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Tensile and wear properties of repetitive corrugation and straightened AI 2024 alloy: an experimental and RSM approach

Y J Manjunath *, H P Thirthaprasada *, A Chandrashekar *, Abdul Razak Kaladgi *, V Mohanavel *, Asif Afzal *, M C Manjunatha * and Dadapeer Basheer *

1 Department of Mechanical Engineering, Bangalore Institute of Technology, Bengaluru, India
2 VTU PG Studies, Muddenahalli, Chickballapur, India
3 Department of Mechanical Engineering, P.A College of Engineering, Mangalore, India
4 Department of Mechanical Engineering, Bharath Institute of Higher Education and Research, Chennai, Tamilnadu, India
5 Department of Mechanical Engineering, P.A College of Engineering, Mangalore, India. & Department of Mechanical Engineering, School of Technology, Glocal University, Delhi-Yamunotri Marg, Mirzapur Pole, Saharanpur, Uttar Pradesh, India
6 Department of Mechanical Engineering, Haramaya Institute of Technology, Haramaya University, Dire-Dawa, Ethiopia
* Author to whom any correspondence should be addressed.

E-mail: chandrashekara@bit-bangalore.edu.in and dadapeerb@yahoo.com

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Abstract

Repetitive Corrugation and Straightening (RCS) on sheet geometries causes Cyclic Plastic Deformation, resulting in potential improvements of mechanical characteristics in metals and alloys. In this study, sample sheets of Al 2024 are subjected to severe plastic deformation with specially designed corrugated rollers to generate heterogeneous repeated plastic deformation at room temperature. The material shows enhanced properties under severe plastic deformation, with 5.07% increase in tensile strength, compared to unprocessed material. Maximum tensile strength was observed at annealed temperature of 150 °C is of about 3.49% increase in tensile strength over other temperature conditions. A wear study was carried out by considering the processed sheet that yields high tensile strength (annealed at 150 °C) by varying process parameters like sliding distance, load and sliding velocity as per design of experiments. In comparison to all other combinations, the wear resistance was shown to be better with a sliding distance of 6000 m, a load of 9.81 N, and a sliding velocity of 1.45 m s⁻¹. The Response Surface Methodology (RSM) approach was adopted for comparing purpose, the experimental findings are found to be more similar to the RSM approach’s outcomes.

1. Introduction

Traditional metal forming processes such as rolling, drawing, or pressing can be used to refine the grains in the materials. These methods, however, are unsuccessful when compared to severe plastic deformation (SPD) procedures for generating ultra fine grains. To obtain ultrafine grained [1] materials for improving strength, hardness, and material properties [2], material processing SPD techniques such as equal channel angular extrusion /pressing [3, 4], accumulative roll bonding [5], repetitive corrugation and straightening, and others [6–8] have been developed. Working circumstances such as strain rate, temperatures, and hydrostatic pressure, among others, have an impact on the structure’s growth. According to general observation, temperature reductions, rise in pressure and the addition of alloying components contributes towards grain refinement under SPD techniques [7]. The repeated corrugation and straightening (RCS) approach is being employed as a unique processing pathway to create contamination-free, porosity-free nanostructured materials that can be easily adopted for large-scale commercial production [8]. As shown in figure 1, the RCS process is carried out in two steps: Corrugation (sheet deformation by corrugated rollers) and straightening of corrugated sheets using straight rollers [9].

