SOME OBSERVATIONS OF HOT WORKING BEHAVIOR OF SUPERALLOYS
ACCORDING TO VARIOUS TYPES OF HOT WORKABILITY TESTS

Dr. R. S. Cremisio - RSC Materials Technology Associates, Clinton, N.Y.

Prof. H. J. McQueen - Sir George Williams University, Montreal, Canada

ABSTRACT

Variations of hot working behavior from alloy to alloy and within heats of the same alloy are the result of differences in deformation, softening, fracture mechanism, and response thereof. These factors in turn are controlled by preexisting processing conditions such as microsegregation, solidification rate and thermal practice. Since these conditions are held as constant as possible in technological operations, it is useful to examine the complex structural changes associated with the various hot working methods as revealed by the more successful hot workability tests.

A brief review of the various types of hot-workability tests will be made. Included for discussion are cylinder upset, cast cone, wedge reduction, tensile impact, hot tensile, hot compression, Gleeble, and cam plastometer. Some correlation of these tests with temperature, strain rate, and structure will be made.

Based on the above, a discussion of the deformation modes related to some specific alloy types will be undertaken. This will include matrix stiffened, precipitation strengthened, and phase transformation strengthened alloys. Yield phenomenon, deformation stresses, static and dynamic recovery, and recrystallization mechanisms will be correlated with these alloy systems to the degree possible with presented data.

Hot working and subsequent cooling determine the suitability and overall property response of alloys for future fabrication and service. The role of sub-structures will be briefly discussed as to possible mechanisms related to superalloy service. The sum total of the above will hopefully yield a better understanding of important testing criteria, the tolerances in their control, and the use of these specific hot working tests to control critical parameters associated with hot working operations such as pressing, forging, coining, shearing, blanking, and rolling.

SUPERALLOY PHYSICAL METALLURGY RELATED TO HOT WORKING

Alloys commonly chosen for advanced service requiring high strength and toughness at moderate and high temperatures are commonly classed as superalloys. These alloys can be classified into five groups according to basic strengthening mechanisms as shown in Table I. Some selected compositions are shown in Table II. (1)* Today more than ever, the processing of advanced alloys must be treated on a systems basis. To begin with a consideration of basic alloy characteristics is in order. This in turn allows the optimal choice of hot working parameters to yield the desired final product attributes. For example, the hot working of an alloy strengthened by allotropic transformation must be carefully maintained above a certain minimum exit temperature in order to prevent cracking due to the formation of brittle transformation products. On the other hand, a precipitation hardened alloy might be quenched on exiting from a hot rolling operation in order to prevent the precipitation of strengthening precipitates which can lower ductility in subsequent operations. Similar care throughout the subsequent reduction steps must be given in order to preserve alloy characteristics such as fine grain size, uniform carbide distribution, and minimized banding in the finished product.

---

*numbers in parenthesis denote appropriate references.

A correlation of temperature as a function of hardener (Ti, Al, Cb, etc.) content (relative gamma prime factor) for a selection of superalloys is shown in Fig. 1. In order to identify the hot working ranges of these alloys as a function of alloy content, we must establish the temperature interval within which the alloy exhibits sufficient malleability while avoiding incipient melting at the upper end (the incipient melting range) and re-precipitation of brittle phases at the lower end (to a first approximation this is considered equivalent to the solutioning range since we desire to keep these phases in solution). The trends indicated by Fig. 1 are consistent with practical observations in the working of superalloys. Normally, we expect the incipient melting range to lower with increasing alloy content. Taken into consideration with the temperature coefficient of deformation (temperature rise due to the hot working itself), the upper forging temperature is severely limited (lowered) in the higher alloyed grades. Another discordant factor limiting the hot working range is the proportionate increase in solutioning temperature with increasing alloy content, thus limiting the lower forging temperature. Obviously the convergence of these two factors heralds the choice of cast alloys over forged alloys in the higher strength applications; a third factor involves the increase of recrystallization temperature with alloy content. Suffice it to say that this factor can cause variation in structure control during forging. Taking the above into consideration, we see that the ideal hot workability test will give both quantitive measurements of these factors as well as corresponding microstructual information as to the conditions existent at temperature for reasons to be developed below.

A given hot working operation, (as typified by hot rolling in Fig. 2), can be thought of in terms of several problem areas peculiar to each method of hot working. Five areas common to nearly all methods of hot working are: (2)

- The nature of frictional boundary conditions between work and tool surfaces. Roll bite, end effects, and die lock are common manifestations.

- The material deformation characteristics within the deformed volume between the tool surfaces at the instant of deformation. Continuum plasticity, work hardening, flow stress, and plasticity are specific factors.

- The properties of the material prior to the hot-working operation - grain size, surface condition, straightness, hardness, hot strength, etc.

- The properties of the material after hot working.

- System factors such as roll deformation, spring back, power, speed, coiling configuration, etc.

In sections to follow, we will attempt to exemplify these five areas either with actual examples or simulative tests as appropriate. It is axiomatic that the ideal test for hot workability includes direct answers to each of the problem areas. Furthermore, it is desirable that information be in quantitative form so that direct comparisons can be made. A following section will delineate these parameters as a function of known methods of assessing hot-workability.

FRICTIONAL PROBLEMS

The frictional effects existing between the working tool and the material being deformed are extremely important in determining the stresses developed in the deformed volume. These problems are particularly complicated in hot rolling because the frictional coefficients of various oxides are not well established. The chemical interactions between the oxide on the work and the oxide on the tool have a profound effect on surface conditions. Frictional forces can completely alter the expected stress

system under consideration if not factored into calculations predicting stress and strain. A number of compatibility criteria have been studied by workers in this field. Not much more will be said here with regard to this problem except to critically point out that the effects of friction must be clearly detailed for perfect correlation between laboratory test and actual plastic deformation experience to be expected.

A macroscopic aspect of frictional boundary conditions has to do with the problem of surface condition. Surface conditions leading to spotty loose scale or intermittent liquid oxide pools are inimical to good surface on finished products. Figures 3a and 3b are examples of surface effects of various elements which could be present as contaminants in steel mill operations on the surface interactions with a nickel and cobalt base alloy. (3)

FUNDAMENTAL MATERIAL DEFORMATION CONSIDERATIONS

When a metal is subjected to a stress it will exhibit a deformation response. This change in dimension will be apparent whether the stress is externally or internally applied. This deformation may be classified as either elastic or plastic. We can visualize an unstressed metal as a continuous lattice with atoms placed at regular intervals. Balancing of attractive and repulsive forces between the atoms leads to an equilibrium distance between them. Forces of any type upset this balance resulting in a change in the equilibrium distance. This reaction causes an external change in dimensions which can be defined as elastic deformation:

$$F = \int \sigma \, dA$$

where F = the deforming force
σ = stress
A = the effective area

These stress distributions are arrived at by observing and measuring the actual strain involved upon application of the force, since stress itself cannot physically be measured. The simplest relationship describing metal displacement is Hooke's Law:

$$\sigma = Ee$$

or
$$\sigma t = E\varepsilon$$

where σ = engineering stress
σt = true stress
e = engineering strain
ε = true strain
E = Elastic Modulus (1/10 to 1/30 dynamic E at hot working temperatures and varies with material and strain rate)

The engineering strain is useful in calculating certain problems in mechanics and evaluating differences between materials on a lot to lot basis. However, for a rigorous analysis of the states of stress and strain in a complex deformation process, one must use the true stress-strain relationship. We see therefore, that the type of relationship is uniquely defined by our definitions of strain, which are:

$$e = \frac{\Delta L}{L_0} = \frac{L - L_0}{L_0} \qquad \text{and} \qquad \varepsilon = \int_{L_0}^{L} \frac{dl}{L} = \ln \frac{L}{L_0}$$

where ΔL = the deformation
L = the finite gage dimension under load
L_0 = the reference gage dimension

In order to change the shape of a metal, plastic deformation is required. In contrast to the elastic case, displacements due to plastic deformation are permanent. This may be visualized on an atomic scale by the actual displacement of atoms of one plane moving in relation with neighboring atoms on other planes over relatively large distances. A material is classified as ductile if it can undergo plastic deformation to the extent of approximately 5%. However, it must be realized that the concept of ductility is a relative factor which must be considered in relation to the stress system being studied. For example, in a hypothetically strengthened steel exhibiting a yield strength of 400,000 psi, 5% ductility would be considered quite high, whereas in the hot working of metal, 5% ductility would be classified entirely as a brittle material. There is still much controversy as to the exact definition and measure of ductility. There are those who feel that the only true measure involves assessment of the deformation energy or area under the stress-strain curve. For the present consideration however, we need not be concerned with a rigorous definition of ductility, and it will suffice to accept the concept that the percentage elongation and/or reduction of the area can be used as a relative index of ductility. Perhaps it is wrong to refer to the percentage reduction of area for example, as ductility, nevertheless this practice has fallen into wide usage among those engaged in the analysis of metal deformation processes. The main purpose of the various theories of plasticity is the prediction of the maximum force which must be applied to a material to cause a desired deformation response. Analyses of plastic deformation are further complicated by the development of work or strain hardening. The most common expression relating stress to strain in this situation is as follows:

$$\sigma = K\varepsilon^n + \sigma_0$$

$$\sigma = \text{true stress} (\sigma_0 = \text{yield stress})$$
$$\text{where } K = \text{a proportionality constant}$$
$$n = \text{work hardening exponent}$$
$$\varepsilon = \text{true strain}$$

Physically the constant σ_0 relates to the intercept of the stress axis at zero strain and is in turn related to the force necessary to move a dislocation from any pinning obstacles. The work hardening exponent is measured graphically by the slope of the stress-strain curve in the plastic region and is fundamentally associated with the resistive forces experienced by movement of dislocations in the lattice either due to precipitates or the force fields of other dislocations. This, of course, leads directly to the very important structural effects which can be achieved by the combined imposition of heat and deformation as in the hot working operation.

