JMEPEG (2003) 12:646-652

Development of Expert Systems for the Design of a Hot-Forging Process Based on Material Workability

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(Submitted 27 June 2003; in revised form 23 July 2003)

Most of the time (and cost) involved in planning hot forging process is related to activities strongly dependent on human expertise, intuition, and creativity, and also to iterative procedure involving extensive experimental work. In this paper, the development of an expert system for forging process design, which emphasizes materials' workability, is discussed. Details of the forging process design expert system, its basic modules, design and implementation details, and deliverables are explained. The system uses the vast database available on the hot workability of more than 200 technologically important materials and the knowledge acquired from a materials' expert. The C Language Integrated Production System (CLIPS) has been adopted to develop this expert system. The expert system can address three types of functions, namely, forging process design, materials information system, and forging defect analysis. The expert system will aid and prompt a novice engineer in designing a forging process by providing accurate information of the process parameters, lubricants, type of machine, die material, and type of process (isothermal versus non-isothermal) for a given material with a known specification or code and prior history.

Keywords C Language Integrated Production System (CLIPS), hot forging process, materials workability

1. Introduction

In the materials science area, expert systems are being developed to automate the design process to achieve quality products. Development of aluminum alloy design inventor (ALADIN),[1] an expert system for aluminum alloy design and welding advisory system for process selection (WASPS),[2] an expert system to decide the choice of welding processes are two common examples. Knowledge-based expert systems are also being developed for various other applications like forging process design to precision forged parts and dies from machined parts,[3] the risk of cold forging defect analysis using expert system,[4] and intelligent knowledge based system (IKBS) for the design of forging dies.[5]

The forging process design involves two distinct aspects: one is geometry related, and the other is controlled by the material behavior. In any forging process design, the material workability need be optimized as a priority to manufacture defect-free (both micro and macro), high-quality products. In the past, most of the research emphasis in the forging process design related to expert systems has been directed toward geometry-related aspects, which involve forging die design. Hardly any work has been reported on the material behavior optimization part. The aim of the present investigation is to develop an expert system for forging with emphasis on the materials workability and its optimization. Such an expert system will aid a novice engineer in designing the forging process, which is hitherto done by expensive, and time-consuming trial and error techniques.

The expert system described in this paper is called FORGEX and has been designed such that it uses the same knowledge for the following multiple functions:

- Forging process design
- Material information system
- Forging defect analysis system

The first part of the expert system that gives forging process design information has been built over the material information and rule bases for the selection of lubricants, die materials, type of forging machine, and isothermal or nonisothermal process. The second part of the system delivers information on the material, like the atomistic mechanisms, grain size ranges, and instability manifestations, which can be used for any kind problem involving microstructural development during forging. The third function of this system is for forging defect analysis, which identifies a defect, analyses its origin and gives a remedy.

Hayes-Roth describes[6] one of the critical ingredients in the typical AI success is multifaceted intelligence; i.e., the system should comprise of many components, exhibit many functions and support many tasks. Further, the necessity of using the proven AI techniques in various aspects of development of the expert system is discussed. One of the suggested new approaches to the AI research is that the knowledge base in the system should be used for multiple functions. In the present investigation, proven AI techniques are used to build the expert

