ISOSTATIC PROCESSING – A NEW ENGINEERING DOMAIN IN THE FIELD OF MATERIALS SCIENCE

V. Jiman, V. Geaman
"Transilvania" University of Brasov, Romania
L. Geaman
High School "ASTRA" Brasov, Romania

INTRODUCTION

HIPing has a growing number of established applications. It is used to squeeze the porosity out of castings and forgings; to press the special steels which are used for cutting tools; to shape the most advanced super-alloys into blades and discs; to consolidate oxide-dispersion-strengthened alloys to make high-temperature components; in short, to make things out of materials which are particulary difficult to shape in any other way. High-performance ceramics fall in this category; so to do metal matrix composites.

The process of HIPing involves generally, powder packed in a thin preform that is subjected to a programme of pressure and temperature. It is a desired to optimise the density "D" as a function of the process variables: the time "t" of pressing; the pressure and the way it is applied "P"; the temperature and its history "T"; the radius "R" of the powder particles and the dispersion of radii; the initial packing density "Do"; and the material properties which describe the sintering characteristics of the particles themselves.

HIPing is an expensive process. A single run in a large press can cost thousands of dollars, and a development programme to optimize a HIPing schedule involves many runs. The primary aim of modelling, is to simplify and guide this optimisation of process, that is to identify the optimal combintion of pressure, temperature and time, and give guidance in choosing the best size, shape and condition of the powder. Ideally, the modelling should lead to a quick, accurate assessment of any proposed HIP cycle, directing the operator to the most efficient combination of process variables.[2].

1. THE STAGES OF SINTERING

The process of HIPing is, of course, a continuous one; but the geometry changes are large, and for that reason it is helpful to think of it as occurring in the three sequential stages. The first stage (stage 0), is that of powder packing. The initial packing density depends on particle shape, on the size distribution, on the degree to which the powder has been shaken down and on the extent to which surface and frictional forces prevent rearrangements which increase the packing density "D".

During stage 1, necks grow at the contact points between particles. A number of mechanisms contribute to neck growth: plastic yielding, creep and various sorts of diffusion. The important characteristics of stage 1, from the point of view of modelling, are that the necks are discrete, so that they can be trated as separate, and the porosity is connected, so that any gas on the pore space can escape.

Final densification occurs in stage 2. By this stage the necks have grown until they impinge and the individual pores have sealed off. From a modelling point of view, the material is now best throught of as a solid containing isolated spherical or polyhedral voids, connected by grain boundaries. As in stage 1, a number of mechanisms contribute simultaneously to the shrinkage of the pores ; they are detailed in the next section.

2. THE MODELLING OF HIPing

It is necessary in modelling the process of HIPing, to distinguish between the "local" and the "non-local" problem. The local problem is the growth of the one neck, and it can be analysed by considering just two neighbouring particles which meet at a single contact.

The pressure at the contact determines the local rates of diffusion, of plasticity or of creep, and thus the rate of growth of the neck or shrinkage of the pore. But this contact pressure depends on the total number of contact neighbours Z per particle, because the applied pressure P is supported on all of them. In the early stages of densification, this number Z is low - typically about 7. But as densification proceeds it increases. The more

contacts a particle makes, the lower is the pressure at each, so the total number of contacts per particle is important in calculating the growth of anyone neck. This is the non-local problem: it depends on the entire surroundings of the particle.[2].

We first consider the local problem: the growth of a single neck. The solution contains the pressure acting across the neck itself. This we derive by considering the non-local problem: the increase of Z with density.

3. THE LOCAL PROBLEM OF NECK GROWTH

During stage 1, the neck can grow by plastic yielding, by power-law creep or by diffusion. Each can be modelled, leading to an equation which describes its contribution to the current density D, the initial packing density D_O, and various material properties. The symbols for these properties are defined in work [1]. The total rate densification in stage 1 is given by adding together the equations for D. The current density is found by integrating the sum, starting at D_i, the density resulting from plastic yielding.

Stage 2 involves a similar scheme. The residual porosity can shrink by plastic flow, by power - law creep, or by diffusion. Modelling gives equations for the rates of densification, or for the instantaneous densit D_i, in the case of plastic yielding. The current density is found by integrating the sum, as before.