SOME EFFECTS OF PRIOR STRUCTURE

Crack free hot working presents different aspects according to whether we consider the deforming of products in the as-cast state, such as ingots, or that of products which have previously been hot worked. In the first case, brittleness phenomena are in fact often observed, which are connected with the as-cast structure of the metal. After a certain amount of hot working, this brittleness disappears and the workability of the metal then corresponds to what we will call its "inherent workability". (4)

The cast structure of the ingot has a characteristically lower workability and this is related to the solidification structure. For example, a study of columnar versus equiaxed structure of as-cast Waspaloy (2.0 Cr, 56 Ni, 4 Mo, 14 Co, 3 Ti, 1.3 Al) indicates a superiority of columnar grains over equiaxed grains. Fig. 4a, demonstrates that the property of ductility, so vital to the forging, rolling, or extruding process, is materially improved when tested parallel to the columnar grains. In fact, even the transverse properties of the columnar grains are superior to the equiaxed case. (Also Fig. 4b in the case of an 18% Cr, 11% Ni alloy). (5)

Control of ingot structure can be realized through the application of fundamental solidification theory and by new control techniques such as nucleation catalysis, ultrasonic vibration, unidirectional solidification, special ingot design and ingot size variation. (6) (7) (8) (9)

MATERIAL CONSIDERATIONS DURING AND AFTER HOT WORKING

Rate of Deformation

High rates of deformation permit higher rates of production and hence lower labor costs per part. But the flow stress is strain rate sensitive to a higher degree at elevated temperatures. Thus, higher strain rates require stronger machines and more power unless the temperature is raised. The limit to which temperature can be increased is set by physical metallurgy limits as discussed above. (10) (11)

Recovery and Recrystallization

Hot-worked metal can undergo recovery and recrystallization (as well as relaxation) when hot, as when the metal has been deformed at ambient temperatures. Since the hot working is taking place at temperatures commonly used for annealing, these mechanisms can occur in the intervals between the end of deformation and cooling of the metal or between repeated deformations. The as worked structure can often be preserved by rapidly quenching, but variously evolved structures can intervene by various holding times. Therefore, different microstructures and substructures can be correlated with variations in the hot working tests as well as to room temperature properties. Hot workability testing, then, should have the flexibility of imposing pre-and-post thermal cycles on the metal as well as variable holding times during deformation steps (as well as variable amounts of deformation). Specimens should be large enough to induce uniform response to deformation. Whereas optical microscopy reveals the size and shape of grains and inclusions, transmission or scanning electron microscopy coupled with X-Ray diffraction are required to provide insight as to substructure and internal stress. (12) (13) (14) (15)

System Factors

System factors involve the reaction of the hot working machinery itself to the forces necessary for deformation. In the various hot working systems this is manifested as bowing of rolls, roll flattening, elastic rebound, effect of heat on dies, etc. The main factor to be highlighted here is that equipment for the hot working of superalloys must be designed for optimum rigidity and speed of operation. The main reason for this criterion is exemplified in Fig. 5 wherein the ultimate tensile strengths of various alloys are compared at hot working temperatures and strain rates. The very nature of superalloys is that they are intentionally designed to exhibit high strength at elevated temperatures. Furthermore, as shown in Fig. 6, most superalloys exhibit a high degree of response to strain hardening (and strengthening) as a function of strain rate. (19) Finally, the exigency of structural uniformity in superalloys requires the utmost in system precision of response. As shown in Fig. 7, it is necessary to work superalloys to close strain precision tolerences in order to assure required structural response (in this case, the avoidance of coarse surface grains on subsequent solution treatment).

HOT WORKABILITY TESTS REVIEWED (16) (17) (18)

In the hot working of metals, the objective is the forming of the desired shape to required properties with the greatest net throughput (yield) at the lowest possible cost. Often questions of economics outweigh technical considerations, thus imposing further restraints. The search of optimum hot working parameters could be carried out by trial and error in full-scale production. However, this is costly, and hot working tests of sub scaled specimens have been developed. The various tests have different attributes.

SIMULATION OF HOT WORKABILITY

Philosophy of Hot Workability Tests

The two philosophies of testing are simulative and universalist (20). In the simulative type, the objective is to deform the specimen under the same conditions as the real process. This is easier said than done since to achieve this with small specimens, either the scale of all test equipment must be the same as that of the specimen to workpiece or changes must be made in certain conditions to compensate. In the universal test, specimens are deformed under a range of precise values of the different parameters and the necessary information for any condition of processing is calculable and repeatably applicable to the alloy parameter combinations used.

It is also useful to evoke certain identifications of terms commonly used interchangeably in discussing working tests:

Workability: Relates primarily to the relative force required for deforming the given alloy by the process chosen (pressability, forgeability, rollability, etc.), as well as ductility, or lack of it. The product yield and quality are also important factors.

Malleability: The degree of permanent deformation of a given material by a given hot working process that can be achieved without visible evidence of fracture as manifested by face or edge cracking.

Ductility: Quantitative assessments of plastic deformation which usually vary with the test method. Percentage elongation, reduction of area, number of twists, indentation diameter, and local deformation in impact are examples.

Frequently, percentage yield is taken as a measure of ease of hot working. In these cases one must be careful to assess the exact cause of yield loss before prescribing remedial action. For example, certain alloys may exhibit higher ductility if forged from a lower furnace temperature, thus, lowering the forging temperature should increase or improve the hot workability. In fact, when the furnace temperature is lowered the net yield is found to be less. Examination of the situation showed that the higher furnace temperature required less conditioning because the scale spalled-off. At lower forging temperature the scale does not spall off and is pounded into the metal necessitating more severe conditioning of the forging and thus lowering the net yield of the operation. This can be taken as another lesson in the advisability of viewing hot working operations as a system rather than at any specific part of the process.

Types of Hot Workability Tests

In the hot working of metals, there are a number of different forming processes, of which the most important are the forging press and hammer, the extrusion press, the rolling mill, and the drawing press. The reduction of the material from ingot to bar or sheet is often done in several reheatings with different processes or tools utilized from one thermal event to the next.

Reduction after initial heating can be done either in several phases, as is customary with the drop hammer, the forging press, bar and wire rolling mills, etc., or in one single pass, as is the case with the extrusion press or the wire-drawing bench, the inclined tube mills, and certain die-stamping operations. When several passes are

used in reduction, the temperature of the metal varies throughout the whole process of working by virtue of normal heat loss balanced by possible temperature increases due to the work of deformation.

Working is done with different average speeds according to the kind of tools used. For comparison purposes, deformation velocities for various hot working operations are in the order of 120-136 inches/second for forging, 70 inches/second for rolling, 0.12 to 120 for hydraulic extrusion and 6 to 60 for mechanical pressing. These velocities vary according to the equipment used and the sizes of the work process involved. They do show the variations in speed of reduction realized in practice.

The essential problem before the operator is to fix for each type of alloy the operating conditions that insure high yield working of the material without cracking. Industrially establishing optimum procedures for the working of any given alloy is a long and difficult matter and involves large quantities of metal if it is carried out directly in the shop. As mentioned above, it is advantageous to carry out preliminary investigations in the laboratory so as to fix the essential factors which will need to be checked during working.

Cracking corresponds to a local rupture of the material associated with a low inherent ductility of the worked material. The experimental analysis of working conditions therefore, essentially leads to the study of the hot ductility of the alloy as a function of methods of working on the one hand, and of the analysis and structure of the steel on the other. It is therefore practical to carry out tests for deforming alloys to fracture under thermo-mechanical conditions comparable to those found in industrial practice. In workability tests it has been principally sought to vary the temperature and the speed of deformation and subsequently, the method of working, either continuously or in several sequences duplicating reduction passes in actual working operations.

The various tests used to establish the hot workability of materials have been designed to duplicate the stress magnitudes and orientations experienced in the various hot working operations as shown in Fig. 8. (21) Brief descriptions of some of these tests are as follows:

Bend Tests. The test consists of bending a sample through 180°F at various temperatures. A flat test piece heated to the required temperature is bent in order to observe the smallest radius of curvature free of cracks at the selected temperatures. (22) In addition, the tests can be conducted at various velocities to study the strain rate factor. The advantages of this method are: a) reduced size and simple shape of test pieces, which is a help in obtaining them, particularly from as-cast material; b) possibility of making large variations in speed of deformation; c) possibility of easily carrying out deformation by successive passes and reheatings.

Quantitative results can be obtained from this bend test by determining for each test condition the critical deflection corresponding to the appearance of the first crack, but this method calls for a large number of test pieces. Moreover, this test is only suitable for fairly brittle materials, deformation being limited to a maximum deflection governed by the geometrical conditions under which the test is carried out.