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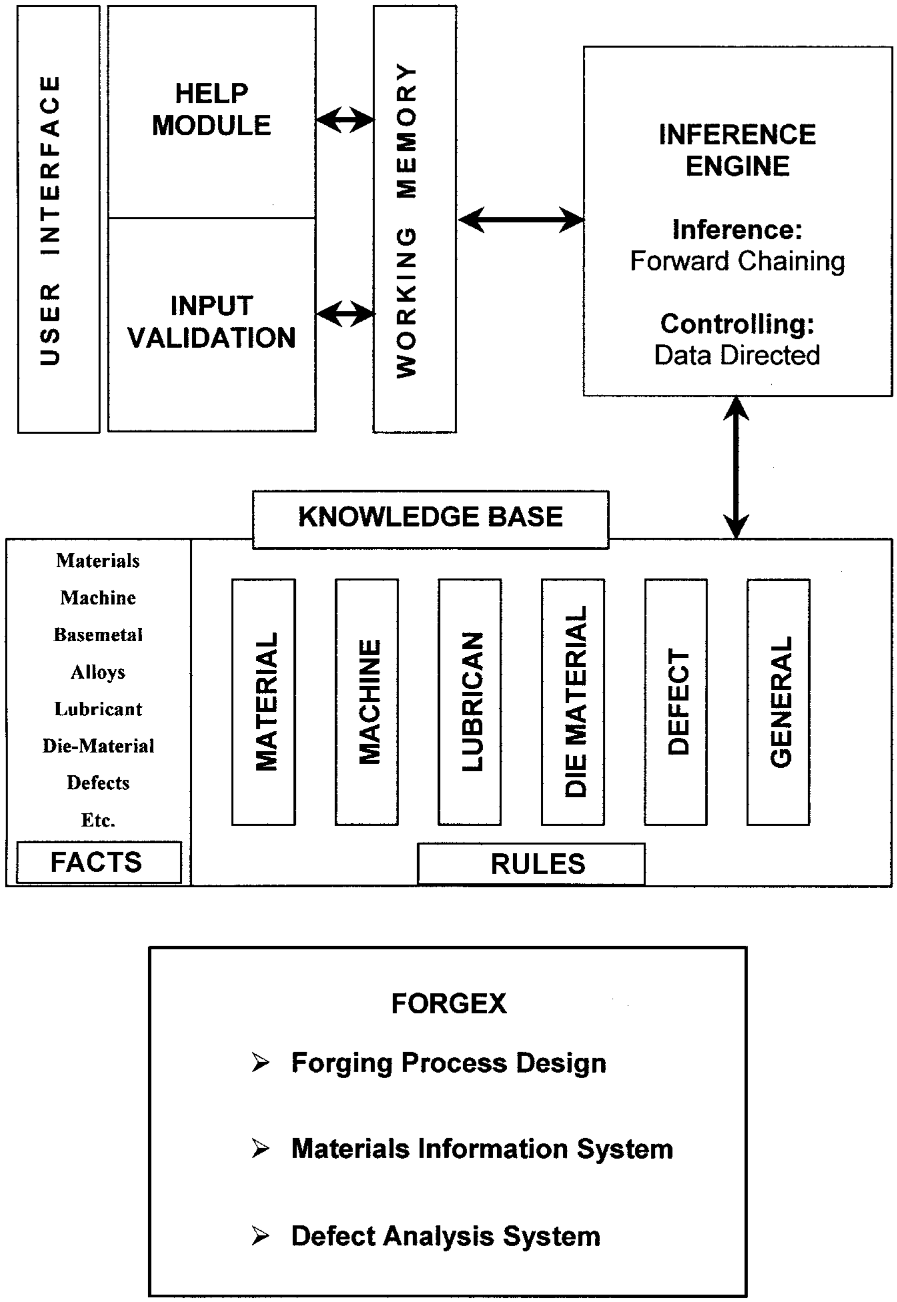

Fig. 1 Modules for the forging expert system FORGEX

system and the knowledge acquired is represented in such a way that it can be used for many functions.

2. Expert System Development

In any expert systems development, the most important aspect is to find an expert in that specific domain. The expertise here does not mean just possession of knowledge or qualification but involves problem solving skills that need be sharpened in a particular domain. To accomplish a reasonable system, expertise on forging process design, knowledge about material behavior, and ability or expertise to use the knowledge to solve problems, are all necessary. The Processing Science Group, Department of Metallurgy, Indian Institute of Science, Bangalore, India, have been doing research on materials hot workability, and this expertise is the basis for the expert system FORGEX described here. Further knowledge on the domain area was acquired from various journals, textbooks, handbooks, literature, etc. Among these knowledge sources, most of the material hot workability data are acquired from the reference book entitled "Hot Working Guide: A compendium of Processing Maps."[7] Success of any expert system highly depends on the quality and the quantity of the relevant knowl-

