MM 208
Theory Of Metal Forming

Group 5 Presentation

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Introduction to Processing maps

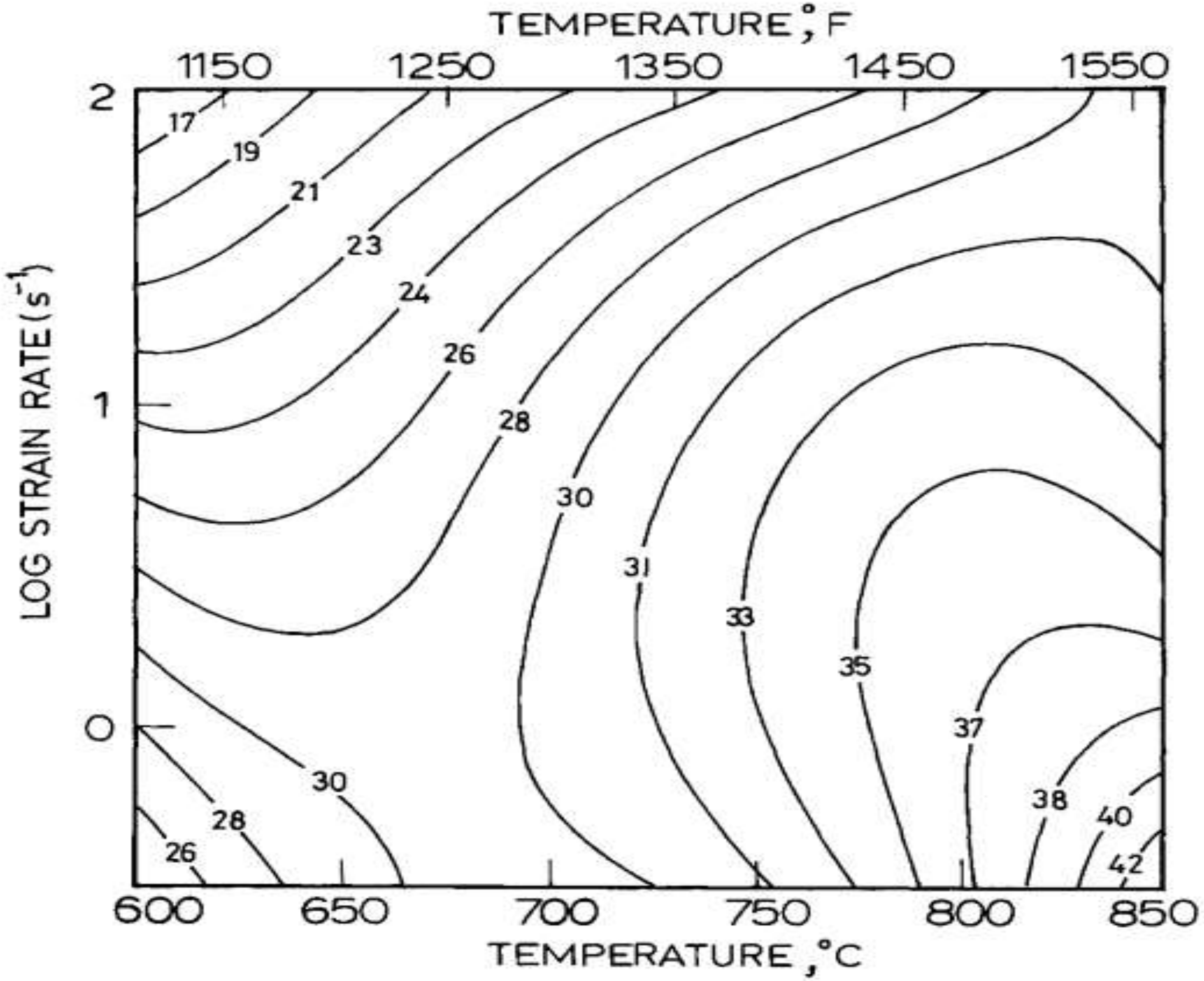
A Brief Explanation about Processing Maps and how to draw them.

What is a Processing Map ?

When a metallic alloy is subjected to deformation at high temperatures, it may undergo microstructural changes through different mechanisms. Some of these (e.g., dynamic recrystallisation and dynamic recovery) are known to be "safe" mechanisms, while others (e.g., void formation and wedge cracking) lead to the formation of defects.

Processing maps depict the hot workability of an alloy, by combining information about the ease with which its microstructure changes upon deformation with delineated regions of unstable flow. As such, they can be a useful tool to assess the ideal processing conditions that ensure a defect-free final product.

Example of a Processing Map -



Processing map for **Cu - 28Zn** at a strain of 0.4. Contour numbers represent percent efficiency of power dissipation

Power Dissipation Map

Processing maps are calculated in the framework of the dynamic materials model, whereby the metallic alloy in the hot working process (i.e., the workpiece) is described as a nonlinear dissipator. Crucially, the power absorbed during plastic flow is written as a sum of two explicit functions of the flow stress, σ, and strain rate, $\dot{}$:

$$P = G + J = \int_0^{\dot{\varepsilon}} \sigma \, d\dot{\varepsilon} + \int_0^{\sigma} \dot{\varepsilon} \, d\sigma = \sigma\dot{\varepsilon}$$

The first integral, G, known as the dissipator content, describes the power dissipated into heat, while J, the dissipator co-content, is related to microstructural changes in the workpiece. Usually, $G \geq J$, and the maximum co-content is obtained for a linear dissipator:

$$J_{max} = \frac{\sigma\dot{\varepsilon}}{2}$$

The efficiency of power dissipation is then defined as the ratio -

$$\eta = \frac{J}{J_{max}} = 2\left(1 - \frac{1}{\sigma\dot{\varepsilon}}\int_0^{\dot{\varepsilon}} \sigma \, d\dot{\varepsilon}\right)$$

The above quantity represents the ability of the workpiece to change its microstructure upon deformation. It may be derived entirely from flow stress data, either measured experimentally or calculated from suitable models. By plotting isovalue contours of η as a function of temperature, T, and strain rate, a power dissipation map is obtained. This forms the first part of a processing map.

Instability Criteria

A power dissipation map alone is, thus, insufficient to fully characterise the hot working behaviour of an alloy. In order to achieve this and, in particular, to optimise the processing parameters, it is important to distinguish those undesirable regions of unstable flow. By using appropriate instability criteria, it is possible to identify such regions and build an instability map, which when superimposed on the iso-efficiency contours results in the final processing map.

Instability criteria may be established under a number of different assumptions. A common route is to apply stability concepts from Ziegler's plasticity theory to the dissipation functions of the dynamic materials model. This approach leads to the Kumar-Prasad and Murty-Rao criteria,

Kumar – Prasad criteria → $\xi_{K-P} = \frac{\partial \ln(m/(m+1))}{\partial \ln \dot{\varepsilon}} + m < 0$

Murty – Rao criteria → $\xi_{M-R} = 2m - \eta < 0$

where m denotes the strain rate sensitivity parameter: $m = \frac{\partial \ln \sigma}{\partial \ln \dot{\varepsilon}}$

Processing maps of Brasses –

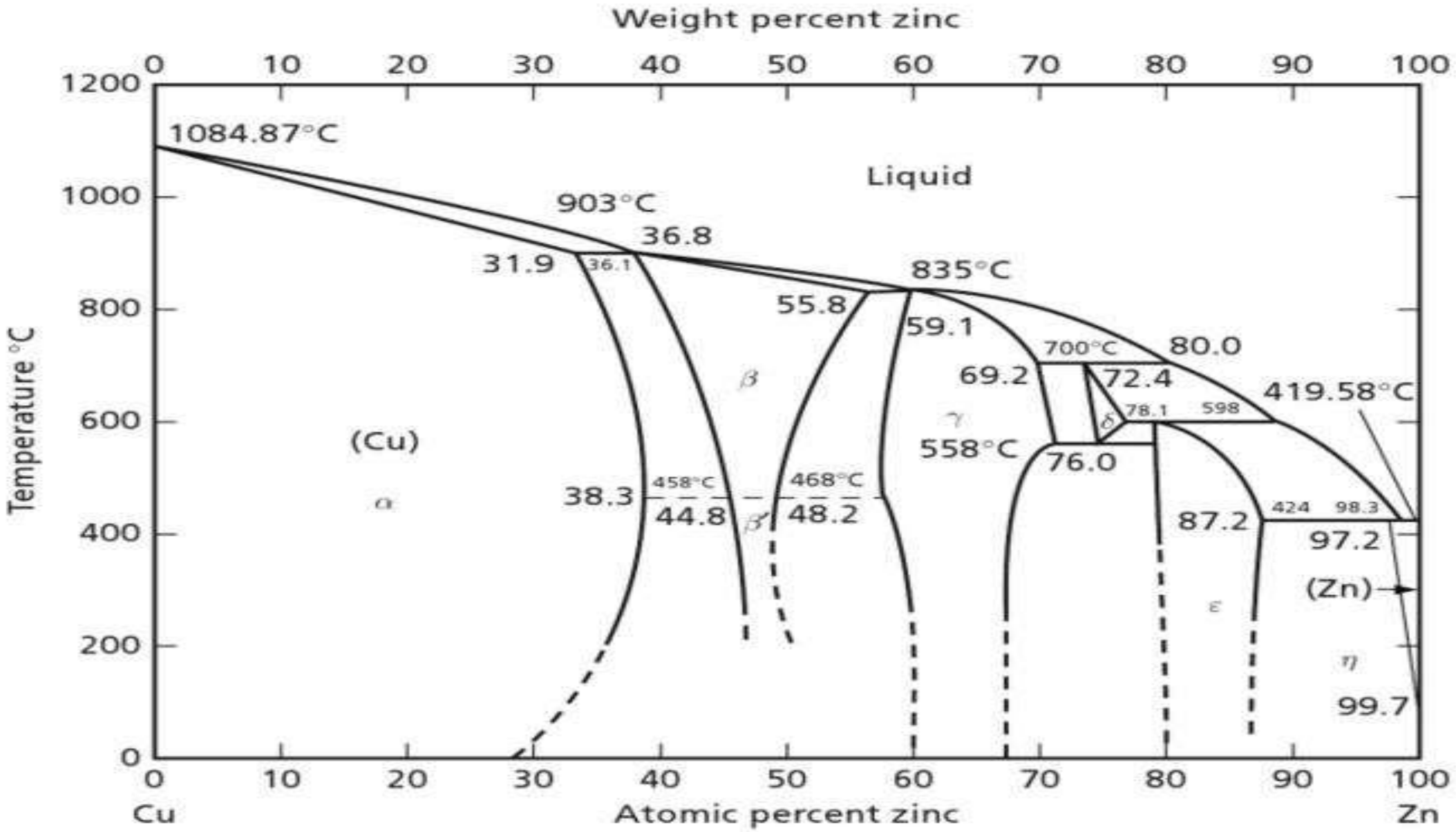
Cu – 3Zn

Cu – 10Zn

Cu – 15Zn

Cu – 21Zn

Cu – Zn Phase Diagram



In the Cu-Zn phase diagram, there are two types of invariant reactions that occur at specific temperature and composition ranges, namely the eutectic reaction and the peritectic reaction.