Upset Tests. The upset test is another old workability evaluation method performed at various temperatures between flat dies. In this test the limit of reduction possible without cracking and the energy or pressure required to accomplish the reduction are important factors used to define hot workability. It is normal to compare results with a standard alloy. A variety of test specimen variations can be used such as cone, cylinder, wedge and notched cylinder to mention a few. The advantages are that generally simple equipment is needed. It can be performed at or near the production units, as well as in the laboratory, and qualitative results can generally be correlated with gross workability behaviors. (23) (24) (25)

Torsion (Twist) Test. The hot-twist test consists of inserting a round bar specimen through a tubular furnace, clamping one end of the specimen, and twisting the other after heating the specimen to the test temperature. Twisting is continued until the specimen fails. The number of twists to failure indicates the comparative workability (ductility) of a steel, and if the test is repeated at different temperatures, the optimum tempera- ture of workability can be determined. The measurement of torque during these tests yields an excellent measure of forces required for deformation at the given temperatures. Torque-twist tests have found extensive use in developing workability information on extrusion and hot piercing processes. The main advantage of this test lies in the fact that true torsional loading results in the development of shear stresses which in turn allows development of the maximum amount of plastic deformation available in the material. Most recent modifications of the simple torsion test have involved a combination of compressive and torsional stresses to more accurately reproduce deformation processing stresses. The attraction of this method of testing largely lies in its ability to promote maximum plastic deformation. The main disadvantage involves a difficulty of testing specimens cut from ingots using this method. The use of tubular specimens allows the development of extremely high strains for research purposes and is easily programmed for the simulation of multipass industrial operations. (26) (27) (28)

Tension Test. Elevated temperature tensile tests have been used to evaluate hot workability by taking note of the ductility (as indicated by percentage elongation and reduction of area), and force (as measured by tensile and yield strengths) as a function of temperature. Strain rates are slow; however, even with special adaptations the deformation velocities seldom exceed 2×10^{-2} feet/second. Another problem associated with the tension test involves the indirect methods of heating usually used (that is by radiation and convection via electrical resistance furnaces). This method of heating does not allow the degree of thermal flexibility required to assess the true hot work- ing characteristics of materials.

The Gleeble. In the past ten years a new instrument for the thermo-mechanical study of materials has become available. The main feature of this device is its ability to reproduce almost any desired thermal cycle on a specimen via resistance heating. Strain rates are widely variable encompassing the major portion of the strain spectrum of deformation processes (see Table III). (2) With this device it is possible to give the specimen a complete multipass thermomechanical history experienced by a given bar or billet during deformation processing. (19) (29) (30) (31)

Impact Tests. A number of investigators have utilized un-notched charpy and tension impact tests to evaluate hot workability of materials. In the case of the charpy test, specimens are heated in an electrical resistance furnace and then quickly transferred to the impact machine anvil. In this way the impact resistance and to a very limited degree, the ductility can be studied as a function of temperature. In the case of the tension impact test, the specimen can be heated (for example by resistance) while held in place either in the head of the impact machine or in a special clutch device connected to the anvil. (32) The general disadvantages of either impact test concern the compara- tively greater mechanical difficulties involved. In addition, the data (in terms of ft-lbs. of energy absorbed) are more difficult to translate to actual hot working pro- cedures. On the other hand, the data have been used successfully in defining differ- ences between different lots and heats of materials.

Recent improvements to impact testing instrumentation now allow the direct assess- ment of force-displacement curves in impact. (33) At this writing this new equipment has not been applied to hot-workability testing.

Indirect Manifestations. Depending on the type of alloy, sequence of operations, and extent of quality control record keeping, one can frequently detect trends in work- ability performance on a heat to heat basis by examining certain product characteristics. For example, stress rupture strength and ductility frequently relate to hot working performance of a given superalloy heat. Heats demonstrating high strength and/or

ductility in stress rupture tests frequently show good yields in the various hot working steps. Another example is the ductility of heat affected zones in weldments. Here again, heats prone to cracking, whatever the reason, are usually also the same heats which reflect poor workability. While these inferences are after the fact, frequently process control parameters can be adjusted on the basis of observing controlled changes in processing parameters under "mill development" conditions.

Rationale. Table IV is a summary of hot working test methods according to McQueen and Jonas (16). Hot working experiments can provide information in a number of interest areas. There is no one "perfect" test for workability. The characteristics of each must be considered in terms of the appropriate production needs. We saw that working loads can be calculated from a study of flow stress/deformation parameters. The limits for successful production can be ascertained from a study of the dependence of ductility on forming conditions. Analyses of microstructural changes taking place during working disclose the mechanisms of deformation and suggest directions of control for yield and productivity improvement. Finally, we saw that data concerning the properties of the product can indicate possible process alterations to meet rigid specifications and product needs. In the sections that follow, several of these test techniques will be applied to superalloys with certain interpretations made as to the data so derived.

ANCILLIARY TESTING CONSIDERATIONS

Sample Selection and Preparation

Any measure of hot workability, regardless of the type of test involved, is only as good as the samples chosen and prepared for study. This factor is particularly trouble-some with as-cast material. As mentioned earlier, samples must be prepared in such a manner as to represent the same general cooling conditions in equiaxed ingot sections. If samples are taken from the columnar region, a choice must be made as to whether they represent sections longitudinal or transverse, to the heat flow direction. In many materials, the ingot must be homogenized or even solution treated in order to allow sectioning by sawing. As implied above, whether the sections are equiaxed or columnar they should be of similar secondary dendrite arm spacing in order to be fully equiva-lent. One of the authors (RSC) has experimented with samples aspirated directly from the melt in quartz tubes (suck samples). In spite of the microshrinkage or micro pipe in each sample, the results were surprisingly uniform for a given state of bath re-finement. An improvement on this technique involved the unidirectional solidification of samples drawn from the bath at various stages of refining.

Wrought samples are not as much a problem but require care nevertheless. In large billet samples, the remnant solidification structure (microsegregation) can persist to rather high reductions. In these cases the same care should be taken to locate samples similarly to both the developing work fibre direction and the previous heat flow direc-tion. As reductions are higher, care should be taken to properly orient samples in relation to the working direction so as not to err in comparing longitudinal to trans-verse results which are nearly always poorer by comparison. It should be obvious that all samples should be in the same metallurgical or heat-treated condition for proper comparison.

In order to promote complete evaluations of hot workability, one should strive for simplicity of sample. In many cases as with the Gleeble, a simple rod suffices. Often the processing sequence orders can call for a small quantity of each heat to be process-ed to a size for ready fabrication to hot workability specimens.

Temperature Measurement

Mention should be made regarding certain temperature measurement problems in hot workability tests. First and foremost, one should be certain of the meaning intended by the term "hot working temperature". To some this means the temperature of the work-piece entering the hot working dies. To others it means the furnace set temperature

prior to forging. Some shops record from furnace control thermocouples. Others use thermocouples attached to the work. Many use optical pyrometers, and far too few apply the proper corrections.

Another confounding factor with superalloys is the so called thermo-plastic effect, or heat of deformation. Temperature builds up very rapidly in superalloys as a function of deformation rate. It is not unusual for the material to leave the working dies hotter than when taken out of the furnace (superalloys have come out of high speed rolls in the liquid state). Some compensation must be made for the "size effect" inherent in this factor when simulating the rolling of certain grades.

Finally, care must be taken depending on the mode of heating used for the test itself. Frequently resistance heating is used as a means of heating because of the flexibility and ease of control. Thermocouples attached to hot surfaces, even by welding, should be corrected as to their output. This correction varies with the size of specimen, diameter of wire, and most critically with the rate of heating. Careful study should be made of the exact temperature/time sequence of operations if a faithful reproduction on a test basis is to be achieved.

SUPERALLOY WORKABILITY TESTS AND INTERPRETATIONS

In this section, we would like to make observations on some superalloy hot workability test results obtained by different techniques. Interpretations will be made as well as comparisons of several methods as they become appropriate. These data have been randomly selected from the Authors' files and bear no relationship from example to example. The comparisons will be made in relation to the specific alloy discussed and those parameters endemic to high temperature alloy service.

Hastelloy X

Refer to Table II for composition. This alloy is used extensively for high temperature service due to its high strength and resistance to oxidation. It is primarily a "matrix stiffened" alloy with modest strength contribution due to carbide precipitation. This alloy is not strengthened by a gamma prime or other second phase reaction. Fig. 9, is a series of hot ductility curves (Gleeble). Samples were taken from slab product (in rolling direction) just prior to intermediate processing to hot band. Microstructures (originally 500X) have been superimposed in order to allow an assessment of structural response to hot working in this alloy. The nominal strain rate for these tests was in the range 17 to 22 inches/inch/second. Tests made "on-heating" showed very large grain size coupled with definite grain boundary liquation. Peak ductility (at 2000F indicated or about 2055F actual) was associated with pronounced grain refinement. Samples tested "on-cooling" from 2200F (about 2250F actual) demonstrated low ductility associated with coarse grain and some grain boundary liquation. On the other hand, samples tested "on-cooling" from an intermediate temperature (2150F indicated or about 2200F actual) showed a ductility recovery peak in the vicinity of 2050F, also associated with fine grain (observe that the grain size at the peak temperature 2200F was very coarse). At lower temperatures, samples tested "on-cooling" from a peak temperature of 2150F indicated (2200F actual) were associated with coarse grain and low ductility.

