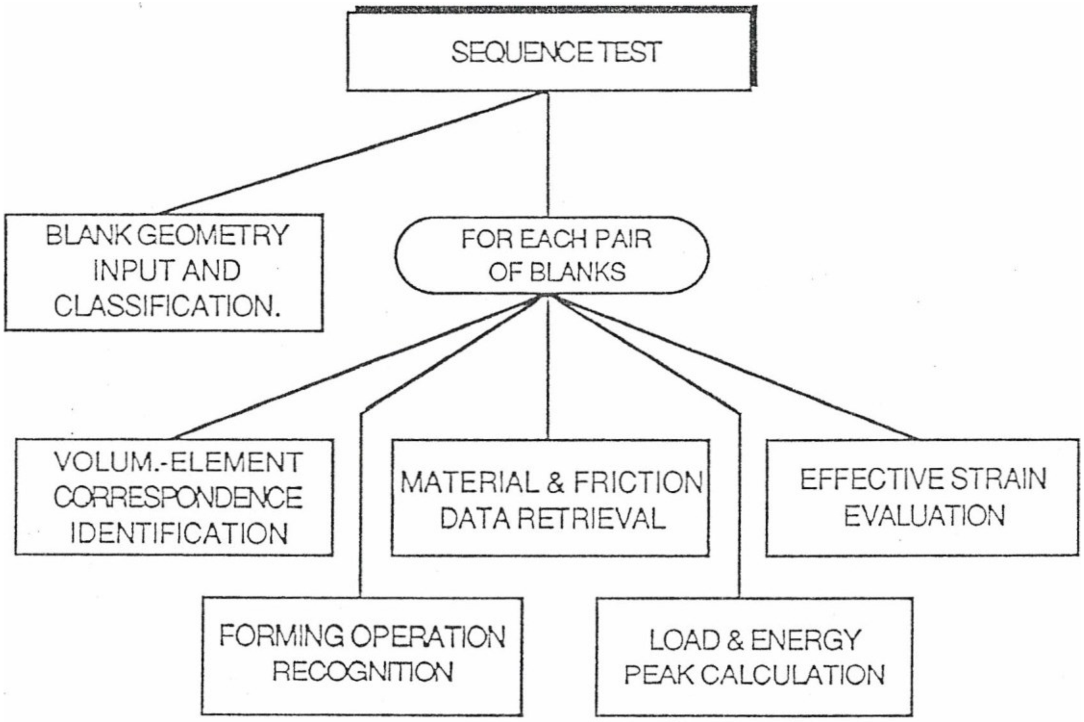


Fig.4. Basic structure of the sequence test procedure.

The part classification and coding used is aimed at accessing the files containing the sequencing rules corresponding to the particular class of the part, which include rules for selecting the billet diameter range suited to that family of parts, as well as the order and combination of the different cold forging operations. The classification system used is substantially based on that proposed by Wagener [19 and 20]. This system covers the entire range of rotationally symmetric cold forged parts and groups components into families according to dimensional and shape attributes directly related to forming operations.