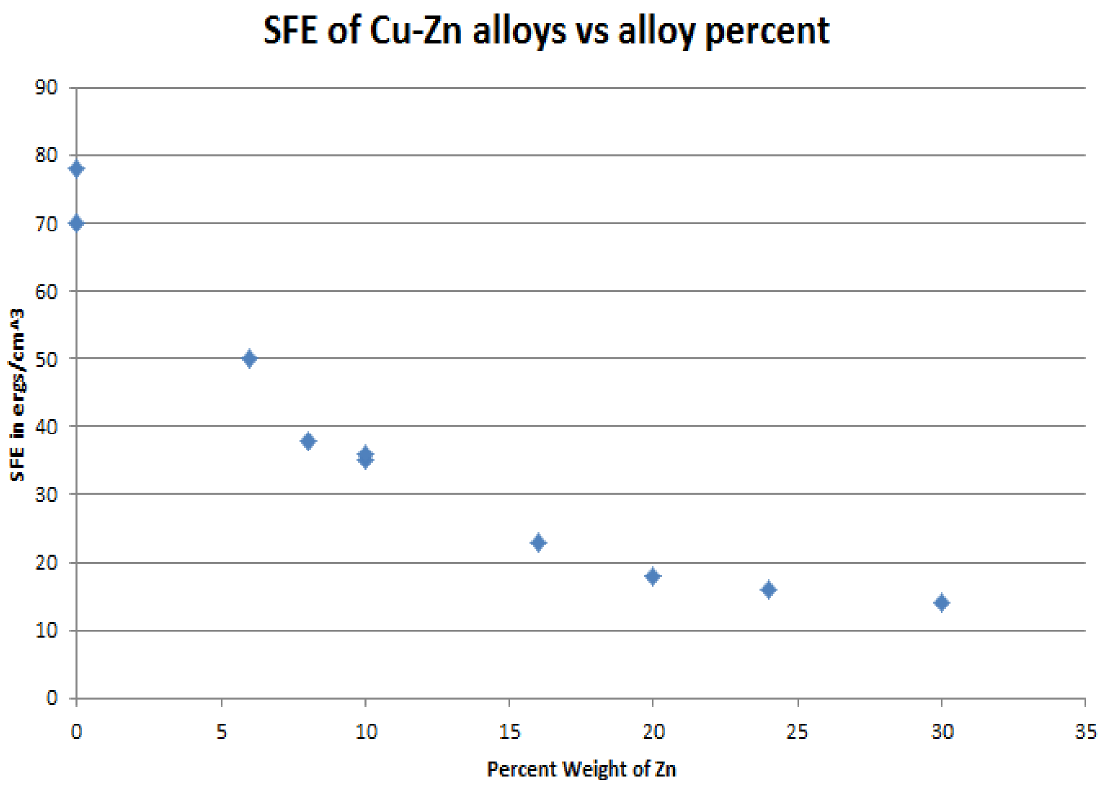
Eutectic Reaction : The eutectic reaction in the Cu-Zn phase diagram occurs at the composition of 63% Cu and 37% Zn, with a melting point of 903°C. At this point, the solid phase transforms into two liquid phases, Cu-rich liquid and Zn-rich liquid. The composition of the two liquid phases is the same as that of the eutectic point.

Peritectic Reaction : The peritectic reaction in the Cu-Zn phase diagram occurs at the composition of 98% Cu and 2% Zn, with a melting point of 821°C. At this point, the solid phase transforms into a liquid phase and a new solid phase with a different composition. The new solid phase has a higher Zn content than the original solid phase, while the liquid phase has a composition equal to the peritectic point.

These invariant reactions are important because they define the boundaries of the two-phase regions in the phase diagram and can be used to determine the solidification behaviour of alloys in the Cu-Zn system.

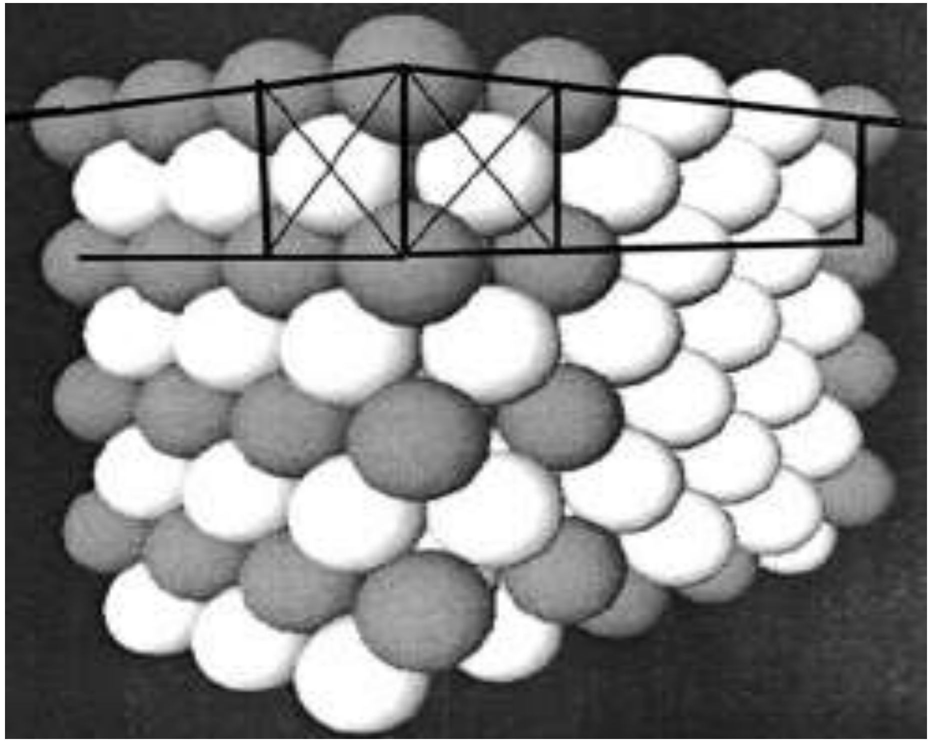
STACKING FAULT ENERGY

- Stacking fault energy (SFE) is a measure of the energy required to create a partial dislocation in a crystal lattice (or) we can say the energy required to create a stack of crystal planes, called a stacking fault, within a crystal lattice.
- It affects the formation and motion of dislocations, which are the primary carriers of plastic deformation in metals.
- Metals with low SFE are generally more ductile and have better formability.
- So, strength of alloy increases with decreasing SFE.



Cu – 3Zn

Composition of the Alloy -: 97.6 % Cu - 3.4 % Zn



The stacking fault energy of alpha brass decreases from 40 mJ/m2 to about 15 mJ/m2 with additions of zinc from 5- 30% while an abnormal increase in the diffusion coefficient is observed at 850 °C.

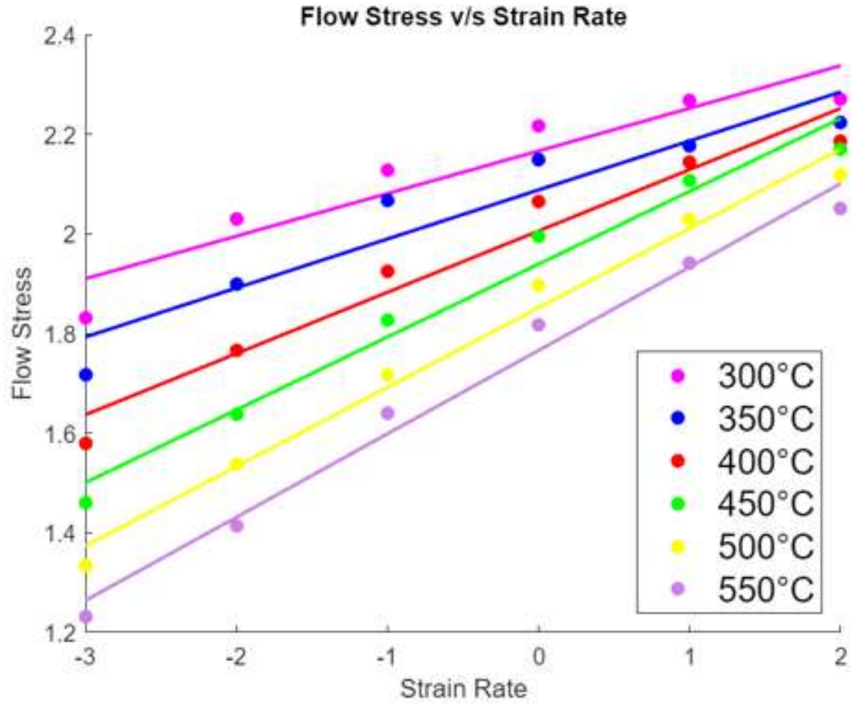
Regions of maximum efficiency occur at :

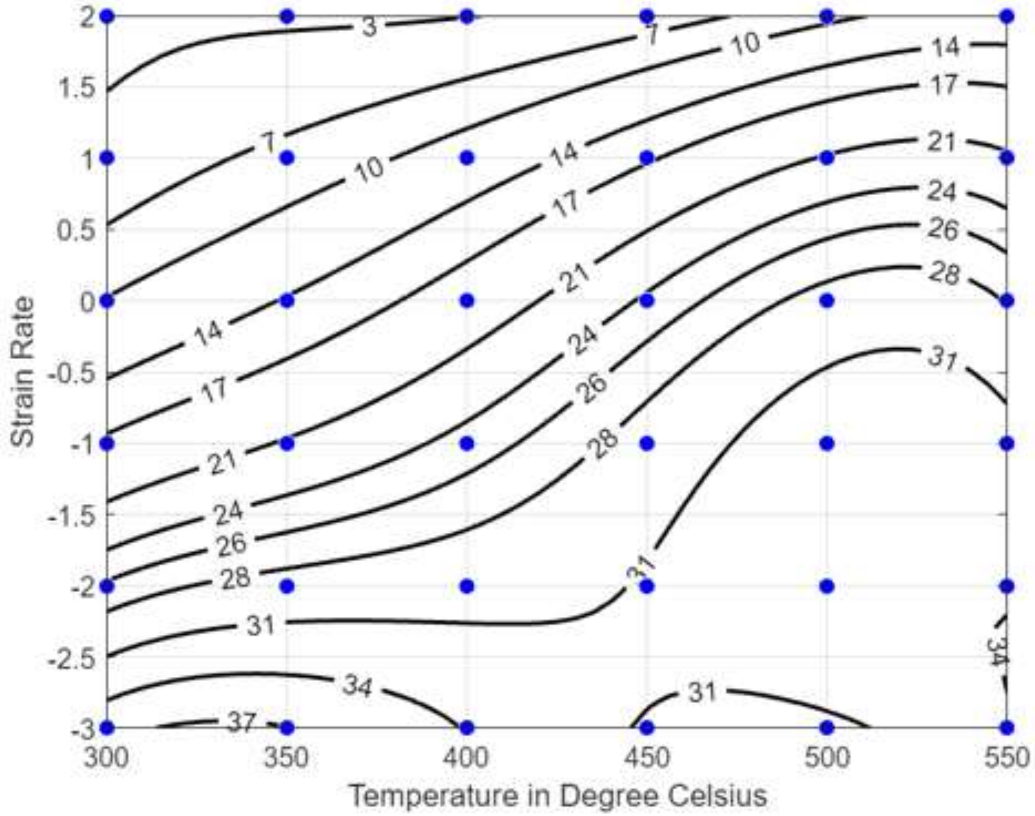
- T=850 °Celsius, ε'=0.1 s-1 with peak efficiency of 34% (dynamic recrystallisation)
- T=600 °Celsius, ε'=0.001 s-1 with peak efficiency of 37% (wedge cracking)