Taking these data as typical, the results show that Hastelloy X workability is limited by low ductility due to coarse grain and grain boundary liquation at temperatures above 2200F. For this type of product and the melt practice used, heating for hot working should not exceed about 2175F in order to avoid permanent damage due to grain boundary liquation. The ductility maximum at about 2050F is interpreted as due to dynamic recrystallization triggered by the optimum combination of deformation at temperature. At lower temperature, for example "on-cooling" from 2200F, the samples were not deformed sufficiently to store the energy for recrystallization. Furthermore, the lower temperatures may not have been sufficient to release whatever energy that was stored.

Inconel 600

This alloy is somewhat similar in type to HX in that it is essentially a matrix stiffened grade (16% Cr, 75% Ni, 8% Fe, etc.). Figures 10 and 11, show similar data as the above for various conditions of prior heat treatment. The rationale of these results is essentially the same as that for HX and is summarized in Fig. 18. (31) Kear et al recently distinguished the difference between recrystallization phenomena in hot versus warm working at high and low strain rates (thermomechanical processing), making quite similar observations relating to sub-structure. (34)

Hastelloy C

This grade is another example of a non-gamma prime hardening system (matrix stiffened). The prime attribute is strength retention at temperatures where oxidation is the prime weakening factor. The composition is basically 16% Cr, 17% Mo, 5% Fe, 2.5% Co, Bal. Ni. As shown in Fig. 12A, this alloy is only slightly affected at its peak ductility temperature by prior heating in the range 2150F to 2250F. However, the available ductility is low (59% R/A) and the strength of the alloy is quite high, thus indicating rigid hot working equipment and rather careful attention to reheating and deformations per pass scheduling. As might be expected, this alloy is highly susceptible to embrittlement by sulfur residuals as also shown in Fig. 12B.

Rene 41 and Inconel 718

Hot ductility curves for these alloys are shown in Figures 13A and 13B. The material for both was the same (essentially 1/2 inch round bar stock for fastener applications). In these alloys, the embrittlement phenomenon described for matrix stiffened alloys is largely surpressed. It is postulated that gamma prime and other precipitates pin grain boundaries so as to promote retention of fine grain during hot working operations. Thus the mechanism of dynamic recrystallization during hot working is retarded in these types of alloys. However, these same alloys are prone to the selective type of static recrystallization phenomenon described earlier so that careful attention must be given to subsequent strain increments preceding solution treatment.

A-286

Data for this popular high temperature alloy are shown in Fig. 14B for bar stock, and Fig. 14A for billet. As shown in Fig. 14A, the available ductility is quite high in the alloy. However, care should be taken with regard to over heating prior to forging as the ductility falls off rather sharply over about 2050F. An interesting feature of Fig. 14B is the rather wide dispersion of nil-ductility temperatures. This is thought to be caused by excessive segregation and is classical of this alloy type.

Torsion and Impact Testing

Typical data for superalloys tested by torsion and impact testing are shown in Figures 15 and 16. (5) (35) Actually, similar trends are quite evident as compared to the aforementioned hot ductility data. Torsion testing allows testing the shear strains of a given alloy which is held by some as more appropriate to hot working. However, torsion testing generally demands specimens cut from barstock and is not suitable for testing as-cast material. Testing of tubular sections offers certain advantages however due to high predictability of stress states. Impact tests suffer some of the same criticisms, however the technique is quite simple and is available in most metal making laboratories.

Udimet 700 (Astrolloy)   (36)

Torsional data lend themselves to further analysis as shown in Fig. 17. These data for Udimet barstock (5/8" dia.) compared quite favorably to actual extrusion results at the same strain rates. The ductility versus temperature curves clearly predicted the optimum hot working range. Hot working of this alloy is accompanied by repeated

recrystallization. It was shown that strain softening leads to a steady state flow stress. This was manifested by changes in the shapes of stress-strain curves and by grain size differences between deformed and non-deformed sections of the same as-quenched sample. Three zones of metallurgical behavior are illustrated in Fig. 18. (31) Corroboration of the optimum hot working range of U-700 by Gleeble tests has been published. (37)

FUTURE CONSIDERATIONS AND CONCLUSIONS

We have seen that a rather large array of hot workability tests have been successfully applied to superalloys. The choice of an optimum test is largely based on the final product rather than the universality of any given test procedure. Any procedure which allows the prediction of hot-working trends in production is a good procedure regardless of its scientific content. However, future demands for greatly increased productivity and reliability plus the growing use of superalloys in more consumer oriented products, will prompt the hot working industry to a reevaluation of hot working test methods.

The whole future of hot metal forming is due for a re-shaping in years to come. Demands for higher yields and achievement of net cross-sections will focus attention on casting, powder preforms, and composites. For example, a new technique for powder preforms (38) is demonstrated by an outstanding ability for closed die type forgings. Extremely high yields and "die casting" type detail sharpness have been claimed for this new technique.

Because of these reasons and in order to improve our understanding of superalloy hot working mechanisms, it is suggested that more use be made of various structure evaluation in conjunction with hot working experiments or tests. The variations in workability from alloy to alloy and within grades of a given alloy are clearly a result of differing response to deformation softening and fracture. The effects of trace elements is only now coming into real perception and effects on hot working characteristics can be profound. However, a "witch hunt" solution to this problem is to be avoided, thus requiring better understanding of mechanisms. Furthermore, microstructures produced by hot working and subsequent cooling determine the properties and therefore the suitability for cold forming and subsequent service. The merger of hot working tests with examination techniques which disclose the complete microstructural changes associated with hot working mechanisms is a fruitful avenue of development work for the future. The authors hope that this paper will be helpful to those for whom the data herein have been sufficiently convincing.

REFERENCES

(1) Sims, C. T. and Hagle, W. (Ed.) "The Superalloys", John Wiley & Sons Inc., New York, (to be published late summer 1972).

(2) Dieter, G. E. Jr., "Mechanical Metallurgy", McGraw-Hill, New York, 1961.

(3) Cremisio, R. S. and Koffler, W. T., Welding Research Supplement, Vol. 34, No. 6, pp 259s-265s, American Welding Society, June 1967.

(4) Freeman, H. and Kelley, T. N., "Hot Working of Super-Duty Alloys"- in "Quality Requirements of Super-Duty Steels", AIME, Interscience Publishers, New York, pp 211-231, 1959.

(5) Sellars, C. M. and McG. Tegart, "Hot Workability", Report MRL A 1/6, BHP - Melbourne Research Laboratories, Fig. 28, July 1971 (submitted to Metallurgical Reviews - 1971).

(6) Cremisio, R. S. Transactions of the International Vacuum Metallurgy Conference, AVS, pp 635-674, New York, 1967.

(7) Troutman, J. W., Ibid, pp 599-613.

(8) Preston, J., Ibid, pp 599-613.

(9) Darmara, F. N., Ibid, pp 343-359.

(10) Rossard C., and Blain, P., J. Inst. Metals, 91, pp 267-73, 1962-63.

(11) McQueen, H. J., Journal of Metals, 20, (4), pp 31-38, 1968.

(12) McQueen, H. J., Bergerson, S., Met. Sci. J., (to be published).

(13) Fulop, S. and McQueen, H. J., "Mechanisms of Deformation in the Hot Working of Nickel Base Alloys", Proceedings Second International Conference on Superalloys: Processing (this session), Seven Springs, Pa., Sept. 18, 1972.

(14) Jonas, J. J. and McQueen, H. J., and Wong, W. A., Deformation Under Hot Working Conditions, Iron and Steel Institute, London, pp 49-59, 1968.

(15) Jonas, J. J., Sellars, C. M. and McG. Tegart, W. J., "Strength Under Hot Working Conditions", Review #130, Metals and Materials, 1969, pp 1-23, (contains complete literature review up to 1969).

(16) McQueen, H. J. and Jonas, J. J., "Hot Workability Testing Techniques" in Metal Forming: Interrelation Between Theory and Practice, A. L. Hoffmann ed., Plenum Press, New York, pp 393-427, 1971.

(17) Moore, P., "Methods for Studying Hot Workability: A Critical Assessment", Iron and Steel Publication #108, London, England, pp 103-106.

(18) Draper, Alan B., "Evaluation of Tests for Hot Workability", ASTM Bulletin, pp 62-67, July 1957.

(19) Cremisio, R. S., Transactions of the Vacuum Metallurgy Conference, American Vacuum Society, New York, pp 75-97, 1965.

(20) Cremisio, R. S., and McQueen, H. J. -"SME - Monograph on Hot Workability Assessment Techniques", Society of Manufacturing Engineers, to be published Fall, 1972.

(21) Thomsen, E. G., et al, "Mechanics of Plastic Deformation in Metal Processing", The MacMillan Company, pp 3-13, 1965.

(22) Gussier, A., et al, "Hot Working of Alloy Steels - Influence of Structure and Composition", Metal Treating and Drop Forging, pp 361-366, July-Aug. 1959.

(23) Hentz, R. D., "A Study of Some Factors Affecting the Upset Testing Performance of Merchant Mill Bars" in Mechanical Working and Steel Processing-VIII, AIME, 1971, Timmers et al ed. , Proceedings 12th Mechanical Working Conference, pp 373-411, Chicago, Ill., 1970.

(24) English, A. T., and Backofen, W. A., Transactions AIME, No. 230, pp 396-407, 1964.