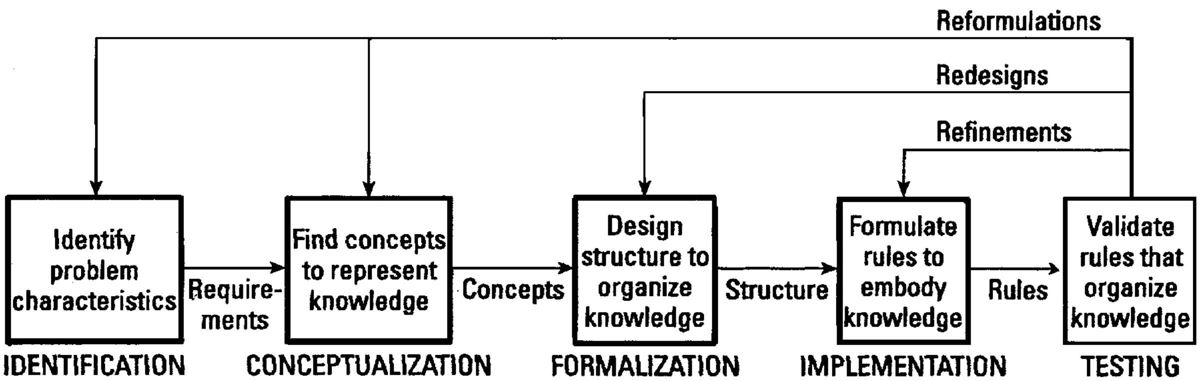

Fig. 2 Stages of knowledge acquisition

edge, and also the way in which these are represented. The schematic diagram of the FORGEX system is shown in Fig. 1.

2.1 Knowledge Acquisition

Knowledge acquisition is defined as "the transfer and transformation of potential problem-solving expertise from some knowledge source to a program."[8] FORGEX has been designed to help the novice in three ways as shown in Fig. 1. First, the system handles the forging process design issues; second, it acts as a material information system and thirdly as a forged product defect analysis tool. To address all these issues, the system has to possess the knowledge about all the above three aspects.

Knowledge acquisition is generally done through interviews with experts and from other sources by the knowledge engineer (or) by using the domain specific automatic knowledge acquisition system, if available, which consists of programs used by the expert. These programs are designed to ask a series of questions to the expert on the basis of whose answers the knowledge engineer builds the basic knowledge base. MOLE[9] is a knowledge acquisition system for heuristic classification problems, such as diagnosing diseases. Several other programs like SALT[10] and META-DENDRAL[11] are used to construct the rules automatically. Since FORGEX is a multifaceted intelligent expert system, knowledge from the expert as well as from various other sources needs to be acquired. The knowledge acquisition here is very complex and has to be done through interactions with the expert to have a good knowledge base. Various stages in the knowledge acquisition are illustrated in Fig. 2. Most of the times, the expert's skills in solving the actual industrial problems were acquired through discussions while knowledge from other sources was acquired and validated using a domain expert.

The important parameters in the hot-forging process design are

- temperature and strain rate window for "safe" (without defects) processing,
- lubricant to be used,
- machine in which the forging has to be done,
- material in which the die has to be made, and
- type of process whether isothermal or non-isothermal forging

Knowledge about the safe hot-working window was acquired from a reference book *Hot Working Guide: A Compendium of Processing Maps*.[7] This book contains the processing maps for a wide range of materials, and these are developed on the basis of the data generated and analyzed at the Processing Science Laboratory, Indian Institute of Science. The information in this book is a testimony to the validity and consistency of the approach and to its applicability to the processing of very complex commercial materials. For more than 200 materials, the flow stress data and the information about the optimum processing parameters are available. The important knowledge relevant to designing this expert system includes the following items:

- The material code, material composition, flow stress data, maximum grain size, safe hot working window for both temperature and strain rate, alert regimes to be avoided, hot working mechanism, and the optimum processing parameters constitute the important information about the materials.
- Details about the available industrial lubricants for the hot forging effective at various temperature ranges were acquired from the expert.
- Available machine types used in forging industries and their speeds (strain rate) were also acquired from the various knowledge sources with the help of an expert.
- The material used to make the die for material wise was collected from the handbook.[12]

Apart from the knowledge acquired from other sources, the knowledge elicited from the expert gave a complete picture about how to classify or group the information and which-contributes-to-what-conclusion and so on.

As in any expert system development, the main bottleneck is the knowledge elicitation from a domain expert since this is a time consuming process. In this system, through a series of lengthy and intensive interviews and discussions with the domain expert the knowledge elicitation was done. The acquired knowledge was well documented in the form of the every-day language.

2.2 Knowledge Representation

Knowledge representation is concerned with the way in which information might be stored and associated in the human brain, usually from a logical perspective (not biological). Knowledge base was extensively indexed and made content addressable, so that any system using it can control the way in which different pieces of knowledge were activated without having to know exactly how they are stored. Sufficient care has to be taken to organize and integrate different pieces of knowledge from the problem solving point of view. The knowledge representation used here is a symbolic representation, which helps in nonnumeric computation in which symbols and symbol structures could be constructed as standing for various concepts and relationship between them.

The main knowledge base components of this system are (1) fact base, which represents the initial state of the problem, and (2) rule base, which contains the operators that can transform the problem state in to a solution. The inference engine matches these facts against the rules to see which rules are applicable. It works in a cyclic fashion as follows:

- Match the facts against the rules.
- Choose which rule instantiation to fire.
- Execute the actions associated with this rule.