Regions of flow instability occur at :

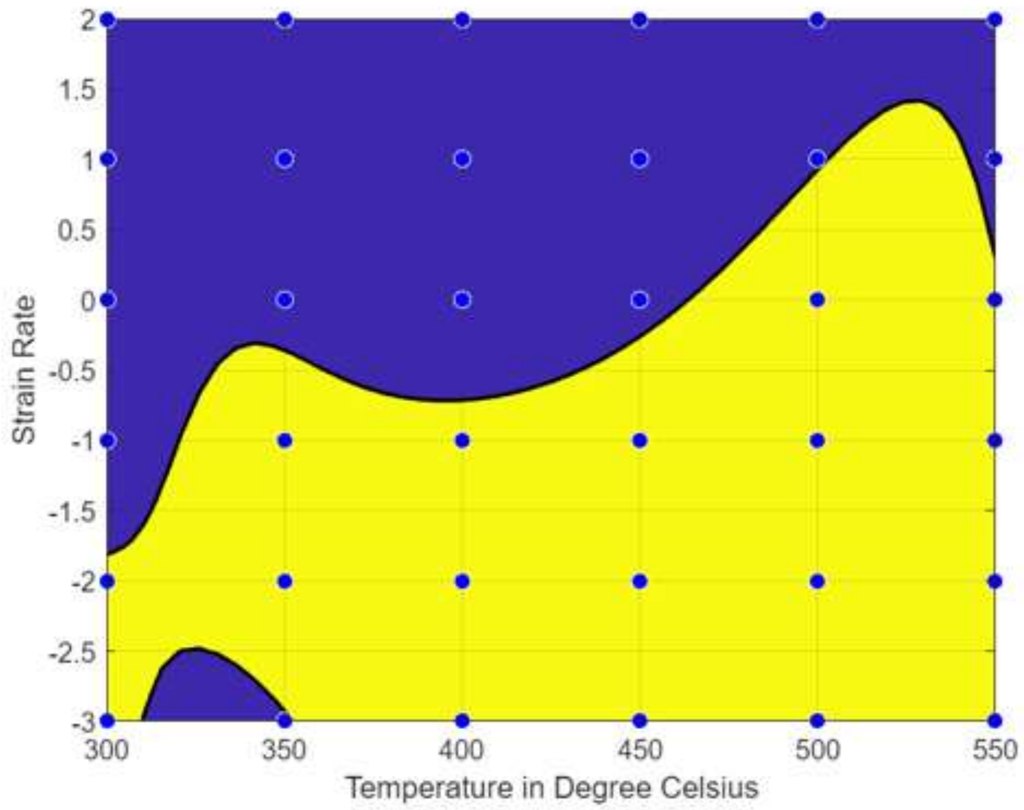
- ε'>=1 s-1 at all temperatures.
- ε'>=0.1 s-1 , T<700

- **Optimum temperature: 850 °C**
- **Optimum strain rate : 0.1 s^{-1}**

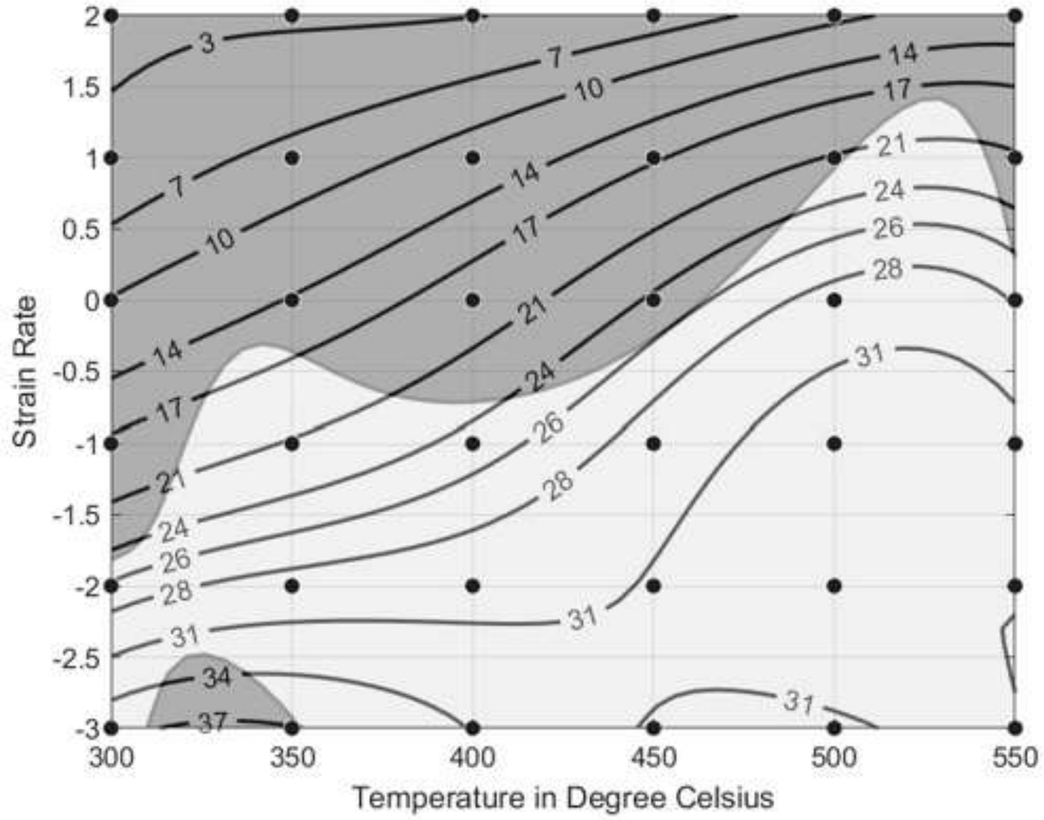




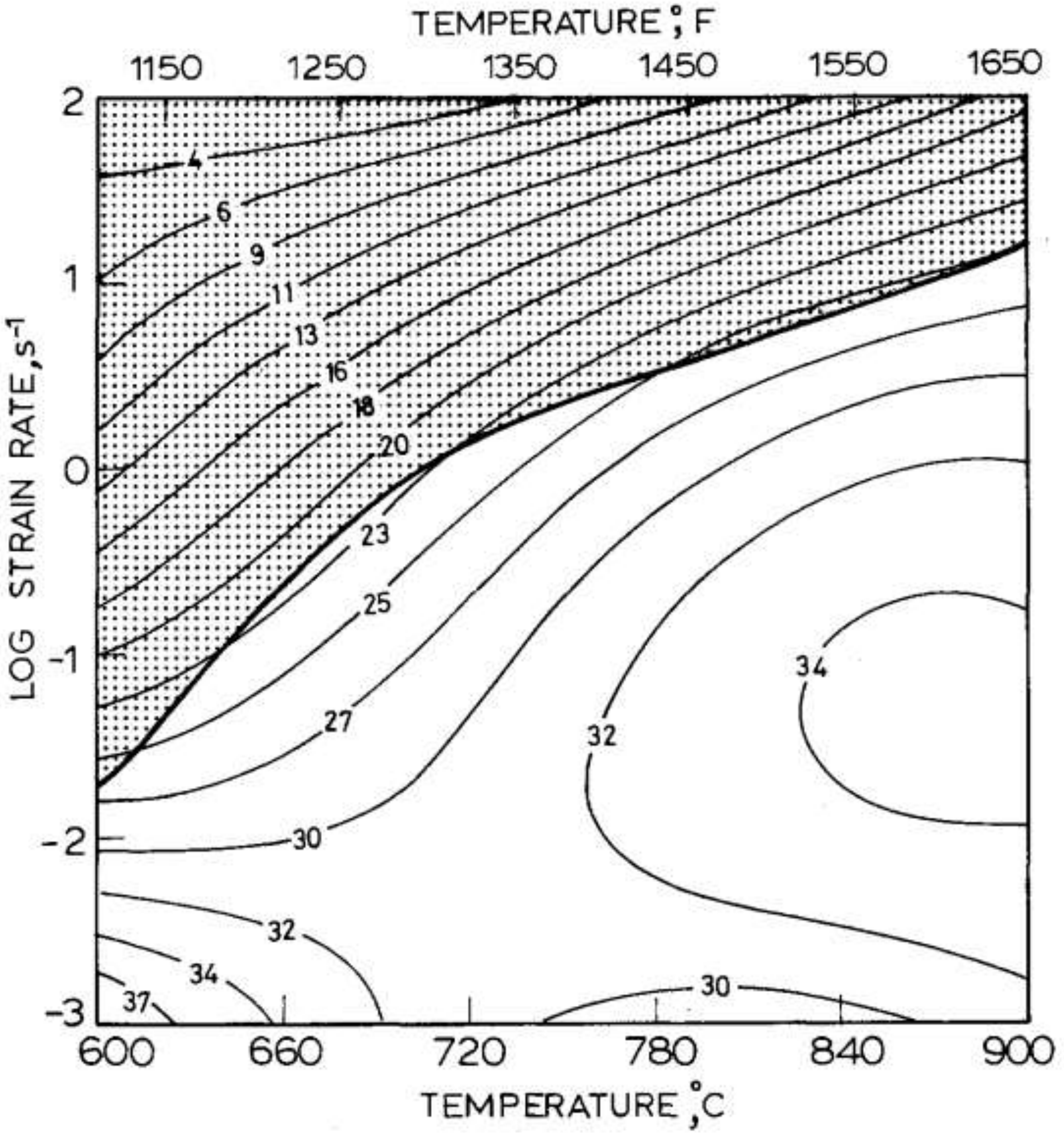
Power Dissipation Map



Instability Map



Processing Map



Processing map for **Cu-3Zn** at a strain of 0.4. Contour numbers represent percent efficiency of power dissipation. Shaded region corresponds to flow instability.

Strain	Strain Rate, s^{-1}	Temperature, °C						
		600	650	700	750	800	850	900
0.1	0.001	64.1	51.9	41.0	31.3	24.6	18.5	13.6
	0.01	86.8	67.3	54.2	43.1	34.7	26.6	21.2
	0.1	99.7	87.8	65.6	55.7	44.3	37.9	31.2
	1	120.0	102.1	85.6	74.3	60.7	51.3	41.2
	10	137.2	106.2	97.6	94.0	80.8	67.9	57.7
	100	130.0	115.7	108.0	106.3	95.0	82.0	75.1
0.2	0.001	71.1	55.3	36.9	29.0	21.9	16.5	12.5
	0.01	100.7	78.0	62.6	44.4	34.7	25.7	20.3
	0.1	123.2	105.8	78.6	64.4	51.2	43.8	35.7
	1	146.5	125.8	104.8	88.8	71.4	60.4	48.0
	10	163.0	134.0	124.0	115.2	96.7	78.3	67.2
	100	162.6	148.0	135.7	129.9	117.6	100.0	90.4
0.3	0.001	67.7	52.2	38.0	28.9	21.6	17.0	13.2
	0.01	107.3	79.4	58.3	43.4	34.4	25.9	20.4
	0.1	134.3	116.7	84.3	67.2	52.0	43.7	34.5
	1	164.8	141.0	115.9	98.6	78.8	65.8	52.6
	10	184.9	150.0	139.4	128.1	106.9	87.5	74.7
	100	186.3	167.8	153.8	147.9	131.7	112.3	101.2
0.4	0.001	64.9	51.6	38.2	29.1	21.5	16.6	13.3
	0.01	105.4	77.0	57.5	43.8	34.7	26.2	20.4
	0.1	140.9	118.9	85.6	65.4	50.3	42.7	34.2
	1	175.5	148.9	123.1	103.3	82.6	67.2	53.5
	10	201.1	160.5	148.8	136.7	114.1	93.1	79.4
	100	209.3	184.6	167.7	160.1	141.8	119.8	108.6
0.5	0.001	64.6	50.1	38.6	29.1	21.9	16.6	13.3
	0.01	104.5	76.1	56.9	43.3	34.3	26.2	20.7
	0.1	143.5	119.9	82.8	64.2	49.4	41.8	33.7
	1	184.7	154.1	125.1	105.1	82.8	65.6	52.4
	10	221.8	170.8	157.2	143.4	120.3	97.8	81.9
	100	229.9	195.8	175.7	168.2	149.0	124.6	113.6

Flow stress values (in MPa) of **Cu-3Zn** at different temperatures and strain rates for various strains (corrected for adiabatic temperature rise).