(25) Sabroff, A. M. et al, Forging Materials and Practice, Reinhold Publishing Co. New York, 1968.

(26) Gussier, A., and Castro, R., "Hot Working of Alloy Steels - Experimental Methods", Metal Treating and Drop Forging, July-August, 1959, pp 255-263.

(27) Clark, C. L. and Russ, J. J., Transactions AIME, No. 167, pp 736-48, 1946.

(28) McG. Tegart, W. J., Elements of Mechanical Metallurgy, MacMillan, New York, 1966.

(29) Bramer, S. E. et al, Short Time High Temperature Testing, ASM, pp 114-134, Cleveland, 1958.

(30) Cremisio, R. S. and Butler, H. M., Radavich, J. F., Journal of Metals, No. 21 Vol. II, AIME, pp 55-61, 1969.

(31) Weiss, B., et al, "The Physical Metallurgy of Hot Ductility Testing", Welding Research, Vol. 35, No. 10, Oct. 1970, pp 471s - 488s. (See also Welding Research Supplement, Oct. 1970 - Welding Journal).

(32) Harnish, C. D. et al, "Determining Forging Ranges by Hot Tensile Impact Testing", Metal Progress, pp 86-88, May 1965.

(33) Wullaert, R. A., "Applications of the Instrumented Charpy Impact Test", ASTM STP 466, pp 148-164, 1970.

(34) Kear, B. H., et al "Thermomechanical Processing of Nickel-Base Alloys", Journal of Metals, Vol. 24, No. 6, pp 25-32.

(35) "The Forgeability of Steel", Timken Roller Bearing Co., Canton, Ohio, Third Edition, 1965.

(36) Young, C. M. et al "Simulation of Hot Forming Operations by Means of Torsion Testing", AFML-Technical Report TR-69-294, Air Force Materials Lab., Dayton, Ohio, pp 32-44, Feb. 1970.

(37) Anon. "ESR Outperforms VAR in Making Superalloys", Iron Age, pp 49-52, May,1972.

(38) Private Communication - Wentzell, J. Pres. Homogeneous Metals Inc., Herkimer, N.Y., Further information available by direct contact.

TABLE I

Types of Strengthening Mechanisms and Alloy Examples

Basic Strengthening Mechanisms	Alloy Groups and Examples
Allotropic Transformation	400 Series Stainless Carbon and Alloy Steels
Solid Solution	300 Series Stainless 19-9DL, L-605, HX
Precipitation Hardenable	Aluminum Alloys Iron, Nickel and Cobalt base Superalloys
Two Phase	Alpha-beta Titanium Alloys 50 Cr - 50 Ni
Combination -- Precipitation and Allotropic	PH Stainless Steels 18% Ni Maraging Steels

TABLE II

SOME NOMINAL SUPERALLOY COMPOSITIONS

ALLOY	C	MN	SI	CR	NI	MO	FE	CO	TA	CB	AL	TI	B	ZR	OTHER
430	.12	–	–	19.0	–	–	BAL	–	–	–	–	–	–	–	
19-9DL	.31	–	–	19.5	9.5	1.4	65.0	–	–	.50	–	.25	–	–	W 1.4
347	.08	–	–	18.0	10.5	–	–	–	–	.40	–	–	–	–	
19-9DX	.31	–	–	19.5	9.5	1.6	65.0	–	–	–	–	.60	–	–	W 1.4
HX	.10	.50	.50	22.0	BAL	9.0	18.5	–	–	–	–	–	–	–	W 0.6
HS25	.15	–	–	20.0	10.0	–	2.0	52.0	–	–	–	–	–	–	W 15
TINIDUR	–	–	–	15.0	26.0	–	55.0	–	–	–	.15	2.3	–	–	
16-25-6	–	–	–	16.0	25.5	6.2	50.0	–	–	–	–	–	–	–	N .15
DISCALOY	–	–	–	13.5	26.0	3.0	54.0	–	–	–	.35	1.8	.006	–	
GR. ASC.	.17	–	–	13.0	2.0	–	80.0	–	–	–	–	–	–	–	W 3.8
S-816	.35	–	–	20.0	20.0	4.0	5.0	44.0	–	4.0	–	–	–	–	W 4.0
A-286	–	1.35	.50	15.0	25.5	1.3	53.0	–	–	–	.35	2.1	.006	–	V 0.3
WASP'L.	–	–	–	19.0	56.0	4.2	2.0	14.0	–	–	1.2	3.0	.005	0.1	
IN 901	–	–	–	12.5	42.5	6.0	34.0	1.0	–	–	.35	2.7	.015	–	
IN 718	–	–	–	19.0	52.5	3.0	18.0	–	–	5.0	.60	.8	–	–	MG .00
B 1900	.10	–	–	8.0	BAL	6.0	–	10.0	4.0	–	6.0	1.0	.015	0.1	
U 700	.08	–	–	15.0	BAL	5.2	–	18.5	–	–	4.3	3.5	.030	–	
H 188	.1	–	–	22.0	22.0	–	1.5	BAL	–	–	–	–	–	–	LA 0.
A 213	.18	–	–	19.0	–	–	–	BAL	–	–	3.5	–	–	.15	Y 0.
REN. 95	.15	–	–	14.0	61.3	3.5	–	8.0	–	3.5	3.5	2.5	.01	.05	W 3.5

TABLE III

Deformation Velocities for Various Hot Working
Operations and Testing Methods

Operation	ft/second	inches/second
Tension Test	2×10^{-6} to 2×10^{-2}	24×10^{-6} to 24×10^{-2}
Hydraulic Extrusion	0.01 to 10	0.12 to 120
Mechanical Press	0.5 to 5	6 to 60
Charpy Impact	10 to 20	120 to 240
Forging	10 to 30	120 to 360
Hot Rolling	5.8	70
Explosive Forming	100 to 400	1200 to 4800
Present Gleeble	-	0.01 to 10*
Modified Gleeble	-	0.01 to 250

* A recently developed accessory allows extension
of the standard machine to 30"/second.

TABLE IV
COMPARISON OF HOT WORKABILITY TESTS

Test Method	Constant Strain Rate	Maximum Strain Rate	Temperature Control	Flow Stress Measurement	Max. Uniform Deformation	Max. Strain In one pass	Limiting Instabilitie	Suitability for Micro-Structural Examination	Specimens for Subsequent Mechanical Testing	Ease of Multi-Pass Simulation
Tension										
Universal Tester	yes	10^{-1}	good	good	0.3	2	necking	poor	poor	good
Gleeble	no	10^2	fair	fair	0.3	2	necking	poor	poor	fair
Impact Tension	no	high	poor	poor	0.3	2	necking	poor	poor	poor
Compression										
Universal tester	yes	1	good	good	1	2	barreling	good	good	good
Cam, axisymmetric	yes	10^3	fair	good	1	2	barreling	good	good	fair
Cam, plane strain	yes	10^3	fair	good	2	3	friction	good	good	fair
Drop weight	no	high	poor	poor	0.2	2	barreling	fair	fair	poor
Forging hammer	no	high	poor	no	0.2	2	barreling	fair	fair	poor
Torsion										
Solid specimen	yes*	10^3*	good	fair	20*	100	(change in axial length)	fair	fair	good
Tubular specimen	yes	10^3	good	good	20	100		good	good	good
Rolling	no	10^2	poor	fair	–	2.3	edge-crack	good	good	fair
Extrusion	no	10^3	fair	fair	–	5	cracking	good	good	poor

* Does not vary with time, but varies radially.
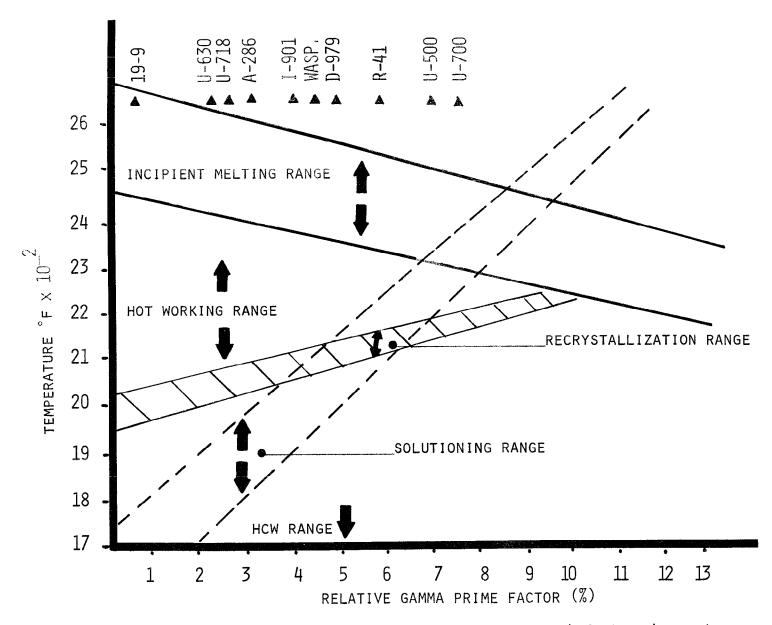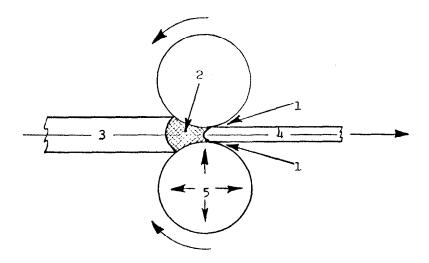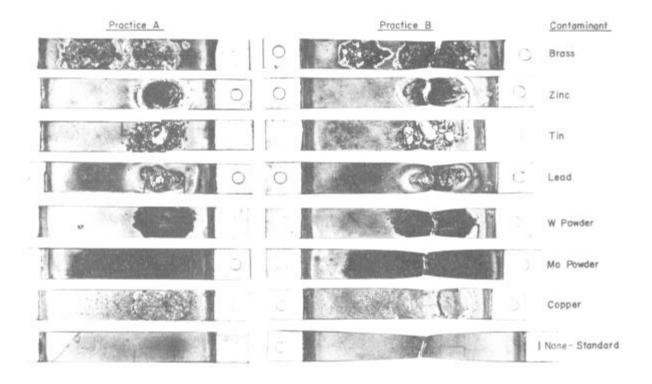
Figure 1. Temperature as a Function of Hardener Content (Relative γ′ Factor) for Various Superalloy Hot and Hot/Cold Working Metallurgical Factors.

