Hot Compression Behavior of AA 6061-2 Wt.% Al2O3 Nanocomposite

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ABSTRACT

This research work is based on the effect of Alumina nanoparticles reinforced with Al 6061 alloy in hot deformation behavior using constitutive model and process mapping. AA 6061-2 wt. % Al2O3 nanocomposites prepared by mechanical alloying of 30 h. Hot compression tests were carried out at three temperatures such as 250, 350 and 450 ̊C and in the strain rates were 0.01s-1, 0.1 s-1 and 1 s-1. Workability zone for various combinations of temperature and strain rates were investigated. The formation of dynamic recrystallization (DRX) and dynamic recovery (DRY) were confirmed by characterization study of hot compressively deformed AA 6061-2wt.% Al2O3 nanocomposites.

Keywords—Flow stress; Hot compression test; Processing map; Constitutive modeling

# INTRODUCTION

When compared to their monolithic counterparts, aluminium alloy-based metal matrix composites (AMMCs) are typically preferred due to their low density, wide alloying range, heat treatment capability, and responsiveness to both primary and secondary processing. Many researchers are interested in matrix strengthening using nano-sized ceramic reinforcement because it maintains strong ductility, high temperature creep resistance, and fatigue properties. Metal matrix composites (AMMCs) and alloys made of aluminium that are traditionally produced (i.e., using ingot metallurgy) have been thoroughly assessed in the past. However, little research has been done on how powder metallurgy processing factors affect the behavior of alloys and composites during heat deformation. The workability of composites made using powder metallurgy (P/M) is difficult to assess.

A thorough analysis of the alloy's hot deformation behavior is crucial for designing the thermomechanical processing parameters, which have a direct impact on the product’s microstructural and mechanical qualities. The processing parameters have a significant impact on a material's properties like ductility, strain hardening, strength, dynamic recovery, and recrystallization. Therefore, when metals or alloys are deformed at high temperatures, it is vital to analyze the interaction between the deformation behavior and processing factors. The deformation behavior is typically characterized using a variety of modelling techniques, such as flow stress-strain curves, kinetic analysis, constitutive models, and processing maps, in order to optimize the processing parameters and better understand the deformation mechanism.

In bulk metal forming processes including extrusion, rolling, and forging at high temperatures, hot deformation behavior refers to how much a material may deform plastically without flow localization or fracture. Its hot working qualities are impacted by the presence of hard ceramic nanoparticles in the soft ductile Al matrix; as a result, various hot working parameters should be examined and contrasted with standard Al composites. The ductile matrix transfers the applied load to the hard reinforcing particles during hot deformation under compression state. As a result, the hard particles do not deform while the soft ductile matrix experiences plastic flow. Depending on how the processing is going, the interface may separate or the particles may break when the accumulated stress reaches a critical point.

Proper constitutive equations, which correlate flow stress, strain rate, and temperature, may generally be used to assess the mechanical behavior of materials under hot working conditions. The uniaxial hot compression testing often provides the data required to extract the constitutive equations. The link between strain rate, flow stress, and temperature is best described by the Arrhenius equation. Zener-Holloman parameter and stress are better approximated by the hyperbolic type function.

In order to determine "safe" and "unsafe" locations, it is crucial to understand material behavior and metallurgical evolution during deformation. The dissipation efficiency and instability characteristics that serve as the foundation for creating processing maps have been established over time using a variety of approaches and techniques. The Dynamic Materials Model (DMM), which is based on continuum criteria, and the phenomenological instability model have both been effectively used to create processing maps for establishing safe working distances during hot deformation. Through efficiency and instability parameters, the DMM approach has been found to be a highly helpful tool for characterizing the hot deformation behavior. Processing maps are frequently used to describe the behavior of deformation in order to improve the processing parameters and make the deformation mechanism clear.

# EXPERIMENTAL WORK

The pure elemental powders of Si, Fe, Cu, Cr, Mn, Mg, Zn, Ti, and Al with an average particle size of 40 m, a purity of over 99%, and a mesh size of 325, supplied by Alfa Aesar, USA, were used to prepare the nanostructured aluminium alloy 6061 alloys and the aluminium alloy 6061 - 2 wt.% Al2O3 nanocomposite powders. Alfa Aesar, USA provided the gamma phase nano- size alumina (Al2O3) powder with a purity of 99.5% and an average particle size of 40–50 nm. The chemical composition of Al 6061 alloy is shown in table 1.