But although, the total densification rate contains several contributions, at a given density, pressure and temperature, one is almost always dominant : it contributes more than others. It is helpful to identify this dominant mechanism. Some mechanisms, like power-law creep, do not depend on particle size; others, particulary those involving diffusion, do; identifying the dominant mechanism tells us whether a change of particle size has any influence on the densification rate. Some mechanisms, like grain-boundary diffusion, are less sensitive to pressure than others, so an increase of pressure has least effect when this mechanism dominates; and the same is true of change of temperature.

4. THE NON-LOCAL PROBLEM

As particles sinter, their centres move towards each other, causing densification. Particles

which were originally close but not quite touching, meet and from new necks. The topology of this problem can equally well be considered by imagining each particle to expand about its fixed centre point.[1,2,3]. Analysis of this problem shows that the mean number of contact neighbours, "Z", grows with D, in a way which is adequately described by equation:

$$Z = 12 D. \tag{1}$$

and the average area of each contact grows, according to :

$$a/a\pi R^2 = D(D-Do)/12(1-Do). \tag{2}$$

where R is the radius of a particle, and "a", the average contact area at a neck.

The total contact area per particle, aZ, determines the contact pressure. When normalised by the total surface area of the particle, $4\pi R^2$, the result is :

$$aZ/4\pi R^2 = D(D-Do)/(1-Do). \tag{3}$$

The results rises from zero at the initial packing density to unity at full density.

The effective pressure acting across each neck, "Peff", is simply the force due to the external pressure, P, distributed over these contact areas. It is calculated from considerations of equilibrum, and is given by :

$$a(R')^2 P = ZaPeff. \tag{4}$$

The quantity R' is slightly larger than the actual particle dimension, because it represents the radius of the total volume associated with each particle, and that includes the appropriate fraction of void space. It is given by:

$$R' = R/D^{1/3}. \tag{5}$$

from which the effective pressure can be calculated as :

$$Peff/P = (1-D^o)/D^{1/3}(D-Do). \tag{6}$$

When the pressure is first applied, the effective pressure is very large because the particles touch only at points. But as densification proceeds the effective pressure falls and becomes equal to the applied pressure when full density is reached.

5. HIPING DIAGRAMS

With the rate equations set above, one can calculate HIP diagrams in the manner as sinter maps are calculated.[1, 3]. Two types of maps are generally produced: density-temperature maps at fixed pressure and density-pressure at fixed temperature. In both cases, the pressure is normalized by the yield stress and temperature by the melting point.

6. THE INCREASE IN USE OF ISOSTATIC PROCESSING FOR ALUMINIUM ALLOY CASTINGS

The castings industry originally perceived isostatic processing as a means to reduce its scrap rates. Prior to the development of HIPing no other non-destructive technique was available for the economic emphasis is now, however, changing towards the exploitation of improved properties as design engineers realize that cost parts which have been HIPed can develop capabilities similar to those expected from forged components.

The paper presents experimental data about compacting during HIP and CIP processes, applied to some types of castings from aluminium alloys very large used in the Romanian automotive industry.The origins of porosity in castings include shrinkage as the materials cools through the liquid-to-solid transition, trapped gases and the generation of gas by reaction. The effect of HIPing on the mechanical properties of castings like strength, toughness, fatigue resistance and creep life can all be improved by the removal of porosity. In addition, HIPing has a particularly beneficial effect by reducing the scatter in values of mechanical properties. This is particularly important where lifetimes must be predicted as accurately as possible.

When the HIPing process was first developed, the high unit-volume cost of a HIPing cycle limited the application of the technique to expensive materials. The following factors have, however, contributed to a significant reduction in the specific cost in recent years: increased vessel utilization, reduced cycle times, increased vessel sizes, increased system reliability, emergence of specialized HIPing sub-contractors, increased level of automatic control.

As a result, HIPing is now economically viable for relatively low-cost materials such as cast low-alloy steel and aluminium parts. This widening in scope is of major significance for the HIPing industry.

Into this "low"- material - cost category fall automotive parts such as cylinder heads, carburetor bodies, transmission cases and connecting rods, made from aluminium alloys. The aluminium alloys are offering the highest degree of hardness by heat treating or chilling followed by aging. The development of the range of these alloys is determined by the fact that alloying is enlarging the possibilities of dispersed hardness.

