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Forming limit diagram and void coalescence analysis of AA5052 coated with molybdenum-based ceramic nanocomposites

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ABSTRACT

Aluminium 5052 alloy sheets of size 75 × 25 mm and 3 mm thickness with double edge semicircular notches of diameter from 2–8 mm have been coated with $MoSi_2$–SiC nanocomposite coatings by sputtering process. The structural morphology of the ceramic coatings was explored by Fourier Transform Infrared (FT-IR) spectroscopy, X-ray Diffraction (XRD) analysis, Scanning Electron Microscopy (SEM), and Atomic Force Microscopy (AFM). The coated and uncoated sheet samples were subjected to tension–compression state of strain up to fracture by varying the notch sizes using INSTRON Universal Testing Machine (UTM). Fracture behaviour studies of the sheets were performed and forming limit diagram (FLD) was drawn. The void coalescence analysis was also carried out by using SEM images and the effect of coating behaviour of combined forming and fracture were analyzed. In the coated sheet, the *L*/*W* ratio was very close to 1.0. Thus, no oblate/prolate voids were observed and the heat generated during deformation was retained for longer time and thereby adiabatic shear band formation has occurred with increased formability.

1. Introduction

Surface engineering and coatings are used to improve surface properties of the substrate, such as appearance, adhesion, wettability, corrosion resistance, wear resistance, and scratch resistance. Some new coatings formed using nanotechnology promise to create a long-term surface protection [1]. In other cases, in particular, in printing processes and semiconductor device fabrication where the substrate is a wafer, the coating forms an essential part of the finished product. Coating and printing processes involve the application of a thin film of functional material to a substrate, such as paper, fabric, film, foil, or sheet stock. Molybdenum-based ceramic coating ($MoSi_2$–SiC) has found a wide range of applications, such as plasma-faced components in fusion reactors, semiconductor substrates in microelectronic systems, coatings on heat pipes, cladding of nuclear fuel, radiation shields for propulsion and space nuclear power systems and anti-corrosion coatings, because of its superior physical and mechanical properties [2].

In sheet metal forming industry, the localized necking failure is recognized as an important limitation on metal formability. For a wide range of metals, the experimental studies on forming limit have been commonly carried out. The forming limit diagrams (FLDs) have been derived from an in-plane stretching test or a hemispherical punch stretching test in which sheets are subject to biaxial stress. Although FLD has been proved to be a useful method in the analysis of formability, the experimental and theoretical studies have also shown that the maximum admissible limiting strains strongly depend on deformation modes, loading history and plastic anisotropy introduced by cold rolling. On this basis, FLDs represent limiting major and minor available principal strains in the plane of the deformed sheet that can be achieved. This causes that the FLD becomes a valuable tool for analyzing sheet metal forming [3]. Following the introduction of the FLDs, many attempts have been made to predict the FLDs, taking into account the theory of plasticity, material properties and instability conditions. Naga Krishna et al. have worked on void coalescence analysis of nanocrystalline cryo rolled aluminium formed under different stress conditions [4]. In real parts the maximum admissible strains are limited by localized necking. Studies on formability and fracture behaviour of various materials were performed and are reported widely [5]. However, no work has been conducted

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Table 1
Chemical composition of AA5052 aluminium alloy (in wt.%).

Elements	Mg	Mn	Si	Fe	Cr	Cu	Ti	Zn	Al
% Composition	2.80	0.10	0.25	0.40	0.25	0.10	0.15	0.10	Rest

on adiabatic shear deformation phenomenon and void coalescence analysis during forming up to fracture in ceramic nanocomposite coated aluminium sheet with different notches.

The main objective of this work is to examine the microstructural properties of $MoSi_2$–SiC coatings in reactive radio frequency (RF) magnetron sputtering process by using Fourier Transform Infra-red spectroscopy (FT-IR), X-ray Diffraction (XRD) analysis, Scanning Electron Microscopy (SEM), and Atomic Force Microscopy (AFM). FLDs for aluminium 5052 of different notches with and without coating of $MoSi_2$–SiC, nanocomposites are determined. The relationship among the fracture parameters is investigated for the case of coated as well as uncoated aluminium sheet. Plastic flow localization and adiabatic shear deformation are analyzed when deformed at high strain rate to large plastic strain during tension. The void coalescence analysis is carried out at fractured region. The ratio of the length to the width (L/W) of the oblate and prolate voids at fracture is correlated with the mechanical properties, microstructure and strains at fracture and triaxiality ratio (T_o). The void area fraction (V_a) is determined from the SEM micrograph and correlated with the triaxiality strain ratio. Hence, in this study, an attempt was made to increase the formability of $MoSi_2$–SiC coated aluminium alloy more than uncoated AA5052.