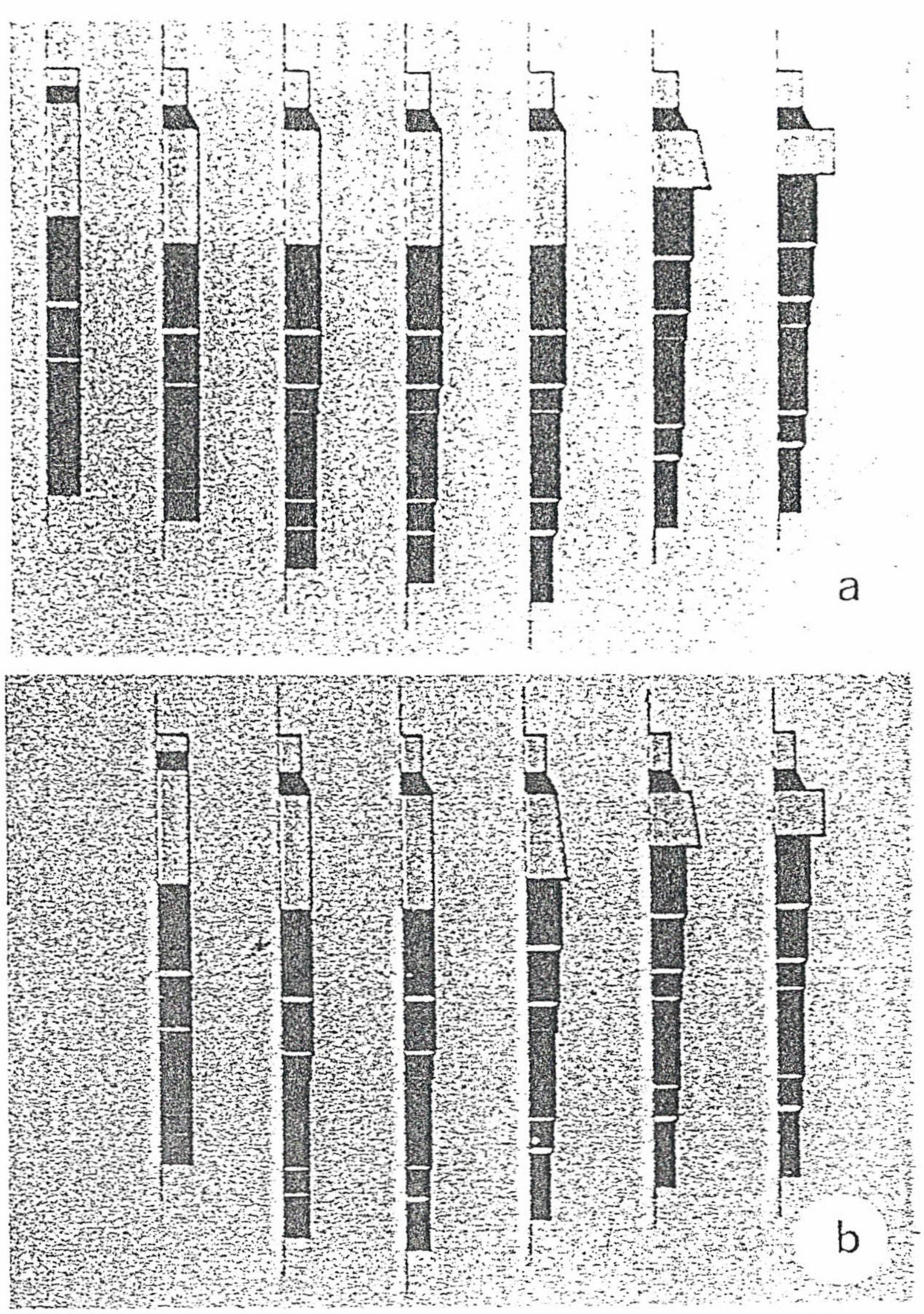


Fig. 5 Feasible (a) and rectified (b) sequences for a solid part.