Pure Al powder was used as the main matrix material, and other pure elemental powders were used as solute materials with an average size of 40 µm.

### **Table 1: The Chemical composition of Al 6061 alloy**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Al | Si | Fe | Fu | Mn | Mg | Cr | Zn | Ti |
| Balance | 0.6 | 0.7 | 0.275 | 0.15 | 1.0 | 0.195 | 0.25 | 0.15 |

The elemental powders required to produce the Al 6061 alloy were blended in a two-station high-energy planetary ball mill (Insmart Systems, Hyderabad, India) at 280 rpm for 2 h. During the blending process, no ball and process control agent was utilized. The combined powders were referred to as microcrystalline Al 6061 and were considered to be the 0 h of mechanically milled powders. All of the constituent powders needed to create Al 6061-2 wt.% Al2O3 were combined into a 30 g powder combination, and 300 g of steel balls (nine balls, each 20 mm in diameter and weighing 33.5 g) were selected, keeping a ball-to-powder ratio of 10:1. Toluene was employed as a process control agent (PCA) to prevent the powder from being too cold-welded. To study the hot deformation characteristics, cylindrical compacts of size of 10 mm in diameter and 13.5 mm in height were mechanically pressed at a compaction pressure of 500 MPa using a double-action compaction die in a hydraulic press (Insmart systems, Hyderabad, India) with a capacity of 40 tons. Zinc stearate was used as a lubricant between the inner surfaces of the cylindrical die to reduce the amount of friction. The sintering of green compacts results in strong chemical bonds, high density and strength of the resulting material. The green cylindrical compacts were sintered for 2 h in the temperature of 600 ̊C under a reducing atmosphere (nitrogen).

Uniaxial hot compression tests were performed on FIE servo hydraulic test machine equipped with an environmental chamber. Cylindrical compression specimens of 10 mm diameter and 13.5 mm height were obtained from the extruded samples such that the compression axis is parallel to the extruded direction. Prior to heating, graphite was added to the top and bottom surfaces of each sample to enhance lubrication. Three strain rates (0.01, 0.1, and 1 s1) and three different temperatures (250, 350, and 450 ̊C) were used in the hot compression testing. Hot compression tests were performed to 50% engineering strain and water-quenched from the test temperature in order to examine the behavior of the material.

# RUSLT AND ANALYSIS

# Hot compression test gives the value of force and displacement at various combination of temperature and strain rate .with these force and displacement value, calculate the true strain and true stress value with some correction. The correction is made because the process of hot deformation is not an isothermal process and some assumption, which are not so accurately followed due to experimental limitations.

…………………………… (1)

e) ……………………………. (2)

True stress–true strain curves for the experimental alloy after testing at temperature range of 250–450 ̊C under different strain rates of 0.01, 0.1 and 1 drawn. The influence of the temperature and strain rate on flow stress level is observed. Flow stress decreases with the increasing of deformation temperature at certain strain rate .The slopes of these curves give information about the strain rate sensitivity. These differences in slopes imply that the strain rate sensitivity varies with strain rate and deformation temperature. Independently from strain rate, all the curves exhibited a peak stress at a strain close to 0.12, followed by dynamic flow softening that lasted until the end of straining. The characteristics of the true stress– strain curves are similar in all deformation conditions. This is because the deformation tests are all under high temperature, recovery and recrystallization will occur with the increase of strain under this condition. When the strain is small, the work hardening effect plays a dominant rule, so the flow stress increases very fast in this region. With the increase of strain, the softening effect caused by recovery and recrystallization gradually dominated so the work hardening effect is reduced, the flow stress reaches the maximum value. Softening effect and work hardening effect eventually turn to a dynamic balance, so stable flow stress occurs. This is the reason; true stress–strain curves are similar in all deformation conditions.

The leading softening mechanism is dynamic recovery and dynamic recrystallization. The DRX mechanism may act as a softening effect, which leads to the decrease in flow stress at higher deformation temperatures for higher temperature at low strain rate level, cyclic dynamic recrystallization with multiple peaks in the flow curves occurred due to coarsening of grains.

