SUPER-PLASTIC FORMING OF METALS.

by

Dr. M.P. Singh
R.I.T., Jamshedpur.

Superplasticity is the name given to a behaviour characterized by very large neck-free elongations to alloys in tension tests, which can exceed 1000%. To obtain such behaviour it is necessary for the alloy to contain fine grains and to maintain them at the test temperatures, and for the alloy to have a large dependence of flow stress on the strain rate. The strain rate dependence of the flow stress is usually expressed as

=K e^m (1) where = **flow** stress

K = constant

4 = strain rate

= parameter of a material (sensitivity of plastic flow stress to deformation rate)

The temperature at which super-plastic behaviour occurs is usually somewhat above half the melting temperature of the alloy in kelvin, and the strain rate (4) required is between creep and the strain rate of conventional hot-working processes. Grain boundary sliding and grain rotation are involved. Thus the principal conditions for the appearance of superplasticity are as follows!

(a) Ultrafine grain size i.e. (1-10 um)

(b) Low deformation rate (4) in the range of 10⁻ˡ 10^{-1}/sec

(c) A relatively high-temp (not less than 0.5 Tmp)

(d) Low stress.

The phenomenon of superplasticity has much in common with creep but differs from the latter in that the process is much more sensitive to the size and shape of grains and there is a sharper dependence of stress on deformation rate.

For a case of uniform deformation, the resulting dependence of the strengthening in a material on the amount and rate of defdrmation can be considered in terms of the parameters 'n' and 'm' in the following way:

6r= K e^n **A'** **(2)** where, e = strain

= dtrain rate

n = work-hardening coefficient.

This relationship, called the equation of state of a visco-plastic solid, has two typical extreme cases:

(a) The dependence of 0 on the amount of deformation is negligible (n 0). Then

K 411 (3)

in such case material behaves as a viscous solid i.e., the one having the highest plasticity, with m=1, there is a direct propertionality between (and 4 (called Newtonian behaviour)

(b) The dependence of on the deformation rate is negligible **(m --→ O).** Then

= K e^n CO

in such case the material behaves as a perfectly plastic solid whose strengthening is determined by the amount of deformation.

The rate of variation of cross-sectional area as a function of cross-sectional area at various values of tml has been ploted in Nglre 1. With low values of m (0.2 to 0.4) and n=0, the rate of variation of cross..sectional area depends strongly on the size of that area, the dependence being stronger as 1m' decreases. This means that4 with a low m, the appearing non-uniformity of the cross-section (local thin44ing) will increase sharply as deformation proceeds.

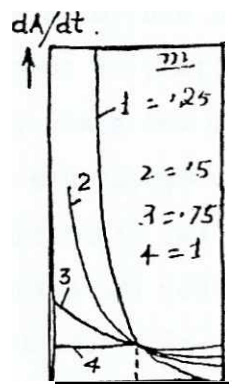


Fig:1-The rate of variation of cross-sectional area as a function of cross-sectional area at various values of m.

With an increase in fml the dependence becomes weaker and at m=1, the rate of variation of the cross-sectional area ceases to depend on non-uniformity in themagnitude of **A.** Thus, i" characterizes the liability of a material to necking, and therefore, its tendency to superplasticity.

Fig.2 shows an experimentally found correlation between 'm' and the maximum relative elongation (V, percent which characterises the highest plasticity. Superplasticity can appear in alloys for which m >0.3, while materials with **m** 4_0.2 exhibit common plasticity. As has beendemonstra_ ted in many works, however, one and the same material, with constant m, may show up different elongation $S_\$$ percent, depending on grain size and the nature of structural changes in the course of deformation.*

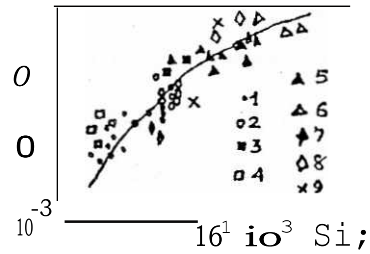


Fig.2: Relationship between tm' parameter and the maximum elongation determined experimentally: top

Determination of 'n' values:

The value of tml can be determined from the results of mechanical tensile tests. With the use of a stiff testing machine, the test is most often carried out by Backofen's method or its Modifications in which rate of tension is varied jumpwise

In Backofen's test, the rate of deformation is changed by varying the load F. A steady flow of metal is obtained, however, only in certain time interval after a change of the load, because of which Iml cannot be found directly on the stress strain diagram. Usually, the relationship, *d=j(c-)* is extraploted in order to obtain the same deformation at different rate of tension.