2.3 C Language Integrated Production System Environment

The knowledge representation language used here is C Language Integrated Production System (CLIPS), a programming language developed[13] at NASA's Johnson's space center in the mid-1980s. This easily available public domain software and is well documented.[14] CLIPS gives a lot of flexibility by allowing foreign function calls and is portable across various operating systems. It borrows all the features from earlier languages like List Processor (LISP) and PROgramming in LOGic (PROLOG) and adds the unique facility of combining rules with objects. The CLIPS developer environment is Windows-based, which provides a good debugging facility. Further, during running of the program, the activities can be viewed in separate windows, which gives transparency to the system so that the decision-making can be traced. Further, CLIPS has the advantage of giving priority in terms of fixing salience values to the competing rules whereby rules with the highest salience value will fire. Thus the language provides the facility to control the sequence of rules to be fired.

3. Results

FORGEX was developed on the Windows 98 platform using the CLIPS 6.2 Windows version on a Pentium II PC with 128 MB RAM. However, a lower version CLIPS can be loaded on even a DOS-based low-end PC. The code written for one platform can be used to run in the other operating system as well.

Initially all the templates and general functions, which are defined for various purposes, are loaded in to the working memory. The next step is to load the relevant rule base, i.e., after getting the base metal detail the corresponding rule set and the functions related to that are loaded to save the working memory space. The sequence of the functioning of FORGEX design is shown in Fig. 3. The following sections describe the output of the expert system for first functionality of the system.

3.1 Materials Information System

Case 1. Material code is unknown, alloy class is known, and composition is unknown. In this case, the knowledge about that particular alloy system is recommended, which is shown in Fig. 4.

Case 2. Material code and prior history are known. This is a straightforward case that tries to match the user input with the system facts, and then the materials information details are delivered.

Case 3. Material code is not known, composition is known, and prior history is known. In this case, the user does not know the standard material code, but the composition of the material is known. The system helps the user to enter the percentage value of the alloying elements based on the alloy system. If the user input composition matches with the material in the system, the output is delivered; otherwise the closest match is found and for that the output is delivered.

Case 4. Material code is known, and prior history is unknown. In this case, the user knows the material code but not the prior history; the system deduces the prior history from the initial shape of the material, if the user gives it. Output delivered for Case 2, Case 3, and Case 4 are given in Fig. 5.

Case 5. Material composition is unknown, and processing details are known as beta or alpha-beta. The output from the system is shown in Fig. 6.

3.2 Forging Process Design Information

The system output of the forging process design details for the material Al-99.999%, like the optimum parameters for forging, lubricants, die material, type of press to be used, etc. is shown in Fig. 7.

3.3 Output From the Defect Analysis System

Generally FORGING defects are classified into
Three major types:

1. Macrodefects
2. Microstructural Defects
3. Powder Forging Defects

Enter the choice of your defect
> 2
Microstructural Defects

1. Wedge Cracking / Micro Porosity
2. Adiabatic Shear Bands
3. Flow Localization
4. Intercrystalline Cracking

Enter the choice of your defect
> 3
To Know about the description: type - what is
To know about the origin: type - why