**Fig.1 True stress –True strain curves for various temperatures**

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F**ig.2 True stress –True strain curve at strain rate 0.01**

The stress–strain data obtained from compression tests under different strain rate and temperature conditions were used to determine the material constant of the constitutive equation. The Arrhenius equation indicated in Eq. (3) is widely used to describe the relationship between the strain rate, flow stress and temperature, especially at high temperatures.

………………………….. (3)

Where, is the strain rate, R is the universal gas constant (8.314 J/mole K), T is the absolute temperature (K), Q is the activation energy for hot deformation (kJ/mole), σ is the flow stress (MPa) for a given strain, A (), α (), and n are the material constants independent of the flow stress and deformation temperature. The value of α represents the stress reciprocal at which the material deformation changes from power to exponential stress dependence. Equation (4) can be written for low stress level (Power law) and Equation (5) high stress level (exponential law)

………………………………. (4)

) …………………………… (5)

Where, A1 and A2 are the material constants independent of the flow stress and deformation temperature. The value of n1 and can be obtained from the slope of the lines in the ln(ɛ̊) versus ln(σ) and ln(ɛ̊ ) versus σ plots, respectively. Because the slope of the lines is approximately the same, the value of n1 and β can be obtained for different deformation temperatures by linear fitting method, and An average value of n1 and β can be computed respectively.

………………………. (6)

………………………… (7)

…………………………….. (8)

The combined effect of strain rate and temperature on the deformation processes can be modeled by a new constitutive equation using temperature compensated parameter Z (Zener–Hollomon parameter) is often called the temperature-compensated strain rate and is given as

…………………………. (9)

From equation 3 we can also write as

………………. (10)

Now taking the natural log of equation 3

…………………… (11)

In order to derive A and Q from the hyperbolic sine type equation, the transformation equation of Eq. (3.8) leads to the following equation at constant strain rate

…………………………. (12)

in order to estimate the effective activation energy

…………….. (13)

called strain sensitivity n̊ which is obtained from the versus plot

called temperature sensitivity s which is obtained from the plot of versus reciprocal of temperature (1/T)

The value of activation energy Q can be easily evaluated by averaging the values of slopes under different strain rates obtained from the above plots.

……………………….. (14)

Substituting the values of Z and α, σ in the above (14), versus curve is plotted by linear regression. The slope corresponding to the value of stress exponent n in (14), and the intercept corresponding to ln A, can be determined. Then substituting for A,α, n and Q in constitutive equation (3) at whole stress condition, a hot deformation constitutive equation can be proposed at a particular strain and is used to estimate the flow stress for the tested material.

Predicted flow stress values calculated by the equation (10)

…………………. (15)