The fig.3 shows load-time curve obtained on a stiff tensting machine in the case when the rate of tension was increased at a certain time (point D) instanteneously from r_i to V_2. The steady state established upon this increase of the load is described by the point **A**

A E C V

Fig.1: Time Load curve of tension with jumpwise variation of tension rate V1 and V2 V_1 (to determine tra' parameter)

---

* It should be noted that the theorptically attainable plasticity at **m < 1** is quite low, for instance e 150% at m = 0.7. Hence superplasticity should not be considered as the problem of stability against necking, since, on the formation of a neck, a specimen may deform further by as much as 500-1000.

To determine 'm' the line of steady flow is extended from the point 'C' at a lower rate V_1 upto the point 'B' which corresponds to the same amount of defor.nation as that obtained in the point A at a higher rate of tension. After that, one can find on the graph the forces corresponding to the points A and B and, neglecting slight variations of m in the extraploted region, determine its magnitude from the relationship:

Lo F B
Log V 1 (5)

Where, FA = Load at V_2 rate

FB = Load at V_1 rate

In order to eliminate the effect of structural changes, it is reasonable to determine 'm' in terms of the forces corresponding to the points G and D, rather than those for the points IA' and 'B', that is:

Log (F D) (6)

The physical sense of this replacement may be explained as follows: As the rate of deformation varies, the instanteneons variation of the stress from the point U to the point G characterises the strain resistance for two given deforlation rates with the lowest difference in the strUCtute.'Rele.tIon .i-ee-by equation (5) as gives high value of and'often unreproducible values of Iml while relation (6) gives lower and less cattered values.

Effect of the conditions of Deformations ?licrostructures and Co position of Metal gn, a_epl/Ltj_sjty andPrincipal parameters of the process:

(1) Deformation rate: The most characteristic feature of superplasticity of an alloy is a typical pattern of the curve relating Iml to deformation rate 4

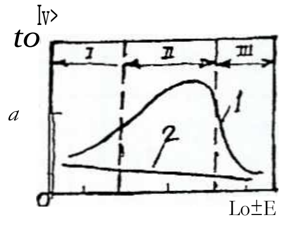


Fig. 4: Effect of deformation rate en 'm' parameter
1: Ultrafine grain alloy in state liable to superplasticity
2: Coarse grain alloy in a state not liable to superjaasticity.

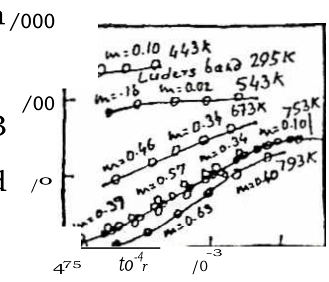
This is readily seen from Fig.}, which gives such curves for an alloy in a state of superplasticity (curve 1) and a state when it is not liable to exhibit this effect (curve 2). The former has a maximum, while the latter is almost linear.

In view of the typical pattern of the m-4 curve, it can be divided into three _sections according to-the deformation rate. Superplasticity appears in the range of deformation rates near the maximum of the curve (region II). As a rule, this corresponds to values of '111[1] within the range of 0.3 to 0.8 and to deformation rates between 10^{-4} and 10^{-1} per *see.* Both at lower (region I) and higher deformation rates (region III), 'm' is smaller and the tendency to superplasticity is accordingly lower, at m 0.3, the material ceases to be superplastic. The position of region II on the scale of deformation rates depends on a number of factors, the most important among them being the size of grains. The temperatures of deformation is essential too.

The relationship between ei and 4 (between flow stress and deformation rate) is less unique and more к unusual. It has been reliably established that in the state of superplasticity 6 is low, a few MPa or even a fractions of a MPa. It is understood that no strengthening of the material takes place upon deformation in region-II. Under conditions of superplasticity, the yield limit 0.2 of the material remains practically unchanged after the deformation i.e. equals the original value.

In contrast to this, deformation of material in region III of deformation rates gives a noticeable strengthening effect.

The relation between deformation rate and elongation 6, percent is seen in correlation between Iml and '5 [1]. It follows from the data given in Fig.3 that superplasticity is not accompanied with a jumpwise variation of but there is a correlation between Imi and which,in the first approximation



Fi : Effect of deformation emp. on the shape and position of d -4 curves of superplastic At+3Y/, Cu all(grain size 7 um) is the form:

$$(5^{-} \% = (100^{11} - 1) \times 100 \qquad (7)$$

Many exceptions are however known which disobey this relationship and still have not been explained properly.