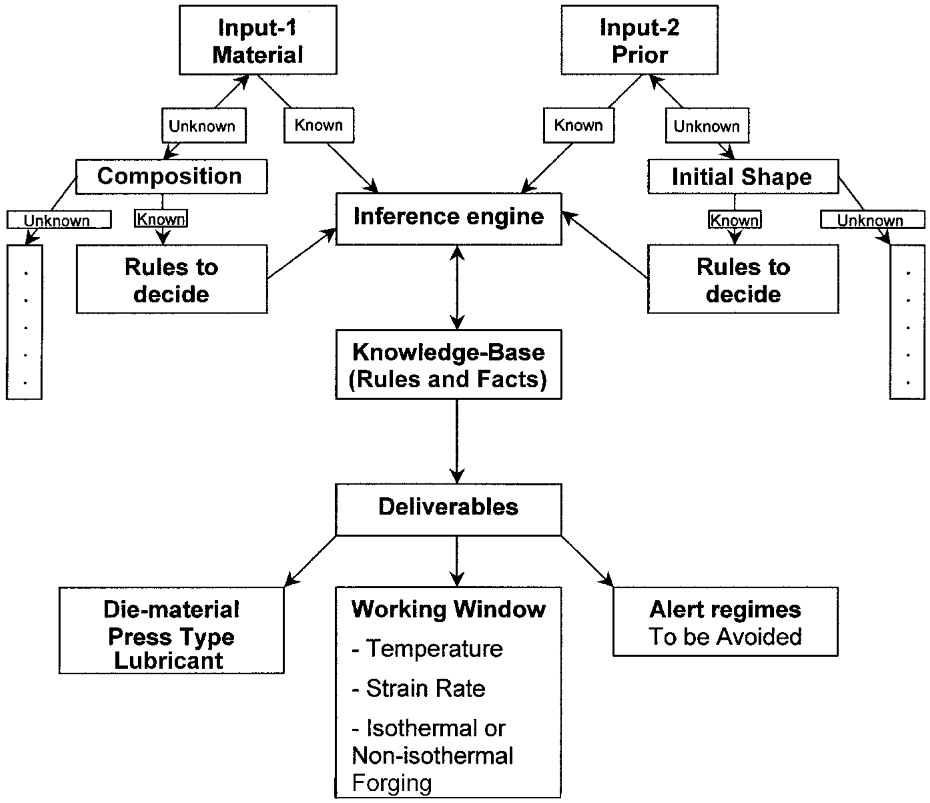

Fig. 3 Forging process design flow chart

General Inference Based on available pure Al Alloy data :
Approx. Forging Parameter for Good Working Domain:
Temperature depends on purity
Lower the purity higher the optimum temperature
Strain Rate range - 0.0001 - 1.0 s-1

Fig. 4 Material information system output for the user inputs: material code unknown and prior history unknown

PROCESSING INFORMATION OF THE ALLOY : al-99.999%
SAFE HOT WORKING WINDOW:-
-> Temperature Range (in Deg. C) : 300-450
-> Strain rate Range (1/s) : 0.001-0.01
OPTIMUM CONDITION FOR PROCESSING:-
-> Temperature (Deg.C): 360 Strain Rate (1/s): 0.001
HOT WORKING MECHANISM:-
-> (DRX, Wedge Cracking)
-> Grain Size Range in the DRX Domain(Microns): 20-100
-> Maximum flow stress in the DRX domain (MPa): 23
ALERT!!! - Un-desirable Regime:-
-> Temperature Range (in Deg. C) : 450-500
-> Strain rate Range (1/s) : 0.001-0.01

Fig. 5 Material information system output for the user inputs: various possibilities of material code and prior history

To know the remedies (Experts Opinion): type how to
> what is
What is Flow Localization?
Description: Flow localization is a milder version of adiabatic shear bands and is associated with broader bands of localized flow. This is a form of instability, which manifests as bands oriented at about 35° with respect to the axis of applied stress.
To Know about the description: type - what is
To know about the origin: type - why
To know the remedies (Experts Opinion): type how to
> why
Origin: Flow localization characteristics depends on several factors like work hardening, flow softening, and thermophysical properties of the material like specific heat, thermal conductivity and density.
> 3
To Know about the description: type - what is

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General Inference Based on available
Near Alpha Ti for beta processing:
Approx. Forging Parameter for Good
Working Domain:
--------------------------------------------------
Temperature Range - 1000 - 1150 deg C
Strain Rate range - 0.001 - 10.0 s-1
--------------------------------------------------
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Fig. 6 System output for the input material composition unknown and the prior history known

To know about the origin: type - why
To know the remedies (Experts Opinion): type how to
> how to
Remedies: Characterize the regimen of instability and work at strain rates and temperatures below the instability.

4. Discussion

Forging is a very important manufacturing process in which the time taken for the process design and the die manufacture is generally long and is called "lead-time." Any model or system that helps in reducing the lead-time is beneficial for establishing a successful forging schedule. The forging process design itself consists of two independent parts as explained in the introduction, namely the materials' workability and the die design. Expert systems for efficient die design have been proposed,[15,16] and these effectively use basic shapes in geometry, which can be put together for realizing the required die shape in a short time. These are developed for specific purposes like design of forging of gears and estimation of risk of defects of forged parts. However, it is generally recognized that the success of the forging process depends critically on the workability of the material and expert systems are not developed to consider this most important aspect. Since most of the forging process designers are not materials engineers, it is necessary to provide a system that will prompt and aid a novice in the area to perform the job. The specialty of the expert system developed in this investigation is that it is based on the materials' workability unlike the geometry-oriented expert systems cited above. The importance of such a system lies in the fact that it is not specific to one shape or process or material but encompasses all the bulk metal working processes (rolling, forging or extrusion), any shape and covers a wide gamut of technological materials.