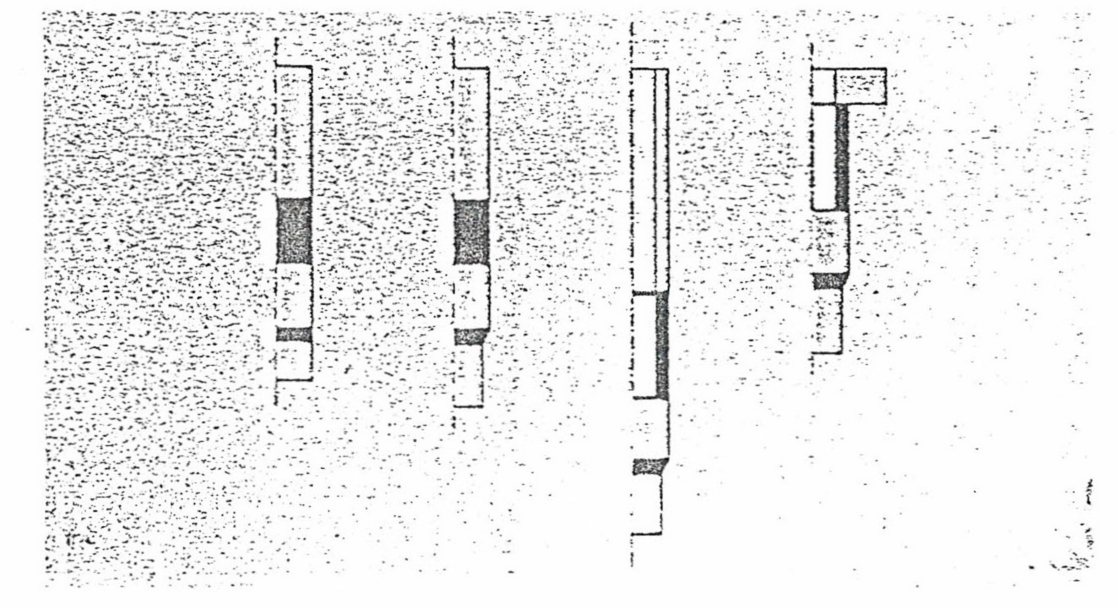


Fig. 6 Four-stage sequence for a hollow part.

When the second subtask is undertaken, the file of the sequencing rules suitable for the specific part family is accessed. The appropriate range of the wire/ billet diameter is provided, together with a list including all the possible principal operations related to that class of part, ordered and grouped according to sequencing and combination rules. Such a list of operations is intended to inform the user only of the general sequencing rules that will be utilized to generate the real sequence for the component. Based only on the class of the part and not on the specific geometry of its form features, this list merely indicates the precedences that each of the principal operations takes over the remaining ones and shows which among them can be performed simultaneously. This sort of concise standard plan can be modified by the user, any change being temporary and, therefore, affecting only the current generation process. Alternative "standard plans" can be stored for the same part family.

Before the control moves to the next subtask, the user has to confirm the plan, standard or modified, and choose the billet/ wire diameter into the recommended range.

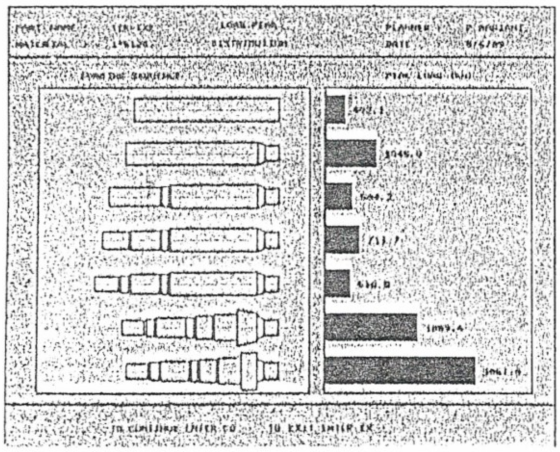
The third subtask consists in completing the automatic analysis of the finished part geometry that began at the first stage with the formability check, classification and coding. At this stage, the geometry is split into basic elements (simple cones, cylinders or curves; solid and hollow), this permitting a representation of the part geometry more suitable for the next subtask than the higher-level representation in the CAD system. Afterwards, the component is oriented and the cutoff length is calculated.

The fourth subtask is the most decision-intensive procedure and this generates the detailed sequence; that is the number of the preforming stations and geometry of the corresponding intermediate steps. The direction of the generative process is the reverse of the forming sequence with the initial and final states in the generation path being, respectively, the final cold forged component and the billet or wire cutoff.

As shown in the diagram of Fig.3, the system works by modifying the basic shape elements until they take on the geometry of the corresponding portion in the wire cutoff. The decision logic directing this transformation has been divided into the following steps:

Step 1 Recognition of the forming operation to be performed as the next operation on each of the elements. Information on the geometry of the element and its location in the list of elements (which the blank has been split into) is processed by a "pattern recognition" logic procedure based on more than fifty decision tables. The next operation is identified for the main elements and for transitional elements, which connect the main elements to make the material flow pattern and cross-section change more continuous. A transitional element "belongs" to an adjacent main element, to which it is automatically assigned on the basis of particular rules included in the above decision tables.

It is worthwhile to notice that this operation identification logic is independent of the particular class of the component.