Deformation Temp. al'

A change of deformation temperature has a strong effect on the pattern and position of the =/(d) curve. With increasing temp., the curve shifts towards higher deformation rates and lower stresses. In fig.5, it is seen that the value of in for superplastic states increases sharply with increasing temp. For instance, M = 0.10 at +3°K (0.35 **Tmp) afrm =** O4 0.61 at 793°K (0.7 Tmp). In contrast to this, in hot deformation of common metals and alloys (which are not in the state of superplasticity), [9]m' increases from roughly 0.02 at Td = 0.4 Tmp to roughly 0.20 at Td

On the other hand, 'm' does not exceed 0.3 upto temp close to 0.4 tn.p. This means that superplasticity appears at temp always above 0.4 - 0.5 Tmp. i.e. this is a typical high-temp process.

Correlation between Td, **4** and or can be described by the Arrhenius equation. Noting that the parameter [1]m' is temp-sensitive, the relationship is of the form:

e (I exp (- QAT) (8)

and do':=5, *4* exp (qm/k) (9)

Where 'Q' is the effective activation energy of the process. The analysis of the above equation provides very useful information. These are:

(1) The activation energies for region **II** of deformation rates are close to the values of activation energy of boundary diffusion and for region III, to those of volume diffusion.

(2) Explanation of the physical sense of Q values found experimentally, needs great care.

(3) Superplasticity is a complicated phenomenon associated with simultaneous occurrence of a number of elementary processes.

(4) 'Q' Represents the effective activation energies of the process and characterizes the temp. dependence of the rate of that process.

Deformation Scheme:

Superplasticity is insensitive to the type of **deformation. Experiments with the alloy of some** composition **deformed in tension, compression or twisting have given identical results. This** is **true however for material free from textures.**

It should be noted that the conditions of high-hydrostatic pressure which inhibit crack-initiation should be favourable for superplasticity and should probably lower **the temp at which the effect can appear.**

Grain size, texture, ohkse dnd chrnical n ositio:

Ultrafi —% is **must for the appearance of super-plasticity. The size of crystallites must be less than 10 um and smaller sizes are preferable. It is procisely ultrafine grain that is responsible for** the unusually strong sensitivity of the flow stress **of superplastic materials to deformation rate g .**

Shape of grain plays a very important role on superplasticity. With lamellar grains, even of a sufficiently small size, the effect of superplasticity disappears. The strong effect of size and shape have be shown in fi►.(6) and fig.(7) respectively.

Fig. (6) gigs the effect of &rain size on tm' parameter of Zn_Al alloy. With an increase of grain size from 0.5 um to 1.8 um, the region of high values of m (region II) is shifted tawa-rds lower deformation rates.

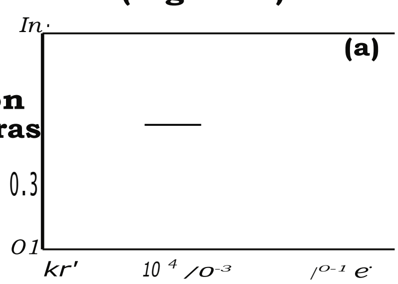
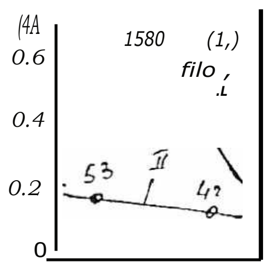


Fig.6: Effect of size of grains on superplasticity.(Im' parameter)foras Zn-Al Alloy (G.8. 1=0.5, 2=0.8, 3=1.4, 4=1.8).



Fit.7: Effect of shape of grain in case of Eutectic Pb-Sn alloy (I=Equiaxed grains, II=Lameller grains) Numbers at curves are elongation age.

Fig. (7) shows the effect of share of grains in the case of Eutectic Pb-Sn alloy w.r.t. to deformation rate and 'm' values.

A superplastic alloy with <u>equiaxed grains</u> 2.5 um in size may exhibit an elongation upto 1500%, but becomes a common alloy with the maximum elongation around 705 if the shape of its grains, for the same size, is changed from <u>equaxed</u> to <u>lamellar.</u> The strong adverse effect of Lamellar shape of grains is evidently associated with that it facilitates crack initiation at the early stages of the process, which results in the loss of superplasticity.

It should be noted that the effect of grain size !di on the stress of superplastic flow 6 sp is opposing to the effect on the yield stress in comlon deformation and has the form:

1sp ^ d^a t where 1s a coefficient close to unity.