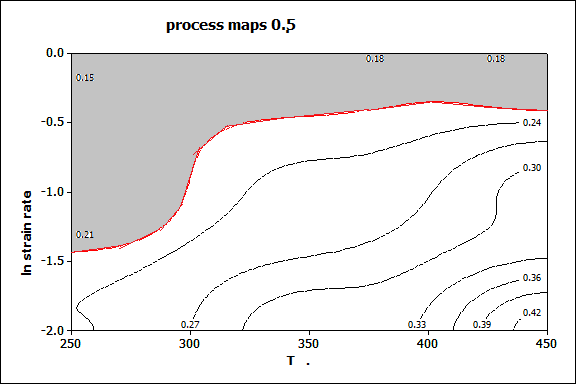
**HOT DEFORMATION AND PROCESSING MAP**

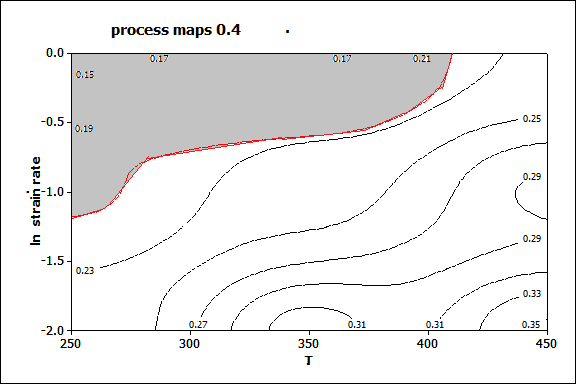
During hot forming process alloy is liable to undergo work hardening, dynamic recovery (DRV) and dynamic recrystallization (DRX), three metallurgical phenomena for controlling microstructure and mechanical properties. The relay of softening mechanism from strain hardening and dynamic recovery to DRX is the reason the term discontinuous has been earned. At a microstructural level DRX begins when strain hardening plus recovery can no longer store more immobile dislocations. When the critical strain is reached, on face centered cubic (fcc) metals of medium to low stacking fault energy, strain-hardening and dynamic recovery cease to be the principle mechanisms responsible of the stress-strain response. In the deformed material DRX would affect the crystallographic texture and thus, material anisotropy. DRX would eliminate some crystal defects, such as part of dislocations resulting from work hardening, which will improve hot plasticity, refine microstructure, and reduce the deformation resistance. High stacking fault energy (SFE) metals, such as aluminium alloys, alpha titanium alloys, and ferritic steels, undergo continuous dynamic recrystallization rather than discontinuous dynamic recrystallization during high temperature deformation. The microstructure of specimen revealed equiaxed grain formation, refinement of grain, and grain boundaries of irregular or wavy in nature describing the occurrence of DRX. During the manifestation of DRX, interface formation (nucleation) and its migration (growth) take place. The nucleation consists of the formation of a grain boundary due to the dislocation generation, simultaneous recovery and rearrangement. This interface will become a nucleus for DRX when it attains a critical configuration of that of a large angle boundary. The nucleus will grow by the process of grain boundary migration. As the material acts essentially as a dissipater of power (negligible energy storage), during hot deformation, the driving force for the migration of interfaces is the reduction of the total interface energy. When nucleation and growth occur simultaneously, the slower of these will control the formation of DRX.

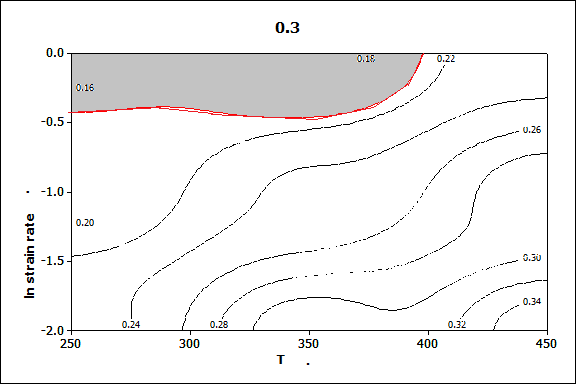
**Fig.3. Variation of flow stress with Zener–Hollomen parameter for a true strain of 0.5**

**Fig. 4. Variation of flow stress with Zener–Hollomen parameter for a true strain of 0.4**

Process maps are drawn for different strain 0.3, 0.4 and 0.5 and instability region also shown in the Figs. 5(a)-(c). The instability region occurs at high strain rate, as the strain increases the instability region also increased.







**Fig. 5. Processing Maps for (a) 0.5 (b) 0.4 (c) 0.3 Strain Rate**

# CONCLUSION

1. True stress–true strain curves for the experimental alloy after testing at temperature range of 250–450 ̊C under different strain rates of 0.01, 0.1 and 1 s-1 drawn. The influence of the temperature and strain rate on flow stress level is observed.
2. Flow stress decreases with the increasing of deformation temperature at certain strain rate .The slopes of these curves give information about the strain rate sensitivity these differences in slopes imply that the strain rate sensitivity varies with strain rate and deformation temperature.
3. Independently from strain rate, all the curves exhibited a peak stress at a strain close to 0.12, followed by dynamic flow softening that lasted until the end of straining.
4. The characteristics of the true stress– strain curves are similar in all deformation conditions. This is because the deformation tests are all under high temperature, recovery and recrystallization will occur with the increase of strain under this condition.
5. The optimum region for hot compression test is in the temperature range 370-450 ̊C and strain rate between 0.1 – 0.01 s-1.
6. The safe working zone is identified for various combinations of strain rate and temperature, which are necessary for any material to make it useful product.

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