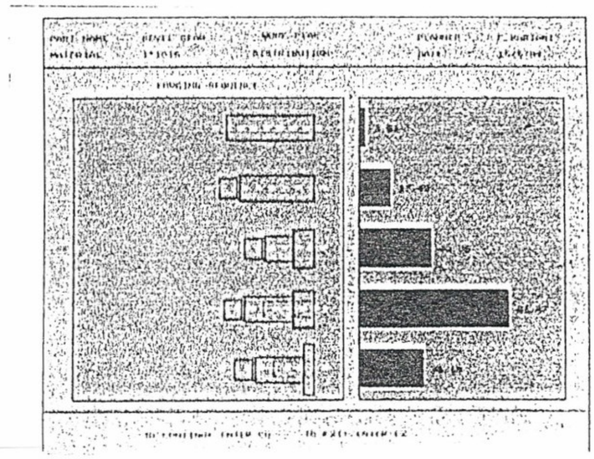
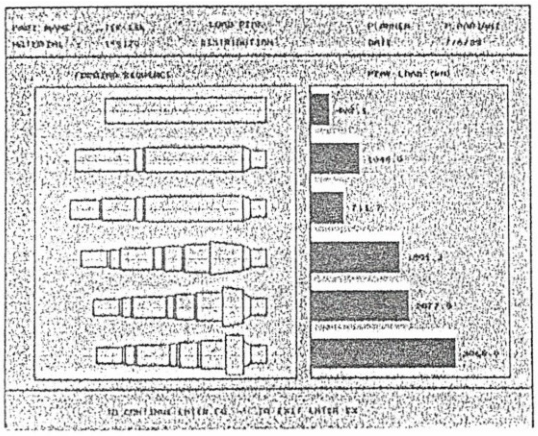


Fig. 7 Peak loads for the sequence of Fig. 5a.

Fig. 9 Energy peak distribution.



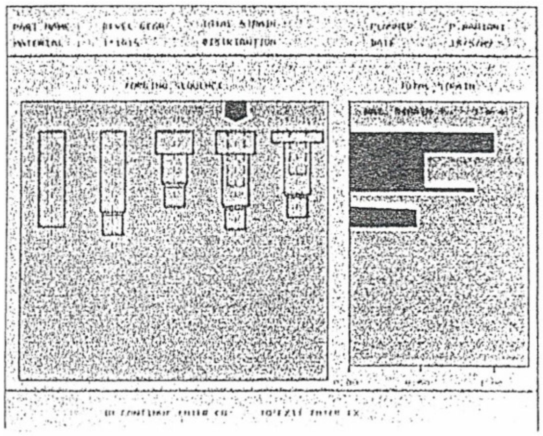


Fig. 8 Peak loads for the sequence of Fig. 5b. Fig. 10 Effective-strain distribution.

<u>Step 2</u> - Determination of the geometric transformation to be applied to each element according to the capabilities of the forging operation identified at the previous step. The capabilities of the operations are represented in the form of a set of rules for both single and multiple operations. In the latter case, that is when the amount of deformation by upsetting or extrusion has to be allotted to different stations, such rules permit the sequence of these operations to be determined.

Guidelines and formulas for determining upsetting and extrusion sequences are given in a number of forging handbooks (e.g. [19]). They have been translated into rules and successfully applied to the operation sequencing problem in [5] and [14].

<u>Step 3</u> - Identification of the basic elements to be transformed at the next station. This decision is made on the basis of the rules for sequencing and grouping different operations, that is the rules relevant to the particular class of the component and accessed after coding. The comparison of the operations recognized as the next ones to be performed within the list of the ordered and grouped principal operations (which corresponds to the component family) leads to the identification of the main and transitional elements to be transformed at the next forming station.

<u>Step 4</u> - Determination of the blank geometry. After shape transformation, the elements identified at the previous step are stacked up together with the remaining non-transformed elements to build up the blank geometry for the next forming station.

3. TEST OF THE SEQUENCE

This section outlines the automatic procedure developed for the sequence test—stage and specifically devoted to evaluate the load peaks at the machine stations and the effective strain distribution accumulated in the workpiece. Details are provided concerning the steps involved in the procedure and its working principle.

Independently of its use as a module for testing feasible sequences integrated into the G,T&R system or as a stand-alone analysis procedure, the program consists of the following steps:

(i) blank geometry input and classification;
(ii) volumetric-element correspondence identification;
(iii) forming operation recognition;
(iv) material and friction data input;
(v) load-peak calculation, and
(vi) effective-s train distribution evaluation.