Cu – 10Zn

Composition of the Alloy -: 90.3% Cu - 9.7% Zn

Cu-10Zn alloy is an **α** solid solution and is called red brass. The alloy has a stacking fault energy of about 36 mJ/m2.

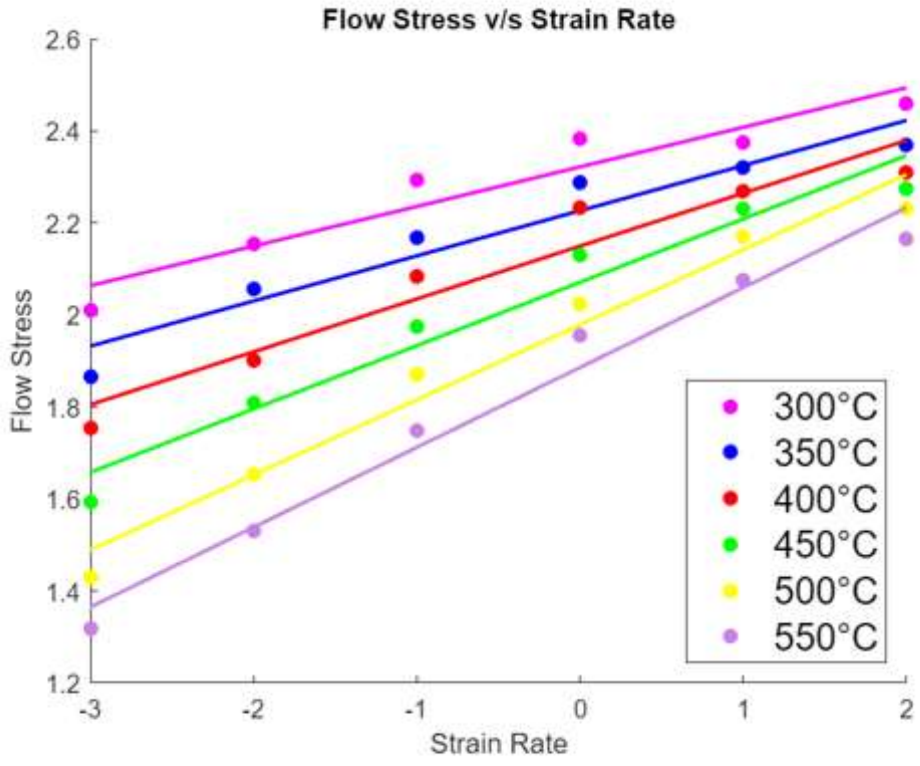
Regions of maximum efficiency occur at :

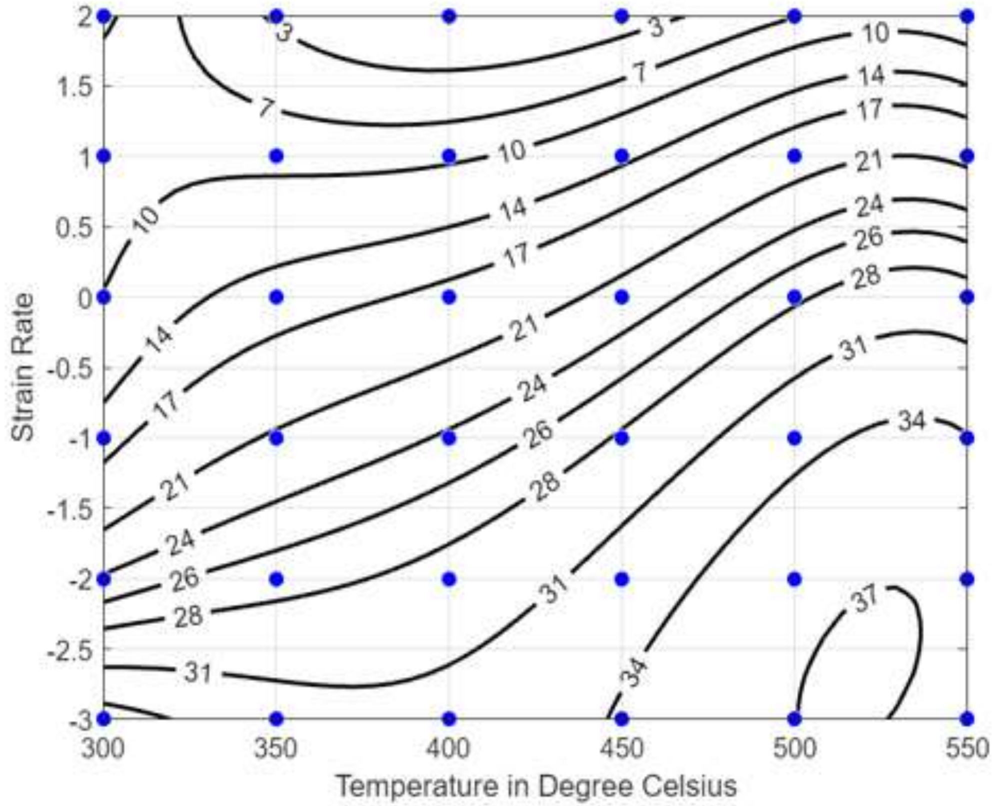
- T=850 °Celsius, ε'=0.1 s-1 with peak efficiency of 36%(dynamic recrystallisation).
- T=550 °Celsius, ε'=0.001 s-1 with peak efficiency of 36%(wedge cracking).

- Regions of flow instability occur at :
- ε'>=3 s-1 at all temperatures.