2. Experimental work

2.1. Materials and equipment's

In this study, aluminium 5052 (AA5052) sheet with 3 mm thickness was used. Semicircular notches of diameter 2, 3, 4, 5, 6, 7 and 8 mm were cut out in two edges of the sheet. The chemical composition of the AA5052 alloy obtained by inductively coupled plasma (ICP) spectrometer (Optima 8000 ICP-OES) is summarized in Table 1 [6]. The mechanical properties of the alloy were obtained by INSTRON universal tensile testing machine (M10-14190-EN Series 5500) with a maximum tensile force capacity of 5 kN as per the standard procedure explained elsewhere [7]. The samples were prepared as per the ASTM: B210 M standard explained elsewhere by cutting along 90° to the rolling direction of the sheets [8].

2.2. Preparation of coated specimen by sputter deposition

Sputter deposition is a physical vapour deposition (PVD) method for preparing thin films using a RF magnetron sputtering process. These processes involve ejecting material from a target that is a source ($MoSi_2$–SiC) onto a substrate (AA5052), as shown in Fig. 1. The aluminium alloy sheets 75 mm × 25 mm with a thickness of 3 mm were polished with various grades of emery sheets and degreased using an acetone solution. The target and substrate were loaded into the RF magnetron sputtering machine. The ceramic coating was deposited onto the aluminium substrates with the $MoSi_2$–SiC target by adjusting the argon gas inlet in the sputtering process. The thickness of the coatings was controlled as 125 nm. The coating depositions were carried out on the both sides of the plates [9].

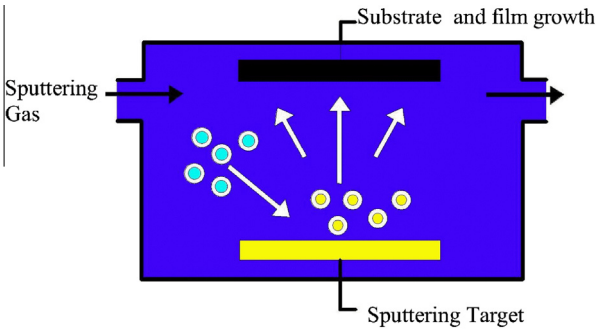

Fig. 1. Principle of magnetron sputtering process.

2.3. Characterization of nanocomposites

2.3.1. FTIR analysis

The Fourier Transform Infrared (FT-IR) spectra were collected for ceramic nano coated AA5052 alloys, using a Bruker Optics GmbH FTIR spectrometer, (*Model: ALPHA, Germany*). The functional groups of the samples were recorded by using FT-IR. Spectra were obtained at 4 cm^{-1} resolution, averaging 24 numbers of scans [10].

2.3.2. XRD analysis

X-ray powder diffraction (XRD) analysis was obtained for the $MoSi_2$–SiC ceramic coated AA5052 samples using a Siefert X-ray diffractometer with Cu Kα radiation (λ = 1.54060 Å) at 60 kV over the range of 2θ = 10–90° with a step size of 0.01708 and a step time of 15.5076 s. The phase purity and grain size were determined by XRD analysis. Additionally, from the XRD pattern of the composites, the crystalline size of the samples is determined using the following Debye–Scherer equation (1):

$$D = \frac{0.9\lambda}{\beta \cos\theta} \tag{1}$$

where λ is the wavelength of the X-ray radiation, θ is the diffraction angle and β is the angular width at half maximum intensity [11,12].

2.3.3. SEM analysis

Scanning Electron Microscopy (SU510 Hitachi, Japan) was used for the microstructural investigation of pure AA5052 aluminium alloy and $MoSi_2$–SiC ceramic coated samples under various temperature conditions. To study the microstructure, the cut samples of the aluminium alloy AA5052 were examined for microscopic studies. Before performing microscopic studies, the samples were mounted by cold setting for easy handling. After metallographic polishing, the microstructural characterization of the samples was characterized using Scanning Electron Microscopy. The microstructures of the AA5052 sheets were annealed at 300 °C and coated sheets were obtained by chemical etching. Prior to examination, all of the samples were ion sputtered to enhance the charging of the particles [13,14].

2.3.4. AFM analysis

AFM is a very important characterization technique for observing the morphological configuration and for structural analysis on the nanoscale. The topography of the nano composite is analyzed with AFM (XE 70, Park Systems–S. Korea). The surface roughness and particle size are examined using AFM analysis [15].