A diagram showing the basic structure of the sequence test procedure is given in Fig. 4.

In step (i), the program accesses the data files describing the geometry of the blanks corresponding to each stage of the proposed sequence. The blanks are then automatically classified and coded on the basis of the inner basic-shape to distinguish solid blanks, blanks with cavity (single or double, stepped and non stepped) and with a through bore. Finally, the volumes of the single blanks are compared to evaluate the maximum deviation from the volume constancy.

In step (ii), the program analyses automatically the pairs of blanks corresponding to adjacent stations. For each pair, the blank geometry is split into elementary volumetric elements and the correspondence between these elements in successive forming stages is then established. In finding the corresponding elements, the maximum deviation from the volume constancy calculated at the previous step is taken into account. At this stage, piercing operations and the related geometric parameters are identified.

Step (iii) of the program is devoted to the automatic recognition of the forming operations performed at each station of the machine together with the related deformation data. To this end the deformation involved in the corresponding volumetric elements is processed by a "pattern recognition" logic based upon more than twenty decision tables. The operation responsible for the deformation is identified among a number of individual operations including no-operation for identical corresponding elements in adjacent workstations. The following are identified:

- operations which contribute to the load peak, such as rod extrusion, can extrusion and hollow extrusion, upsetting, etc;
- "ancillary" operations, without any contribution to the peak load, such as the operation carried out on the metal trapped at the die zone of the rod extrusion;
- operations which cannot be performed on multi-station cold forging machines.

At step (iv), the program accesses data files to calculate the material current flow stress and the frictional resistance at the material-tool interface. The strength coefficient and the strain-hardening exponent of the power law which approximates the material true stress-true strain curve are stored, together with the shearing resistance, the latter being used to calculate both shearing and piercing load peaks. In the same data file, the friction coefficient values are arranged corresponding to the workpiece material, to the lubrication and forming operation and, for operations such as the hollow extrusion, to the particular tool- workpiece interface.

The load peaks at the forming stations are then calculated on the basis of the recognized operations, the relevant deformation data, the material flow stress and friction coefficient.

Lastly -step the effective-strain distributions accumulated in the blanks at the different stations are evaluated. In calculating the strain, only homogeneous deformation is taken into account in determining the total effective-strain, the contribution of the redundant deformation being neglected.

4. APPLICATION EXAMPLES

In order to illustrate the capabilities of the system at the present stage of development, examples are given of the output obtained from generating and testing some forging sequences for two work parts.

Figures 5a and b show two sequences for the same solid part; two different colors are used to distinguish adjacent basic elements.

The first sequence is a feasible sequence which results from the generation stage. It consists of seven stages; reducing, extrusion and upsetting operations are performed at different stages and the deformation by upsetting is allotted to two stages. The latter sequence (Fig.5b) results from a rectification procedure. The rectification measures are:

- combination of reduction and extrusion at the second stage,
- combination of forward extrusion with the first upsetting operation at the fourth stage, and
- allotting the deformation by upsetting to three stages, as a consequence of a lower upset ratio.

Figure 6 shows the four-stage sequence generated as initial hypothesis for a SAE1015 steel bevel gear.

The distribution of the peak loads at the shearing and forming stations are shown in Figs. 7 and 8 for the sequences of Fig. 5a and b, respectively. Figures 9 and 10 illustrate for a regenerated sequence of the bevel gear of Fig. 6 the energy peak distribution and the effective strain accumulated at the fourth stage.

5. CONCLUSIONS

A prototype of computer-assisted environment for the design of preforming sequences for cold forging has been developed.

The design approach is based on the G,T&R strategy and the consequent separation of generation of feasible sequences from test for suitability.

At this stage, the system is capable of generating feasible sequences for cold forging of solid and hollow rotationally symmetric parts and then test sequences for suitability on the basis of load-peak distribution in the different forming stages, as well as the effective strain accumulated in the blanks and the finished part.

Further developments are taking place both to extend the scope and operations currently covered by the generate and test components of the system and to design and develop the automated mechanism for the rectification and regeneration of the sequences.

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