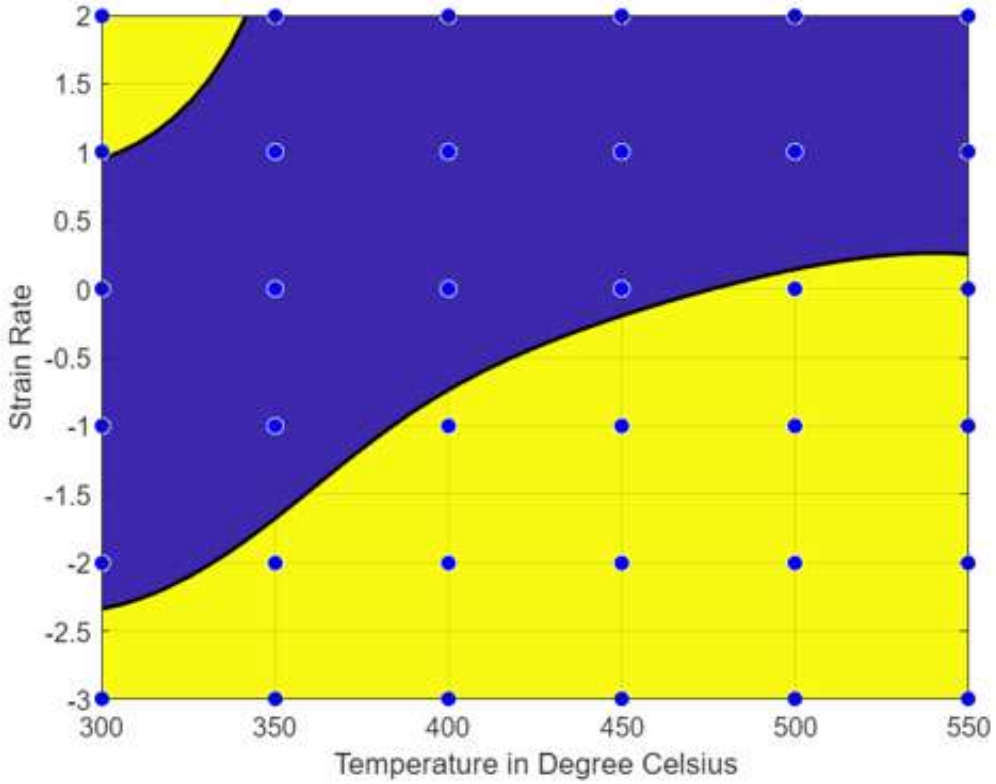
Optimum temperature: 850 °C

Optimum strain rate : 0.1 s^{-1}

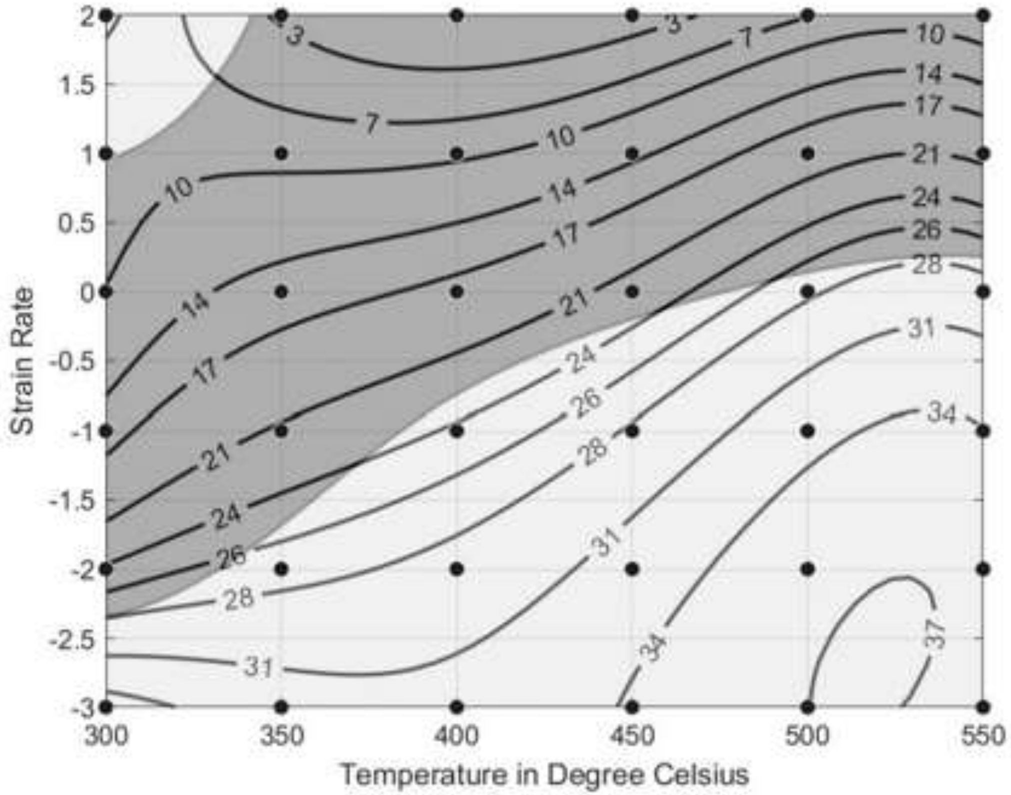




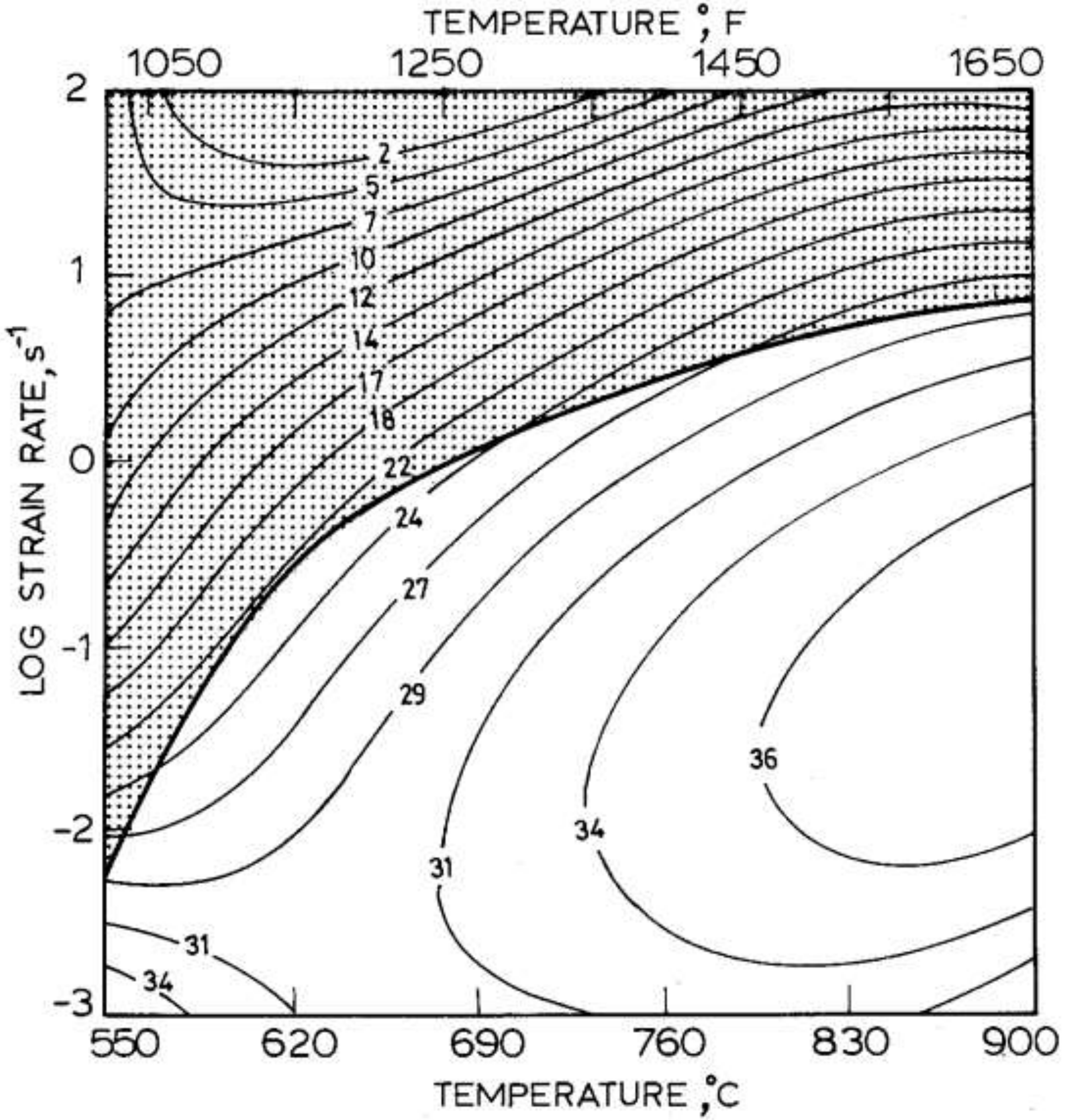
Power Dissipation Map



Instability Map



Processing Map



Processing map for **Cu-10Zn** at a strain of 0.4. Contour numbers represent percent efficiency of power dissipation. Shaded region corresponds to flow instability.

Strain	Strain Rate, s^{-1}	Temperature, °C							
		550	600	650	700	750	800	850	900
0.1	0.001	87.5	69.0	51.8	41.6	29.1	21.9	17.4	12.6
	0.01	115.0	96.2	71.3	59.9	44.3	34.9	26.7	20.7
	0.1	148.0	118.1	100.4	80.1	66.4	50.1	39.0	32.5
	1	184.6	149.1	134.8	108.4	87.6	74.9	62.9	48.4
	10	176.0	152.0	135.8	128.9	115.8	95.5	83.1	67.0
	100	203.7	166.2	148.2	139.9	126.1	106.2	97.8	82.5
0.2	0.001	98.0	77.4	58.5	39.9	27.1	20.8	16.8	11.8
	0.01	133.9	109.4	79.3	67.2	44.8	34.0	25.9	19.0
	0.1	176.2	136.5	114.5	90.8	74.2	54.6	42.3	35.3
	1	220.6	178.0	159.7	125.5	99.1	84.2	70.4	53.5
	10	214.9	190.6	170.0	154.4	135.8	110.2	93.4	73.6
	100	252.7	209.8	187.0	171.6	154.3	130.1	116.4	96.9
0.3	0.001	102.1	73.4	56.9	39.3	27.0	20.8	16.3	12.0
	0.01	142.4	113.6	79.8	64.5	44.9	34.0	25.5	18.4
	0.1	196.2	147.3	121.6	94.5	74.3	56.0	42.2	33.7
	1	241.9	193.8	171.5	134.6	105.9	90.1	74.6	57.0
	10	237.1	208.8	185.6	169.6	148.6	119.3	97.8	78.8
	100	288.9	234.7	204.2	188.7	170.5	146.6	129.9	104.7
0.4	0.001	99.6	72.3	57.1	39.2	27.2	20.5	16.3	11.9
	0.01	145.5	112.2	76.6	64.4	43.6	34.1	25.4	18.8
	0.1	204.8	150.9	123.1	93.3	73.6	53.7	41.1	32.7
	1	268.5	205.9	177.1	139.9	109.2	91.6	75.5	57.2
	10	253.4	220.4	193.9	176.9	153.7	124.1	102.5	83.3
	100	341.2	256.7	213.7	199.1	181.5	153.7	136.3	110.8
0.5	0.001	99.0	71.5	57.3	38.9	27.5	20.7	17.0	12.4
	0.01	144.5	112.1	74.4	63.5	43.7	34.4	25.3	18.8
	0.1	213.4	152.1	122.0	92.5	72.5	52.6	40.4	32.2
	1	301.2	215.1	179.3	140.1	108.7	90.3	75.4	56.4
	10	269.5	229.9	202.2	184.0	159.5	127.9	104.4	84.9
	100	396.4	274.3	220.8	205.6	183.2	155.8	139.2	110.7

Flow stress values (in MPa) of **Cu-10Zn** at different temperatures and strain rates for various strains (corrected for adiabatic temperature rise).

Cu-15 Zn

Composition of the Alloy -: 85.1% Cu - 14.9% Zn

Cu-15Zn alloy is called gilding metal and is used as tubes and rods produced by hot extrusion. The alloy has a stacking fault energy of about 25 mJ/m2 .

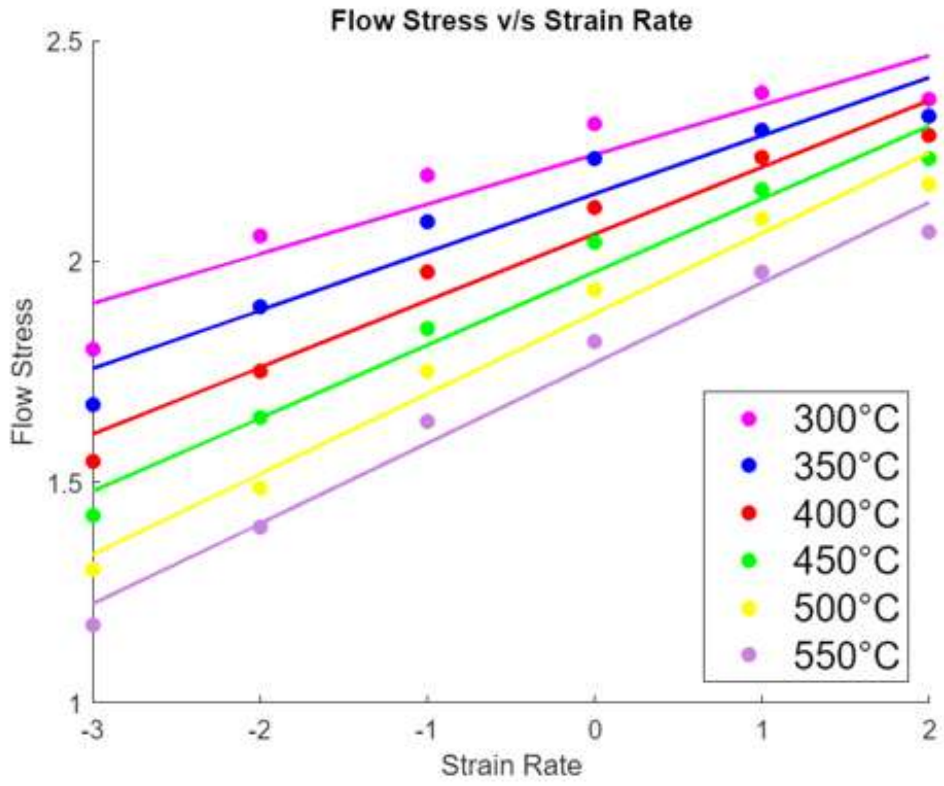
Regions of maximum efficiency occur at :

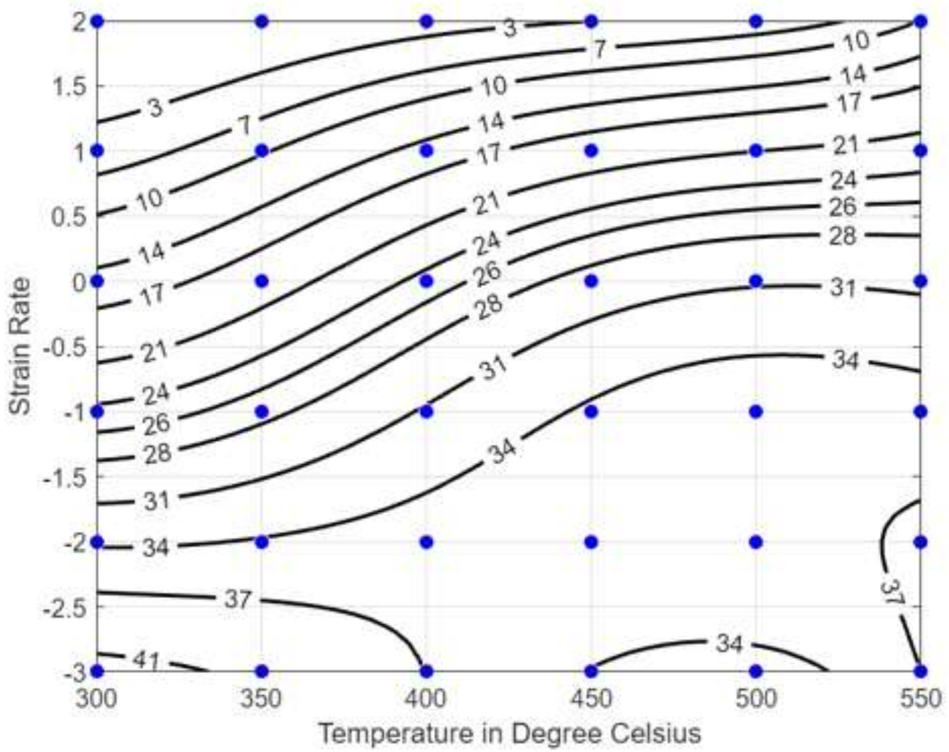
- T=850 °Celsius, ε'=0.1 s-1 with peak efficiency of 36% (Dynamic Recrystallisation).
- T=600 °Celsius, ε'=0.001 s-1 with peak efficiency of 37% (wedge cracking).