This system FORGEX is designed for use by the forging industry such that the recommended design parameters (temperature, strain rate, type of forging machine, lubricant, die material, and isothermal or nonisothermal) are delivered as against an in-put of material specification and prior history. The database, facts, and rules used for achieving the results using this system totally avoid the trial and error methods involved in the conventional forging process design.

Furthermore, the expert system is designed such that it can act as a materials information system (safe processing window, optimum processing parameters, hot-working mechanisms, microstructural details, and maximum flow stress) and for defect analysis, both of which are useful for learning more about the material's response to deformation processing. The system is designed in such a fashion that additional data, facts, or rules may be modified or upgraded without redoing the entire database. Such a design is preferable for forging process since the system may have to be useful for handling many new materials in future. FORGEX offers several advantages.

- While it works accurately if an exact match of the candidate alloy in terms of its composition and prior processing history with any one of the alloys given in the database, it can be used even if a closest match is found or the input is not matching with any of the existing alloys.
- In the latter case, the expert's knowledge about the particular alloy system is used to answer the query. The answers given by the system in this case will be less accurate but are much better than those offered by the conventional trial and errors methods.
- The system is designed to query the user to get the required information, to check and validate the answers against wide possibilities, and to prompt with suggestions for correcting inputs.
- The most useful part of this expert system is to address the problem of defect analysis specific to forging. Here again, the system will separate the problems of defects in terms of those arising from die design and those caused by limitations of material workability about which it offers complete solutions.
- One of the limitations of the present expert system is the nonuniform representation of the material information on various alloy systems; e.g., Al materials have more than 50 alloys while very less information of steels (details are shown in Table 1). However, this limitation may be overcome in course of time as more and more information is added to the database from additional sources.
- The other limitation of not taking into account the geometry-related die design problems is already discussed since the specialty of the present expert system is materials orientation.

5. Conclusions

- It is possible to acquire knowledge about various aspects related to forging process design and problem solving skills of a domain expert and effectively represent in a form that can be used to solve forging design problems from materials viewpoint.
- The C-like Language for Integrated Production System (CLIPS) is an effective language to build the expert system for forging process design.
- The expert system will aid and prompt a novice engineer in designing a forging process by providing accurate information of the process parameters, lubricants, type of machine, die material, and type of process (isothermal versus non-isothermal) for a given material with known specification or code and prior history.
- The expert system also gives solutions to the forging de-

PROCESSING DESIGN INFORMATION OF THE ALLOY : al-99.999%
SAFE HOT WORKING WINDOW:-
-> Temperature Range (in Deg. C) : 300-450
-> Strain rate Range (1/s) : 0.001-0.01
OPTIMUM CONDITION FOR PROCESSING:-
-> Temperature (Deg.C): 360 Strain Rate (1/s): 0.001
Iso-thermal Forging
Forging has to be done Isothermally i.e. the Die is heated to the same temperature as that of the workpiece for which special die material (superalloy) are to be used).
Suggested Machine Types:
-> Hydraulic Press
Suggested Die materials:
-> 6G - Hardened and tempered low alloy steel
(0.55C, 0.8Mn, 0.25Si, 1.0Cr, 0.45Mo and 0.1V)
-> H12 - Chromium based hotwork die steel
(0.35C, 0.4Mn, 1.0Si, 5.0Cr, 1.5Mo. 0.5 V and 1.5W)
Suggested Lubricants:
Graphite and/or MoSo2

Fig. 7 Forging process design output for the material Al 99.999%

Table 1 FORGEX: Facts, Control Functions and Rules

	Facts	Functions	Rules
Al alloys	51	10	27
Cd alloys	2	3	4
Cu alloys	27	5	14
Ferrous alloys	24	7	17
Mg alloys	10	6	12
Ni alloys	20	5	14
Pb alloys	2	2	3
Ti alloys	16	6	18
Zn alloys	4	3	4
Zr alloys	6	5	8
Die material	…	…	9
Defect analysis	…	4	59
Lubricant	…	…	9
Machine type	…	…	1
General	…	8	…
Total	162	64	199

sign problems even on materials whose exact code or prior history is unknown, provided the material composition, alloy base, or initial shape is given.

- In addition to the forging design parameters, the expert system provides additional information on the material behavior and the microstructural mechanisms, which may be used for microstructural control in the product during forging.
- The expert system provides forging defect analysis, wherein the origin for a particular forging defect is identified and remedy is suggested.

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