7. EXPERIMENTAL DATA

The particularities of the final heat treating made on casted peaces from aluminium alloys are determined by the characteristics of the casting structure as: high granulation, dendritical segregation, aciculate and dendritical form of the inter metallic compound, etc. Also the diffusion, which allows solubilization and than resettling of secondary phases is done much more slowly than in case of plastically treated alloys. Besides these particularities, when choosing the heat treating conditions, it must be considered also the shape and dimensions of the peaces. The increasing of the value for resistance by heat treating applied to bar strips is explained by the development of a solid solution with a better capacity of alloying as the one obtained by partial or total solidification and globulisation of secondary brittle particles [1].

By hardening, the $CuAl_2$ particles from the eutectic $Al-Si-CuAl_2$ are mainly peeled and the fragile eutectic is ending his existence. The silicon is globulising and the not peeled $CuAl_2$ particles will be uniformly distributed in the structure.As it is known, the value of mechanical properties of nonferrous alloys is lower in the immediate period after hardening, in the so called "incubation period". According to this, there was tried to isostatically compact samples by fast cooling immediately after hardening. Therefore, from the ATSi5Cu1 alloy, there were isostatically compacted, in cold medium (CIP), samples right after hardening.

The experimental results are included in Table 1, were is given the variation of the porosity related to the compacting time.

From these experimental data, it clearly results that the porosity is quickly eliminated, respectively at the same time of compacting the number of pores is decreasing with approx. 28%. The same result was obtained also by reducing the working pressure with 20%, from 150MPa to 120MPa, keeping the same time of exposure.

This can be explained by the deformability of the material after hardening, with the existence of solid soluble α supersaturated in Cu, which is homogenizing and after hardening is preserved relatively mild, with tenacity and formability.

Table 1. Variation of porosity related to compacting time

Sample nr.	*Compacting time [min]*	*Porosity after (Cast + CIP)[%]*	*Porosity after (Cast + Fast cooling + CIP)[%]*
1	0	3.219	3.219
2	3	3.113	2.986
3	5	2.875	2.672
4	10	2.676	2.335
5	15	2.280	1.710
6	20	2.043	1.159
7	60	1.116	0.966
8	120	0.846	0.509
9	150	0.620	0.131
10	180	0.328	0.085

In the case of ATSi5Cu1 alloy, after (2-4) hours, it begins a spontaneous hardening, a natural aging of the alloy, through submicroscopical sagging, extremely fine-molecularly dispersed - of the defined compound, followed by the increasing in volume, which, at this low temperature, determines the cold-hardening, the increasing of hardness, resistance and formability, which reaches a maximum (4-6) days after chilling. With a slight heating to (120-170)^{o}C and artificial aging, the same result, a little faded, can be obtained in a few hours.

According to these aspects, the authors are proposing two new technological ways of compacting by cold isostatic pressing (CIP), for the ATSi5Cu1 alloy, with the following parameters:

a). Variant I: P = 120MPa; T = 20°C; t = 120 min.

b). Variant II: P = 150MPa; T = 20°C; t = 95 min.

In comparison with the "classical" way of working (P = 150MPa; T = 20°C; t = 120 min.), the two new variants proposed, gives us advantages than in the first case the working pressure can be reduced and in the second case the time of exposure. Although this decreasing is major in the case of an industrial production, it has an essential role concerning the productivity and with the decreasing of working pressure, all the components of the high pressure installations are protected, which leads to the growing of fiability and security in exploitation.

8. CONCLUSIONS

Much progress has been made in the modelling of hot isostatic pressing. The mechanisms which contribute to each stage of densification have been identified and studied, and most are now well characterised. The preferred process coditions can be formulated. Experiments are currently being conducted to check and refine the calculations. Once this has been done, the remaining problem is that of technology transfer: how can these complex results be presented in a way which helps the materials engineer to design HIP cycles and select materials for HIPing process.

The best way of doing this, appears to be through the careful preparation of computer software which, for a selected material, will evaluate the consequences of any proposed HIP cycle, showing to operator the final density, other possible changes of structure, and suggesting to him the way in which the process variables can be traded off against each other to optimise.

References

1.Frost F.J. and Ashby M.F. - *Deformation - mechanism maps. Pergamon Press, Oxford (1982).*
2.Atkinson H.V. and Rickinson B.A. - *Hot Isostatic Processing. Adam Hilger -Series Editor, UK (1991).*
3.Geaman V. - *Hot Isostatic Pressing Diagrams for Aluminium Alloys, in "The First International Conference on Materials and Manufacturing Technologies" - 18-20 May 1994, Cluj - Napoca, Romania, 173 -178.*