- Regions of flow instability occur at :
- ε'>=1 s-1 at all temperatures
- ε'>=0.1 s-1 , T<700

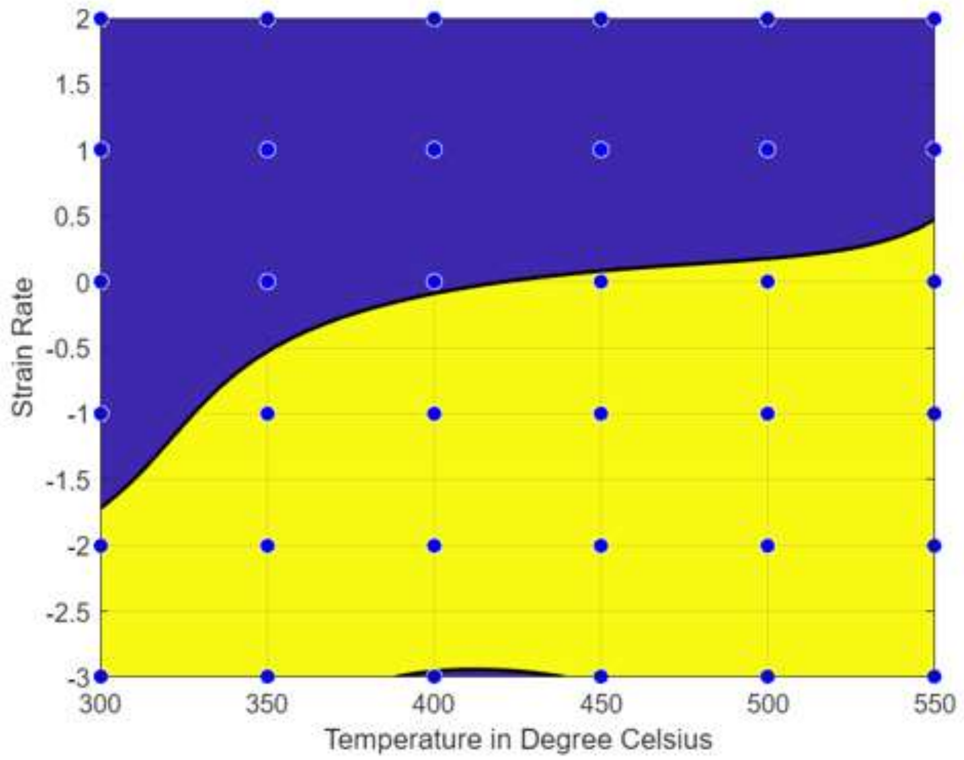
Optimum temperature: 850 °C

Optimum strain rate : 0.1 s^{-1}

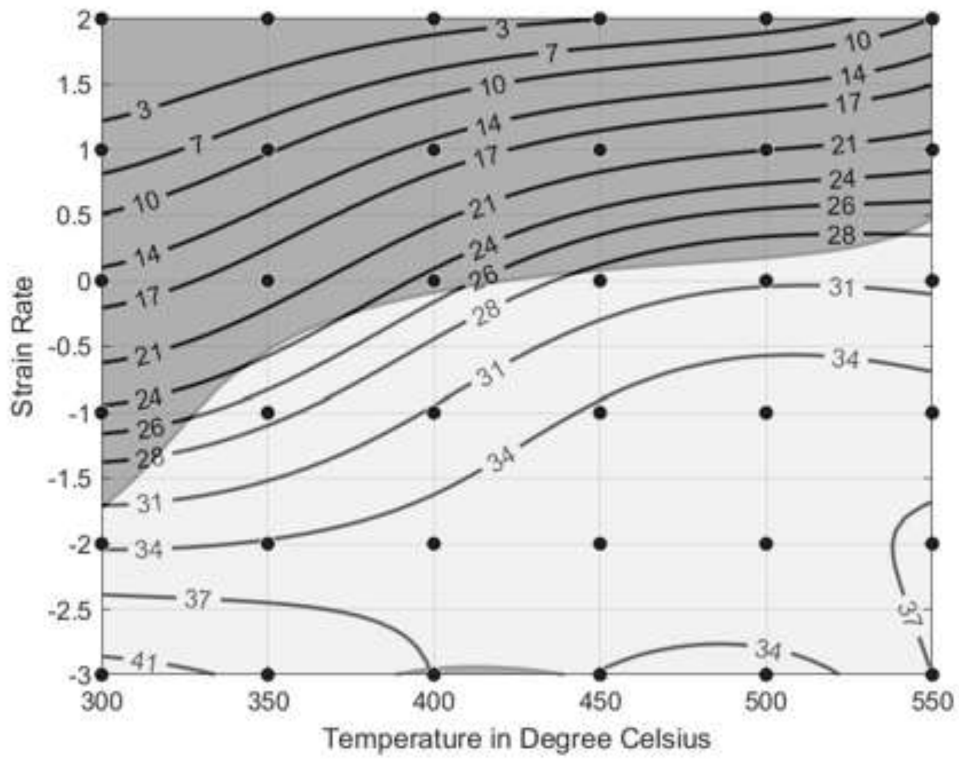




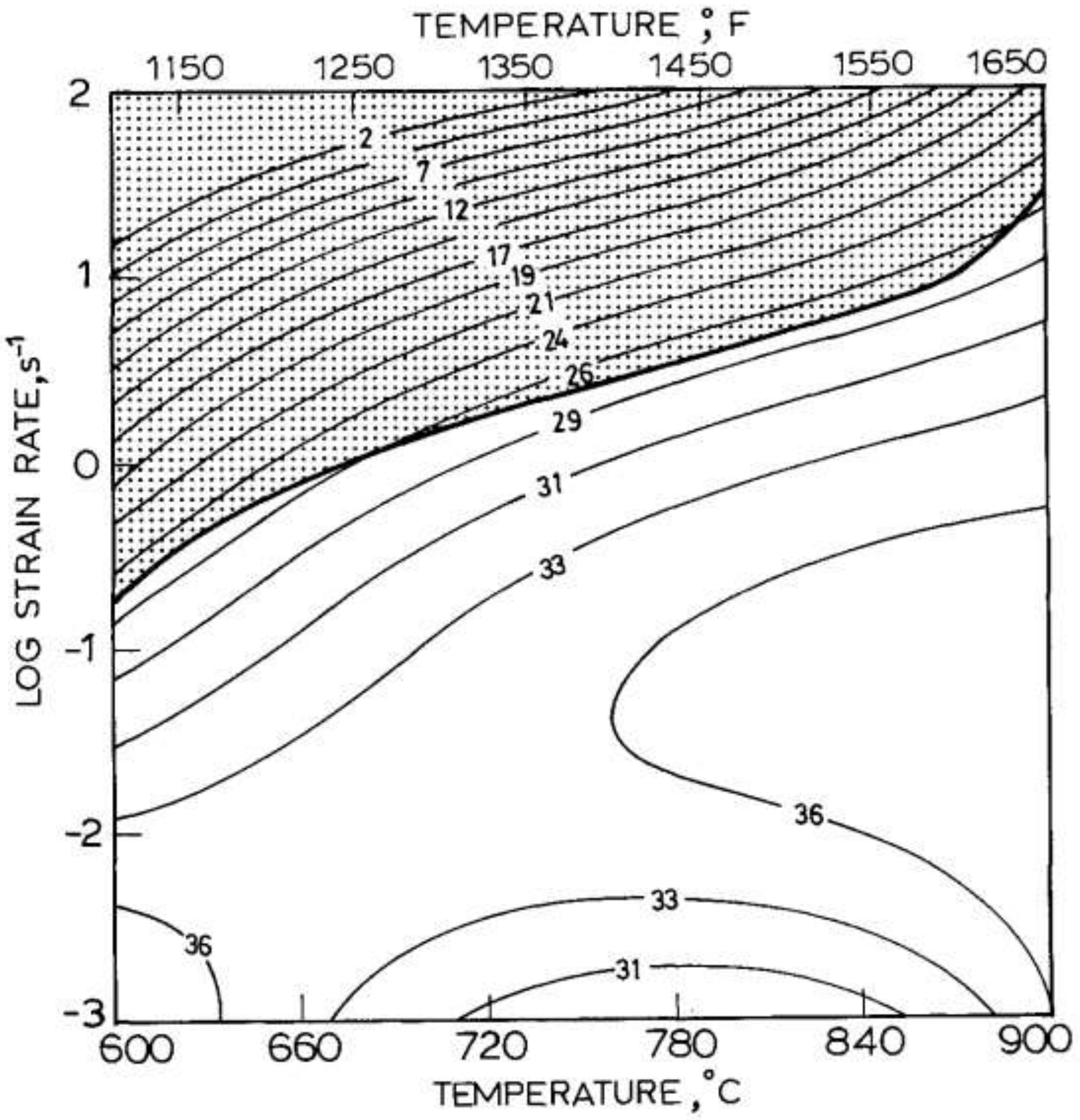
Power Dissipation Map



Instability Map



Processing Map



Processing map for **Cu-15Zn** at a strain of 0.5. Contour numbers represent percent efficiency of power dissipation. Shaded region corresponds to flow instability.