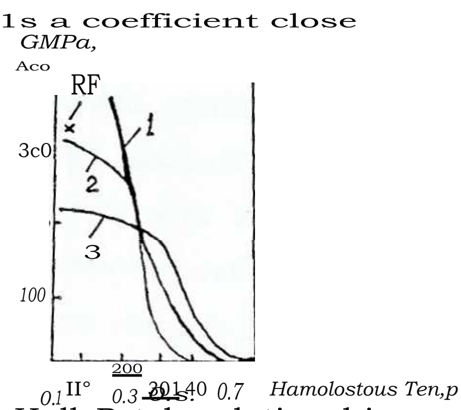


Fig. 8: Tiomogeneous temp. T_1K
Effect of deformation temp on superp1astic flow stress in specimens of (Zn+22'1, Al) alloy with grain size (1) 1.1 um, (2) 2.5 um, (3) 4.5 um,
BF = Brittle fracture.

If it is compared with the Hall_Petch_relationship, then it will be found that there is difference in the index power i.e.

$$= O + K_y r^{n}$$

where, n = 0.5 for B.C.C., i.e. (= 'O $K_y d^{-0.5}$

for (3-sp tf^a where a

The effect of temperature of an deformation for (A1+22'1 zn) having grain size 1.1 um, 2.5 um and 4.5 um has seen shown in fig. P.

Below 0.4 Trap, 6Sp is higher with lower grain size, at temp below 0.4 Tm.p., it increases with increasing groin size. The temp. at which the shape of the d curve changes is the point of transition to superplastic state.

Rethodp_of_Sh$_n$ping_ in Superolastic deformwtion:

Superplastic deformation methods depend on a number'of factors, in particular on the shape of original blanks. In modern practice of superplastic deformation, the most popular methods are shaping and deep drawing of sheet metal. Methods of vacuum and vacuuni-gas pressing (pneumoshaping) are used increasingly. Some methods of vacuum-gas thermoplastic shapping are illustrated in fig.;'. This method ensures a high uniformity of elongation and can be used for deformation of intricatee-shape articles in a single

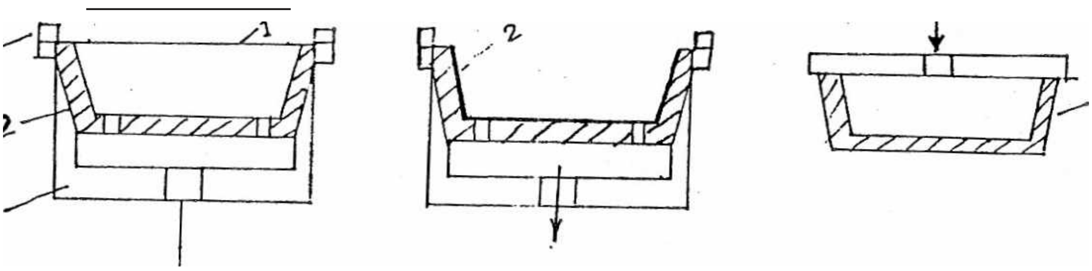


fig_.9: Diagram of vacuum gas superplastic shaping.
1. blank, be deformed. 2. **Die,** 3. Vacuum chamber
4. Cover, 5. Clamp.

operation without intermediate annealing and, in many cases without finishing operations.

An original method using superplastic flow has been developed for dieless drawing of tube blanks. A tube blank (fig.10) is clamped at one end in a holder **(1)** and drawn at the other and at a controlled rate V_2. An inductor (2) heat up the tube locally to the temperature of superplastic state and is moved at a rate V_1 **in** the direction opposite to drawing. The resulting reduction is determined from the relationship.

$$(D_1/D_2)^2 = (V_2/V_1) - 1$$

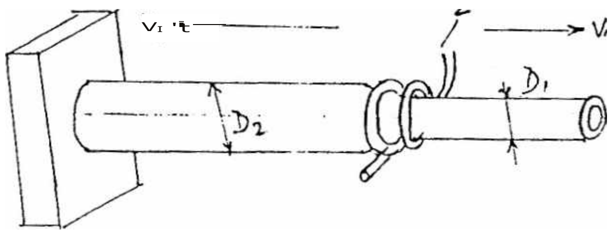


Fig.10: Dieless drawing of tube blank in superplastic state.

The reduction per pass is upto 501 but heavier reductions can be obtained in two or more passes. This method can also be applied for shaping tube blanks into conical parts. In that case, one of the two speeds must be constant and the other, variable.

guperplastic s:

The Superplastic alloys have been listed in Table 1.