1. Frictional boundary conditions between the work and tool surfaces.
2. Continuum plasticity problems related to the deformed volume
3. Properties of the alloy prior to deformation processing
4. Porperties of the alloy after deformation processing
5. Problems related to the mechanical system

Figure 2. Problem Areas Typical to a Hot Working Process

A. Surface reactivity of Hastelloy X at Hot Working Temperatures

B. Same for Hastelloy 25 Alloy (L-605)
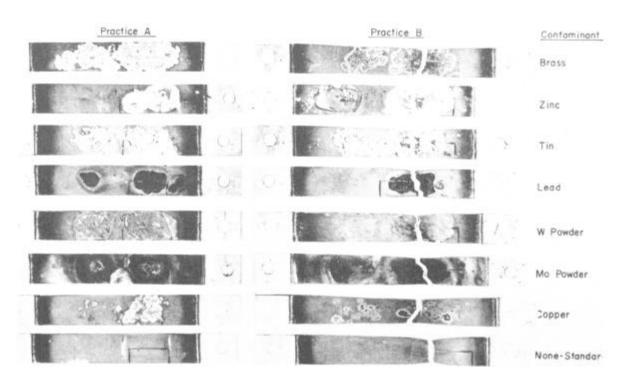
Figure 3. Simulated Surface Reactions on Heating (Process A) and During Deformation (Process B) for a Nickel and Cobalt Base Superalloy

a. Comparison of hot workability via hot tensile
   tests at high strain rate--material cut from an
   air melted, statically cast ingot of Waspaloy.

b. Influence of ingot structure on the du[ctility]
   of as cast 18%Cr, 11%Ni (hot ductility
   at 12/sec strain rate) (5).

Figure 4. Some Effects of Prior Ingot Structure on Ductility Under Hot Working Conditions
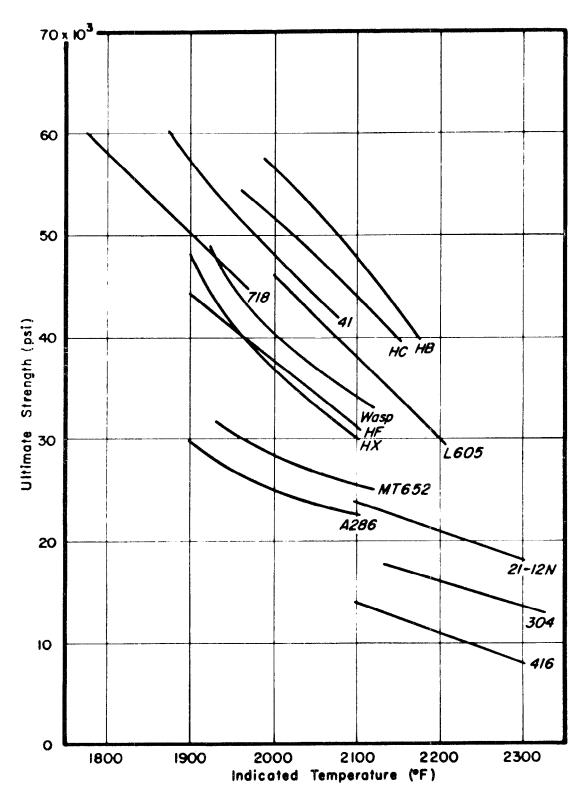
Figure 5. The Strengths of Various Superalloys Under Hot Working Conditions (Gleeble Hot Ductility Tests) (19).

FIG. 6   EFFECT OF STRAIN RATE ON
THE TENSILE STRENGTH OF
L605 (HS-25)   (19)
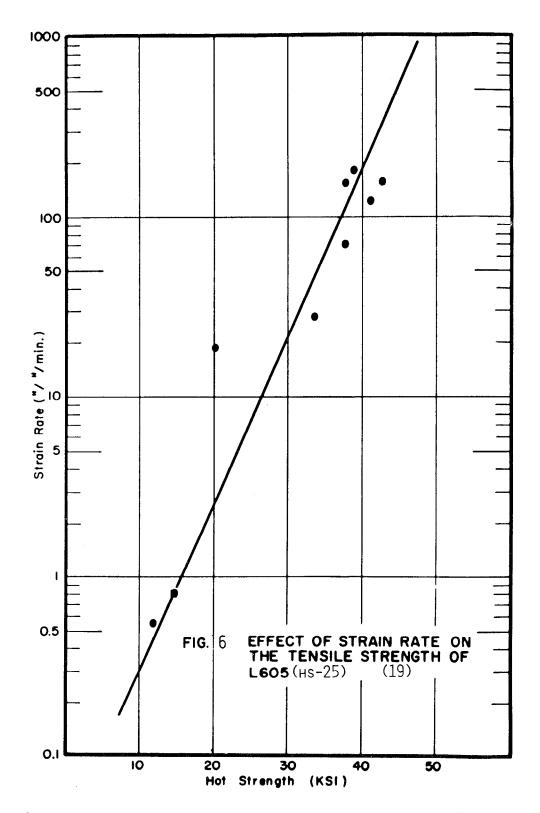
Figure 6. Effect of Strain Rate on the Tensile Strength of L605 (HS-25)   (19)
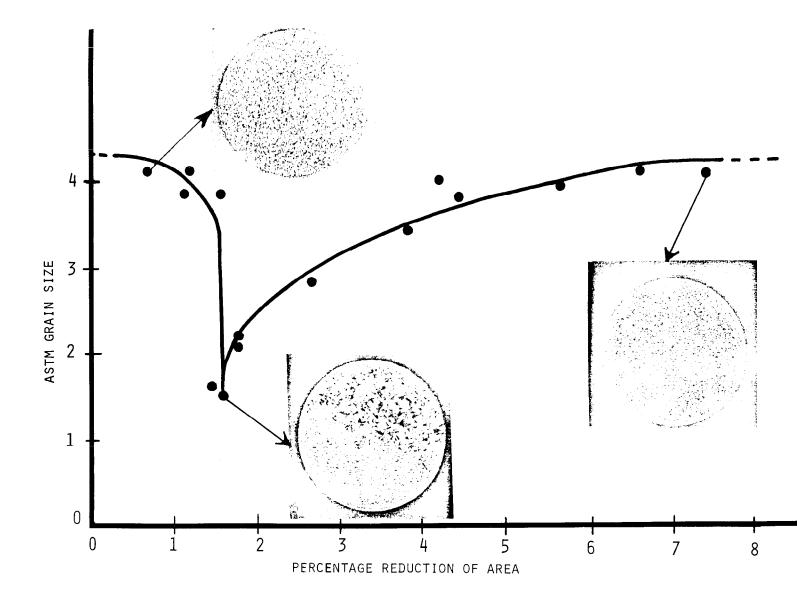
Figure 7.   Grain Size Variation of I-718 Under Simulated Cold Heading Conditions in Gleeble
(Rapidly Strained at Ambient Temperature Followed by Heating to Solution Temp.)

| Basic Deformation Mechanism | Forming Process | | Approx. State of Stress (Unit Cube) | Instantaneous Zone of Deformation (Shaded) | State of Deform. |
	Name	Diagram			
SQUEEZING (Chipless Forming)	UPSETTING (Open Dies)			Whole Part	Nonsteady
same	EXTRUDING FLATS AND ROUNDS (Direct or Forward)			Zone Near Orifice	Steady
same	EXTRUDING FLATS AND ROUNDS (Indirect or Backward)		same	Zone Near Orifice	Steady
same	EXTRUDING HOLLOW SHAPES (Reverse Canning)		same	Zone Under Punch	Nonsteady
same	ROLLING FLATS, R'DS Etc. (w/o Front and Back Pull)			Zone Under Rolls	Steady
same	SWAGING and KNEADING			Zone Under Tools	Nonsteady
DRAWING (Chipless Forming)	WIRE and BAR DRAWING			Zone in Die	Steady