Strain	Strain Rate, s^{-1}	Temperature, °C						
		600	650	700	750	800	850	900
0.1	0.001	62.8	46.3	35.4	27.9	22.5	15.4	10.3
	0.01	104.6	72.5	54.8	45.0	31.7	26.0	19.1
	0.1	130.1	104.8	82.0	63.3	52.4	40.5	31.6
	1	158.3	137.3	109.5	93.8	73.6	57.5	50.2
	10	178.1	149.6	134.9	117.7	103.8	79.8	67.1
	100	155.8	150.6	142.6	130.3	115.3	92.0	83.8
0.2	0.001	68.0	48.0	35.8	25.5	20.4	14.6	10.6
	0.01	111.1	80.6	61.1	45.5	30.5	25.4	18.2
	0.1	150.1	116.5	90.5	68.4	55.9	43.7	33.7
	1	191.1	160.2	125.0	104.7	82.8	63.9	54.4
	10	225.1	186.2	161.1	136.0	118.0	89.0	74.5
	100	210.7	194.8	175.3	156.4	135.8	107.1	98.6
0.3	0.001	66.4	48.9	33.7	25.8	20.1	14.5	10.5
	0.01	113.9	78.7	56.5	44.4	30.6	25.1	18.3
	0.1	156.7	123.0	94.4	70.6	56.6	43.4	32.8
	1	205.5	171.3	132.8	110.5	86.0	65.7	55.6
	10	240.8	198.3	172.7	145.5	125.0	94.7	78.7
	100	232.9	213.6	192.8	171.3	149.3	116.8	108.0
0.4	0.001	63.1	47.4	35.3	26.5	20.1	15.0	10.7
	0.01	110.6	76.1	55.9	43.7	31.1	24.7	18.4
	0.1	158.7	125.9	95.0	69.7	55.1	41.9	32.0
	1	212.8	176.8	136.0	112.5	85.7	65.1	55.1
	10	256.1	207.5	179.3	151.6	130.6	97.9	81.7
	100	245.2	223.4	200.2	178.7	156.5	122.4	113.2
0.5	0.001	63.0	48.5	35.4	27.2	20.5	15.2	11.0
	0.01	106.7	74.0	55.3	43.2	31.1	24.5	18.3
	0.1	156.9	125.0	93.6	69.2	54.2	41.8	31.4
	1	229.9	182.2	136.2	112.4	84.2	63.2	53.4
	10	285.3	218.3	183.9	155.1	133.2	98.8	82.9
	100	263.7	235.6	206.8	181.4	158.7	123.7	116.0

Flow stress values (in MPa) of **Cu-15Zn** at different temperatures and strain rates for various strains (corrected for adiabatic temperature rise).

Cu-21Zn

Composition of the Alloy -: 79.8% Cu - 21.2% Zn

The stacking fault energy for given alloy is about 16 mJ/m2. Beyond this composition , the diffusion coefficient at 850 °C sharply increases.

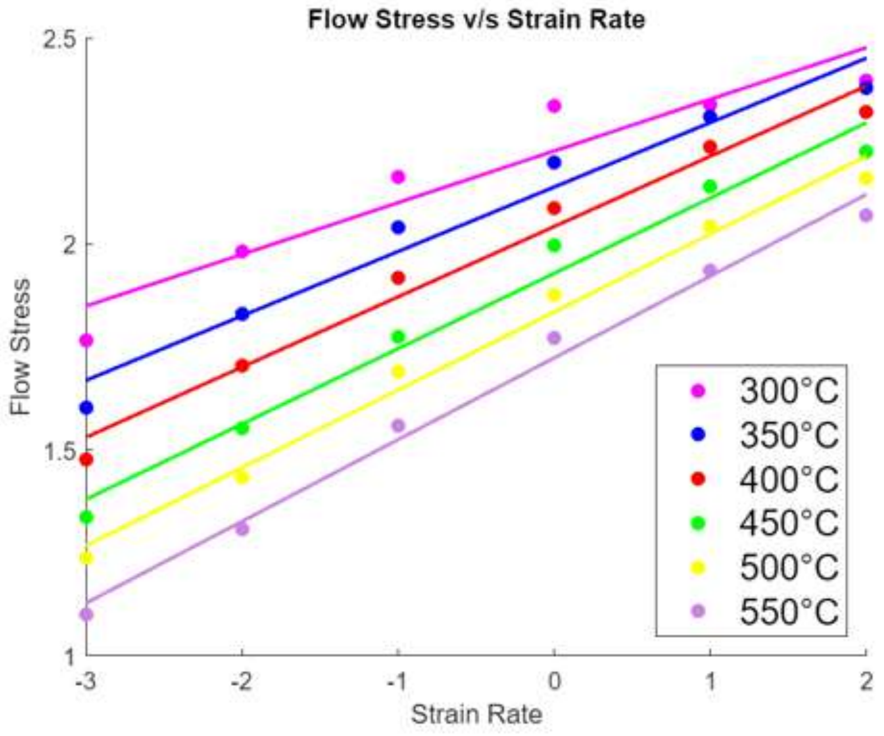
Regions of maximum efficiency occur at :

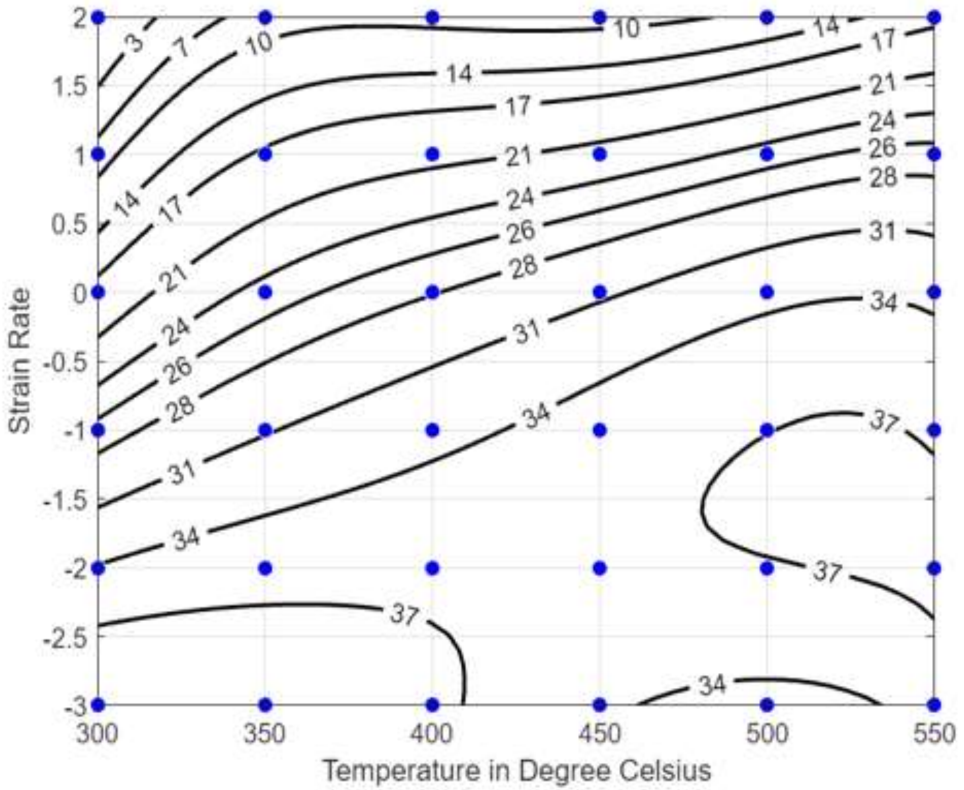
- T=850°C, ε'=0.1 s-1 with peak efficiency of 37% (Dynamic Recrystallisation)
- T=600 °C, ε'=0.001 s-1 with peak efficiency of 40% (wedge cracking)

- Regions of flow instability occur at :
- ε'>=3 s-1 at lower temperatures.