MEDIUM TEMP. MATERIAL,

Si. No.	Composition	Optimum temp. of superple= sticitr	Strain rate	Elonga-tion	Gran size
1.	B-Plutonium	180°C	10^{-3}/sec	680	
2.	Al + 33% Cu	500°C	10^{-4}- 10^{-2}/sec	500	1-2
3.	Al + 5% mg	350 - 475°C	x	1000	
4.	mg + 32% Al	375°C	2 x 10^{-1}	1500	2.2
5.	In + Al	250 - 270°C	10^{-2}- 10^{-1}	1500	0.7
6.	Al+6% Cu + o.5% Zr	4500c	$1o^{-3}$	POO	6

HIGH TEMP. MATERIAL.

Sl. No.	Composition	Optimum temp. of superpla.. sticity	Strain rate	71Briga7: tion	size
1.	W+(15-30)% Re	2000°C		200	
2.	Cu+10% A1+4% Fe + 0.8% Zn	800 °C	10^{-3}/sec	700	10-12
3.	Ni+10%Cr+18%C0 +4.5% Ti+3.5%Ai +3%Mo+0.750 +0.5%Zr	1050-1300°C	10^{-4}-10^{-3}	1000	5
4.	Ti+6%A1+41/	900-950°C		1000	2

Table - 2

Microduplex Sinless

Alloy No.	Prior condition	Test Temp	Gauge length	Strain rate₁ pin	V T S KSi	Elongation	Mean auste-
1.		871	31.8	0.160	10.8	304	
1%	As hot-worked	927	31.8	0.160	7.3	304	3.61
2.	From 1204°C	871	31.2	0.160	10.5	160	
2.		927	31.8	0.160	6.9	208	
1.		871	19.1	0.266	10.5	433	
1.	Hot worked	927	19.1	0.266	7.6	600	2.19
1.	From (1204°O	982	19.1	0.266	5.4	500	
2.	then cold worked	871	19.1	0.266	11.8	300	
2.	80%	927	19.1	0.266	8.4	200	
2.		982	19.1	0.266	5.2	200	

Table-2 presents high-temp. tensile test results on two of the stainless steel compositions shows as Alloy 1 and 2.

Alloy 1: 25 **Cr,** 5.7 **Ni,** 0.69 Ti, 0.1 Al, 0.02 C, Bal. Fe

Alloy 2: 29.6 Cr, 6.0 **Ni, 0.70 Ti, 0.16 Al, 0.02 C,** Bal. Fe

The alloys were tested in two conditions. The first group was from 15.8 mm square bar stock which had been hot-worked starting at 1204°C. The second group was from similarly hot worked bar stock which was later cold rolled to 9.5 mm square. **In** the As hot-worked condition the microstructure was essentially ferritic, but on heating to the temp for tensile testing, there was appreciable austenite precipitation.

EX10.11016.22ligg±12112f SuDerplasticitv in Plastic working of metals:

Superplastid deformation has become most promising processes of plastic working of metals. It offers new possibilities for improving the properties and deformability of metals.

On the other hand, the method is by no means universally applicable. For the best utilisation of the method, one has to know its possibilities, advantages and drawbacks.

Advantages of Superplastic deformation:

1. Possibilities of shaping by plastic deformation are increased.

2. Superplastic deformation is done by using less force Which makes it possible to increase the size of articles to be deformed or to use Jess powerful equipment.

3. New deformation process such as vacuum shaping can be used.

4. This method is more suitable for drawing of sheet-metal.

5. Cost of dies is reduced as wear and tear are least.

6. The defect is minimised.

7. Shaped articles have high stability of dimension and high-corrosion resistance1 as there is residual stresses left in the articles.

8. An equiaxed ultra fine grain structure with weak or no texture is formed on sucerplpstic deformation. This gives complex mechanical properties of metal for operation at moderate temperature with high-yield strength impact and fatigue strength and good surface finish.

9. In case fine grain is unwanted, the structure can be coarsened by final heating.

contd... 13

Drawbacks of the Process:

1. Low rate of deformation.
2. Articles (Blanks) for superplastic deformation must have ultrafine-grain (1-10 um) and the structure must retain this property during the whole process of superplastic deformation - which is difficult.
3. Tools for superplastic working must be hot and retain the specified temperature during the whole time of the process.
4. Special difficulties arise in superplastic deformation of high-temperature materials (heat resisting nickel alloys, alloys of high-melting metals).
5. Articles must be held in the die until their temperature drops down below the limit of superplasticity, otherwise, they change their shape or dimensions under an occasional slight stress.