Figure 8. A Comparison of Deformation Processes as a Function of Shape Changing Stress Systems Required for Simulation
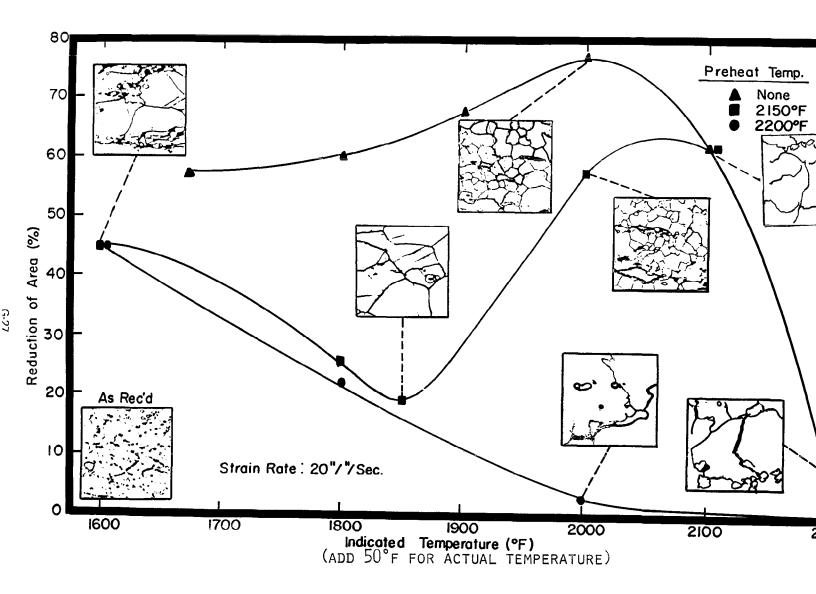
Figure 9. Example of Dynamic Recrystallization in Hastelloy X Ring Rolling Bar Stock
(Gleeble-Longitudinal Samples)
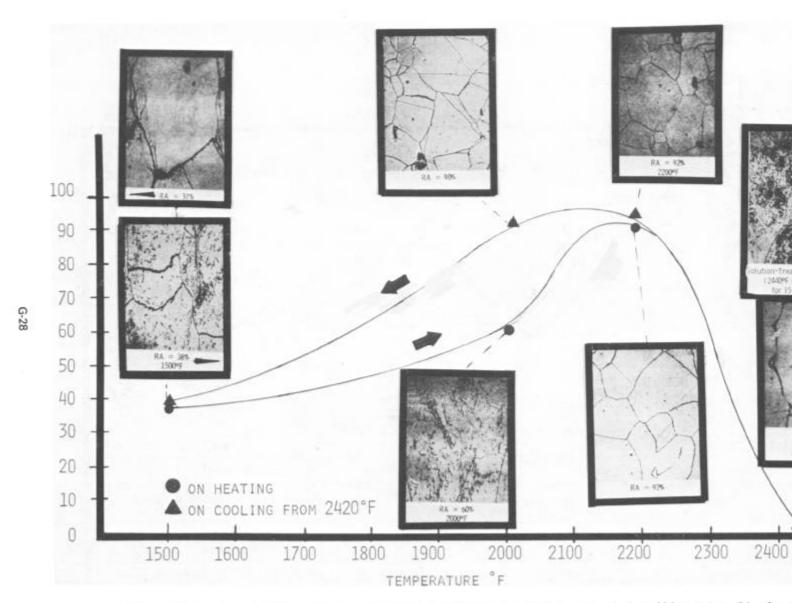
Figure 10. Recrystallization Behavior of Solution Treated and Aged I-600 During Simulate[d] Hot Working Conditions (Gleeble Data from Reference 31)
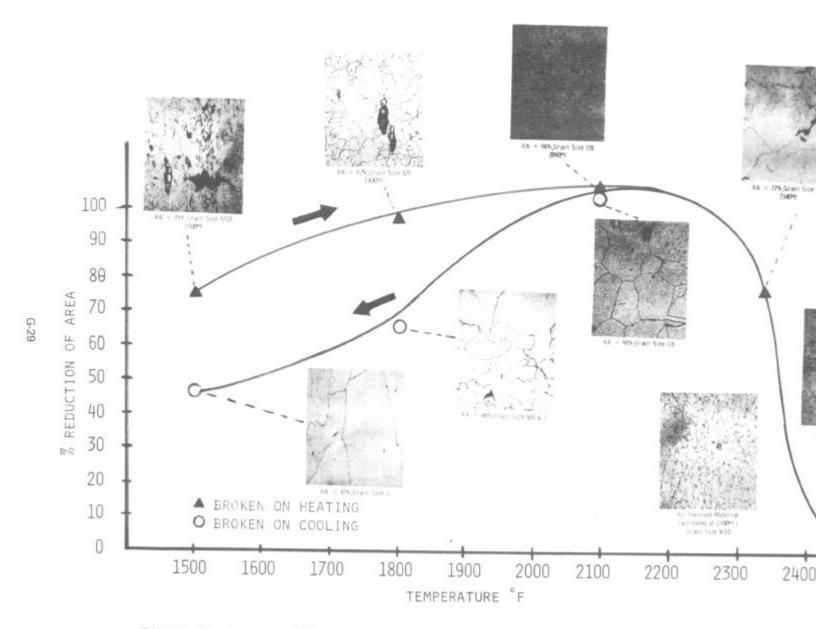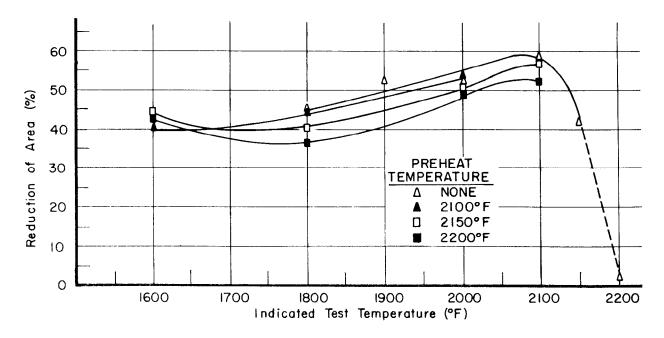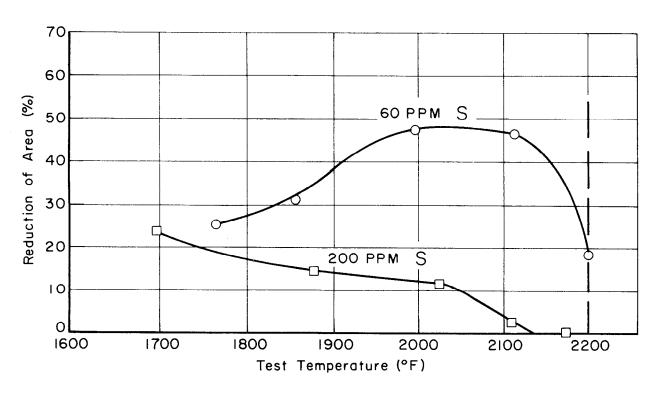
Figure 11. Recrystallization Behavior of I-600 During Simulated Hot Working Conditions
(Gleeble Data from Reference 31) (Materials in As-Received Condition)
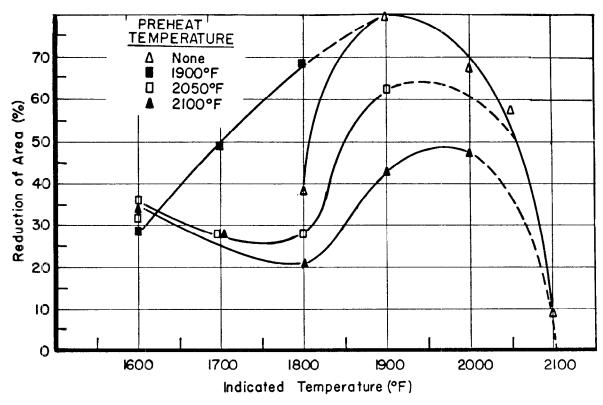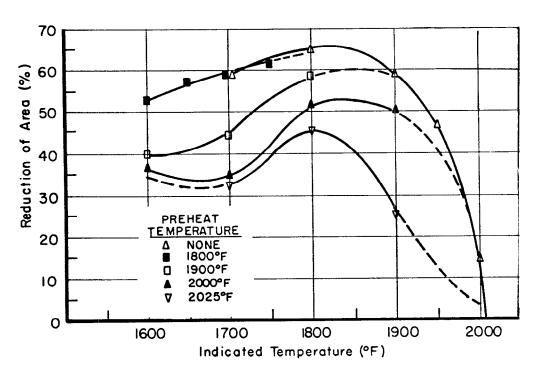
a. 4" VAR billet tested in gleeble at 20/sec

b. Experimental ingot sections gleeble tested on cooling
   from 2200°F

Figure 12. Production and Experimental Hot Workability Tests on Hastelloy Alloy C
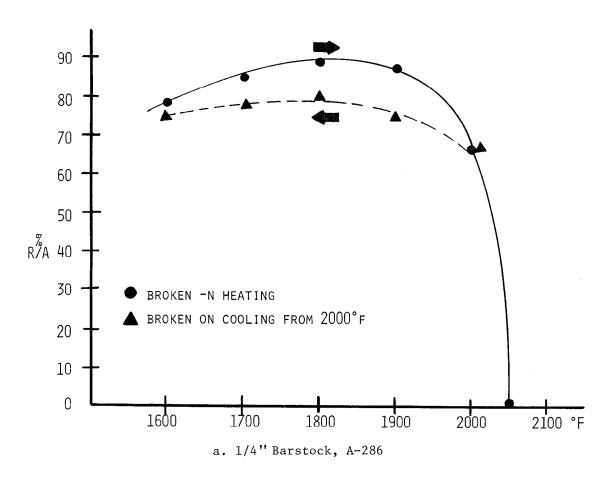
a. Rene 41 5/8" diameter barstock

b. I-718 fastener stock cold drawn
and solution treated

Figure 13. Gleeble Hot Ductility Tests of Two Nickel Base Alloys (Strain Rate 10/sec)
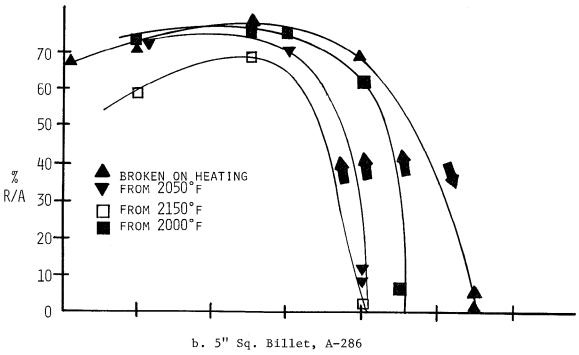
a. 1/4" Barstock, A-286