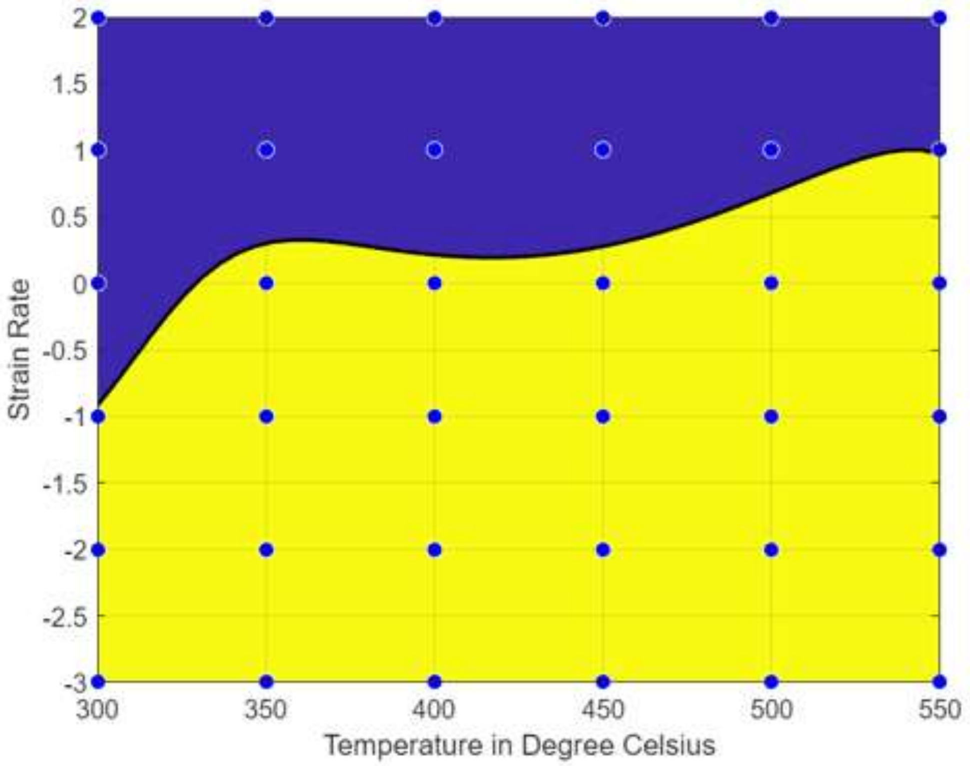
Optimum temperature: 850 °C

Optimum strain rate : 0.03 s^{-1}

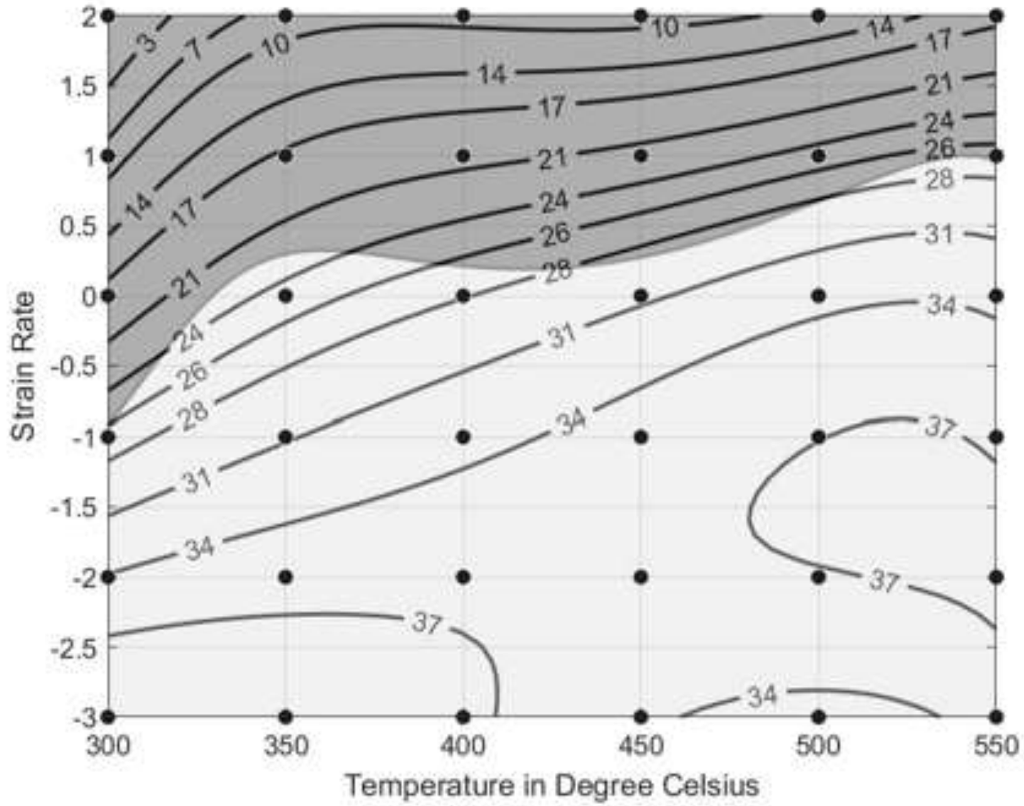




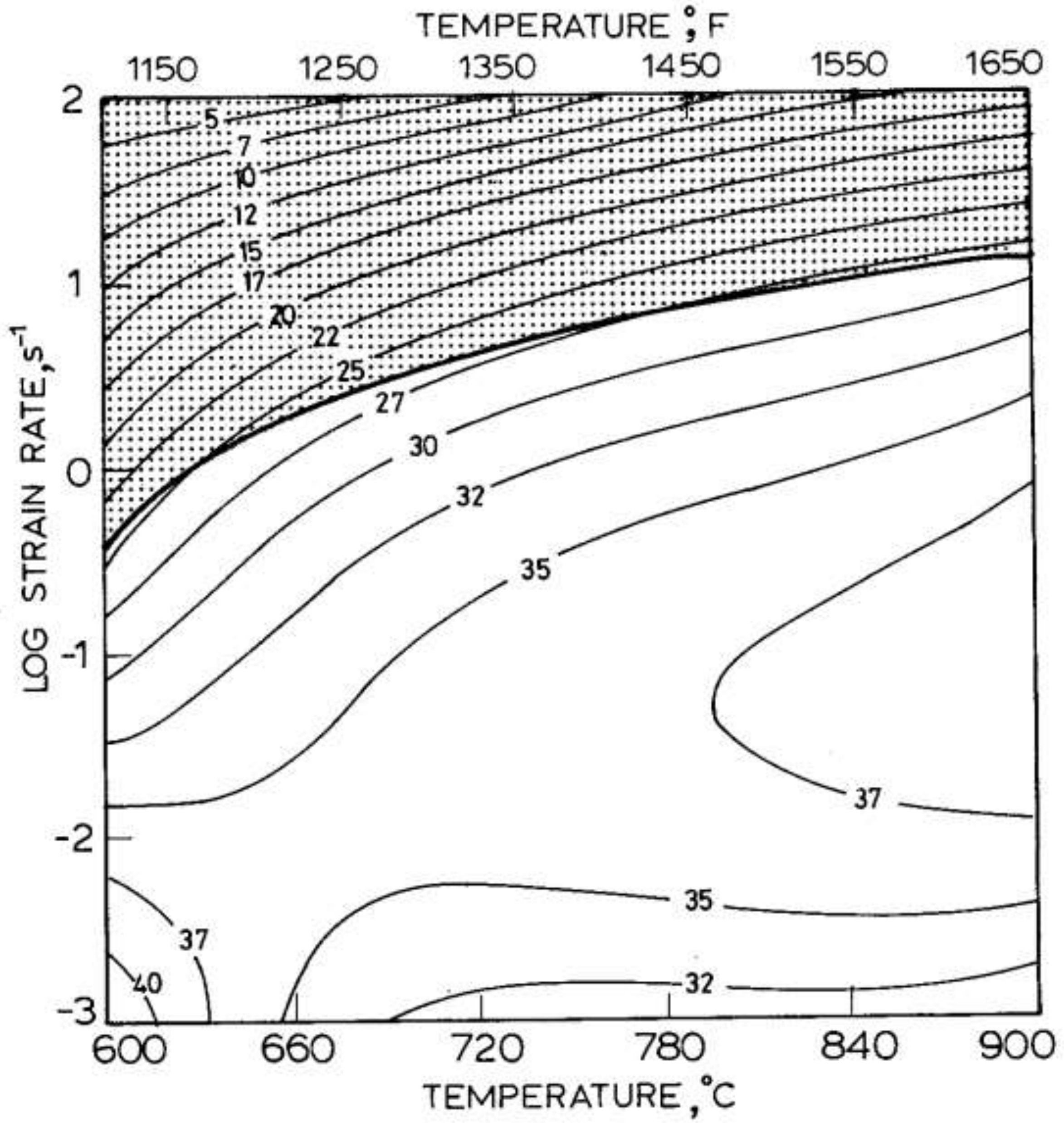
Power Dissipation Map



Instability Map



Processing Map



Processing map for **Cu-21Zn** at a strain of 0.5. Contour numbers represent percent efficiency of power dissipation. Shaded region corresponds to flow instability.

Strain	Strain Rate, s^{-1}	Temperature, °C						
		600	650	700	750	800	850	900
0.1	0.001	56.0	42.5	30.6	23.7	18.0	12.6	10.5
	0.01	85.6	63.1	48.3	37.1	27.8	21.9	16.9
	0.1	123.6	98.5	74.2	54.4	45.4	34.6	26.7
	1	166.8	134.5	107.4	85.8	66.2	53.4	42.4
	10	145.4	150.9	138.8	117.2	97.7	77.3	63.3
	100	162.0	169.9	157.7	131.2	115.7	93.4	79.3
0.2	0.001	60.9	39.6	29.1	22.3	16.7	12.3	9.7
	0.01	92.2	68.5	51.3	36.0	28.2	21.2	15.7
	0.1	138.1	107.0	80.8	59.9	48.7	36.3	28.3
	1	197.7	149.4	117.1	93.8	72.2	57.5	45.1
	10	198.4	188.4	161.5	129.7	105.4	83.7	66.7
	100	216.5	216.3	191.1	154.8	133.7	107.7	89.0
0.3	0.001	58.3	40.0	30.0	21.8	17.3	12.6	9.8
	0.01	95.7	67.8	50.8	35.7	27.2	20.3	15.6
	0.1	145.5	109.9	82.5	59.6	49.1	36.3	28.2
	1	216.1	157.5	122.6	98.9	75.2	59.2	46.6
	10	218.3	203.8	172.0	137.9	110.5	86.3	71.0
	100	248.5	239.7	208.7	167.2	144.8	117.6	96.6
0.4	0.001	56.2	41.4	29.9	22.5	17.6	12.7	9.8
	0.01	95.2	66.8	50.5	35.3	27.2	20.5	15.8
	0.1	149.6	109.4	83.2	59.3	48.9	35.9	27.8
	1	221.7	160.0	124.6	100.3	76.1	58.6	47.4
	10	228.9	213.8	178.4	141.6	114.2	90.7	73.3
	100	267.2	250.0	214.8	172.2	149.7	122.6	99.8
0.5	0.001	56.0	41.8	30.1	22.3	17.8	12.7	9.8
	0.01	92.3	65.2	49.9	35.9	27.2	20.3	15.7
	0.1	150.2	107.4	82.7	58.8	48.2	35.4	27.1
	1	223.8	160.8	124.2	99.8	75.8	57.8	46.6
	10	231.1	215.8	179.9	144.3	116.1	91.7	74.7
	100	279.9	252.6	214.4	173.4	150.5	123.0	99.7

Flow stress values (in MPa) of **Cu-21Zn** at different temperatures and strain rates for various strains (corrected for adiabatic temperature rise).

MATLAB Code

```
datan= table2array(data);
% 0.1 strain
strain_1 = datan(13:18,2:end);
sr1 = strain_1(:,1);
strainlog = log10(sr1);
stress1 = strain_1(:,2:end);y = zeros(6,6);
stresslog = log10(stress1);
C = {'m','b','r','g','y',[.8 .5 .9]};
hold on
for r = 1:length(stress1)
    Scatter(r) =scatter(strainlog,stresslog(:,r),'filled','MarkerFaceColor',C{r});
    c= polyfit(log10(sr1),log10(stress1(:,r)),1);
    y(:,r) = polyval(c,log10(sr1));
    plot(log10(sr1),y(:,r),'LineWidth',1.5,'Color',C{r})
end
ylabel('Flow Stress');xlabel('Strain Rate');
title('Flow Stress v/s Strain Rate')
legend(Scatter,'300°C','350°C','400°C','450°C','500°C','550°C','Location','southeast','FontSize',15);
hold off
```

```
%slope or strain rate sensitivity
%slope or strain rate sensitivity
m= zeros(length(stress1),length(stress1));
for k =  1:length(stress1)
 for p = 1:length(stress1)
        c1= polyfit(log10(sr1),log10(stress1(:,k)),3);
        deriv = polyder(c1);
        m(p,k) = polyval(deriv,strainlog(p));
 end
end

e= (2*m./(m+1))*100;
T= 300:50:550;
%instability zone
e1= e/200;

slope= zeros(length(stress1),length(stress1));
for k =  1:length(stress1)
    for p =  1:length(stress1)
        c2= polyfit(log10(sr1),log10(e1(:,k)),3);
        deriv = polyder(c2);
        slope(p,k) = polyval(deriv,strainlog(p));

    end
end
iz = slope +m;
```

```
%% Fit: 'untitled fit 1'.
[xData, yData, zData] = prepareSurfaceData( T, strainlog, e );

% Set up fittype and options.
ft = fittype( 'poly45' );

% Fit model to data.
[fitresult, gof] = fit( [xData, yData], zData, ft, 'Normalize', 'on' );

% Make contour plot.
figure( 'Name', 'Power Dissipation' );
h = plot( fitresult, [xData, yData], zData, 'Style', 'Contour' );
% Label axes
xlabel( 'Temperature in Degree Celsius', 'Interpreter', 'none' );
ylabel( 'Strain Rate', 'Interpreter', 'none' );

grid on
set(h(1),'ShowText','on','LabelSpacing',144)
set(h(1),'LineWidth',1.5,'Fill','off');
set(h(1),'LevelList',[3,7,10,14,17,21,24,26,28,31,34,37,41,45,48,52])
fig = gcf;
saveas(gcf,'pd0_5.jpg')
```

```
%% Fit: 'untitled fit 2'.
[xData, yData, zData] = prepareSurfaceData( T,
strainlog, iz );

% Set up fittype and options.
ft = fittype( 'poly45' );

% Fit model to data.
[fitresult, gof] = fit( [xData, yData], zData, ft, 'Normalize',
'on' );

% Make contour plot.
figure( 'Name', 'untitled fit 2' );
w=plot( fitresult, [xData, yData], zData, 'Style', 'Contour' );
% Label axes
xlabel( 'Temperature in Degree Celsius', 'Interpreter', 'none'
);
ylabel( 'Strain Rate', 'Interpreter', 'none' );
grid on
set(w(1),'LineWidth',1.5);
set(w(1),'LineWidth',1.5,'LevelStep',2);
fig = gcf;
saveas(gcf,'is0_5.jpg')
```

```
% BASIC IMAGE PROCESSING : SUPERIMPOSE
fig1 = imread('pd0_5.jpg');
fig2 = imread('is0_5.jpg');
fusionimage=imfuse(fig1,fig2,'falsecolor','Scaling','joi
nt');
op=rgb2gray(fusionimage);
imshow(op);
title('Processing Map')
fprintf('Coded By: Mudit Vyas IIT INDORE')
```

Thank You !