- ● BROKEN -N HEATING
- ▲ BROKEN ON COOLING FROM 2000°F

b. 5" Sq. Billet, A-286

- ▲ BROKEN ON HEATING
- ▼ FROM 2050°F
- □ FROM 2150°F
- ■ FROM 2000°F

Figure 14.   Some Typical Hot Workability Profiles for A-286 (Gleeble at 20/sec)

TEST DETAILS

SPECIMEN SIZE . . . . ½″ RD. BAR
SPEED OF TWIST . . . . 180 R. P. M.
HEAT TREATMENT . . . HOT ROLLED OR FORGED
NUMBER OF HEATS TESTED . . . SINGLE HEATS
Except 16-25-6

HOT TWIST DATA

1. 16-25-6
2. GREEK ASCALLOY
3. VASCO JET 1000
4. WASPALLOY
5. A286
6. S-816
7. M-252
8. UDIMET 500
9. J-1570

TEMPERATURE, DEG. FAHR.

RECOMMENDED MAXIMUM FORGING TEMPERATURE . . . ↓
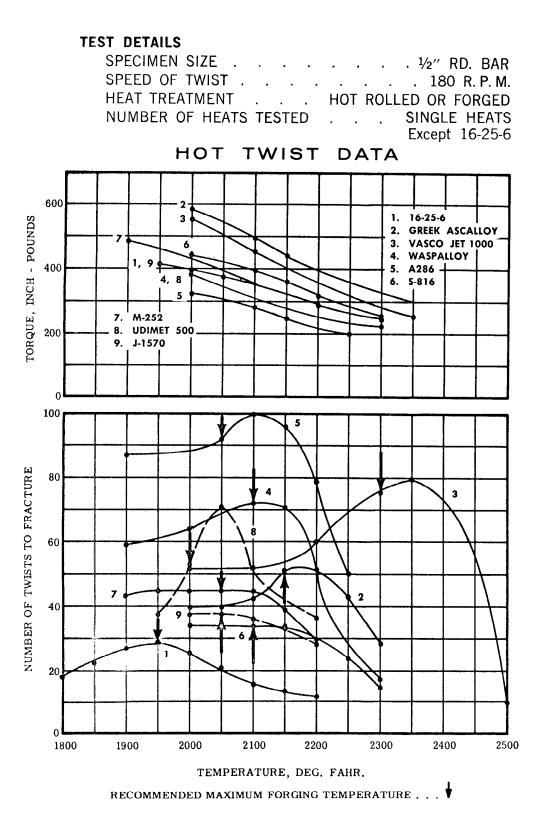
Figure 15. A Compilation of Torsion Hot Workability Curves for Superalloys
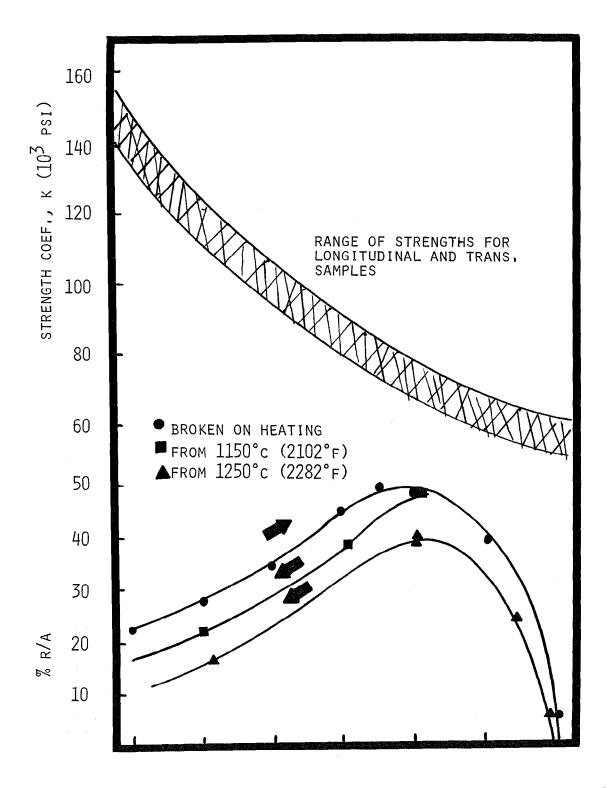(Courtesy Timken Roller Bearing Company)

Figure 16. Assessment of the Hot Working Characteristics of 21-4N Valve Steel by Means of Tensile Impact Tests
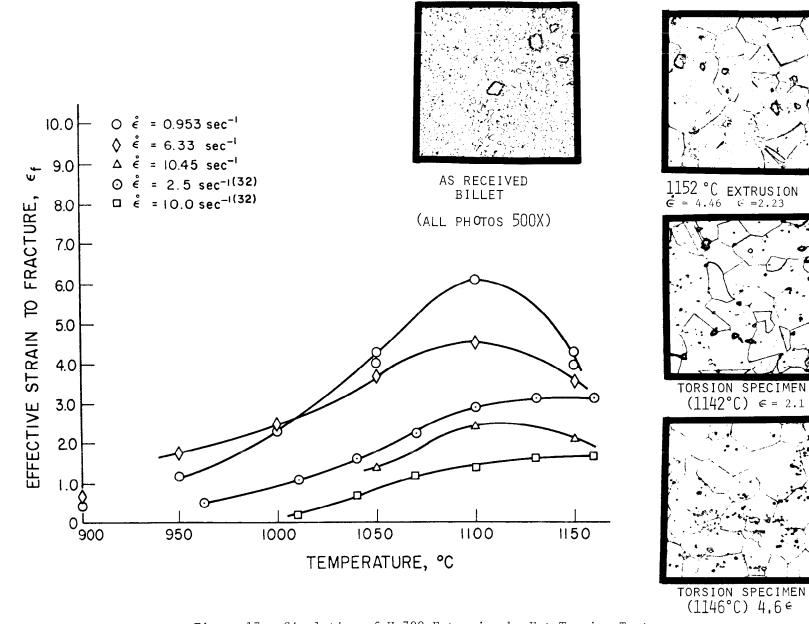
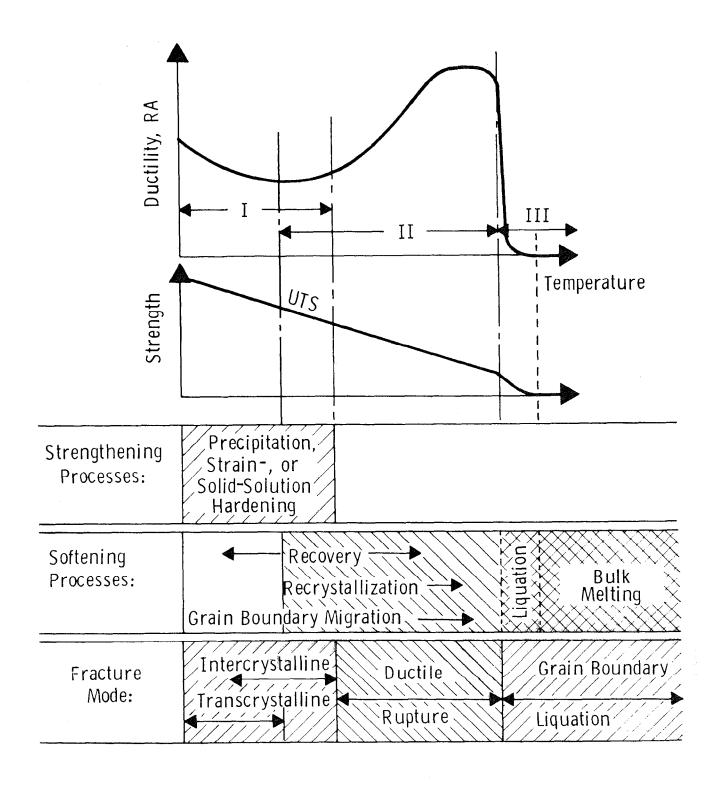Figure 17.   Simulation of U-700 Extrusion by Hot Torsion Tests

Figure 18. Schematic Portrayal of Hot Strength and Ductility Factors
(Courtesy of Welding Research Society)