Many researchers have investigated considering various base metals and alloys using RCS process [10–14]. With perpendicular rotation after each pass, Pandey et al [15] discovered a substantial improvement in hardness,
and further strengthening in Al-Cu and Al-Cu-Sc alloy processed by RCS technique. Having equal channel angular pressed Al-Zn-Mg cast alloy, with increasing volumes of alloying elements and decreasing levels of wear factors such as load and sliding velocity, Manjunath et al [16] found an increase in wear resistance. A comparison of High Pressure Torsion (HPT) treated AA1050 alloy with as-received alloy was carried out [17]. HPT reduces an alloy’s resistance to wear, impairing strain hardening ability following extreme plastic deformation [18]. Dipankar Dey et al [19] shows that adding SiC to the Al2024 alloy reduces volume loss, large surface contact between sliding faces. On the other hand, this increase wear rate regardless of the presence of SiC. Using a Linear - radial basis function model, the impact of process variables such as sliding velocity, sliding distance, and applied load on the wear parameters of Al2024-T351 alloy was investigated by Ashwin et al [20]. It has been discovered that, as sliding velocity rises, so does wear rate, but when sliding distance improves, wear rate decreases. Up to a certain point, a substantial increase in wear rate with applied load has been recorded and further a declining tendency prevails. By evaluating the impact of wear resistance on ECAP processed Al–Cu alloy, Mohamed Ibrahim et al [21] adjusted the wear parameters on load and sliding distance and found significant wear loss with the number of passes. Furthermore, it was discovered that sliding distance had a greater impact on wear rate than other factors. Mohamed Ibrahim et al [22] investigated a high-pressure torsion method for an Al-7% Si alloy and discovered enhanced wear resistance owing to grain refinement and homogeneous Si particle dispersion. The combination of adhesive and abrasive wear has been ascribed to the transition of wear mechanisms from delamination, adhesive, oxidation wear and plastic deformation bands following the study. Ezequiel et al [23] designed a new die with known characteristics to produce heterogeneous repeated plastic deformation of AA 5754 alloy at room temperature and also tested the deformation homogeneity, ductility, and strength of processed sheets. Outcomes showed heterogeneous distribution of the deformation, decrement in ductility, and significant increase in yield strength of the material. The thermal stability of the AA8090 Al-Li alloy produced by the RCS method was studied by Jenix Rino John Xavier Raj et al [24]. The specimens were annealed for two to six hours at temperatures ranging from 200 to 400 degrees Celsius. The findings revealed that the material is relatively stable up to 300 degrees Celsius, and that temperature has a higher impact on thermal stability than annealing time. It was also discovered that the activation energy for grain development is 76 kJ mol$^{-1}$. Abolfathi et al [25] focused on Fe-24Ni-0.3C Transformation Induced Plasticity (TRIP) steel that has been rolled and subjected to RCS. The volume proportion of martensite produced owing to deformation induced by amplification of applied strain during the RCS process was approximately 75%, with a high fraction of low angle boundaries. After 40 cycles of the RCS process, yield strength (which climbed from 150 MPa to 1157 MPa), elongation (which decreased from 170 percent to 30 percent), and hardness (which went from 130 to 340 HV) all showed significant improvements.

From the literature, it was observed that various research works have been reported on severe plastic deformation (SPD). Investigations done till now is found suitable methods among SPD techniques available for achieving homogenous and enhanced properties. Very few literatures reported on the optimization of the process parameters such as number of passes, thickness, angle, friction factor, ram speed etc However, there are no studies in the literature to optimize RCS parameters such as load, thickness, temperature and number of passes. Mohammed Iqbal et al [26] studied the effect of various process parameters of twist extrusion process on AA6061-T6 alloy using response surface methodology. Interactions of defined parameters were carried out by applied analysis of variance. Study clearly implies that the number of passes was the most significant factor which affects the properties. Okan Unal [27] studied the effect of shot peening parameters on surface roughness and
surface hardness via response surface methodology. The input parameters such as air pressure, shot diameter and peening duration were considered in the study and their effects on output responses were determined by using ANOVA regression analysis. Also, they have verified the model adequacy by the confirmation tests. Bassiouny Saleh et al [28] studied the equal channel angular pressed AZ91 magnesium alloy for its wear characteristics. The sample specimen was pressed up to sixteen passes to achieve significant grain refinement. Wear resistance of pressed alloy was optimized via response surface methodology and compared with the as-received alloy. There was a significant improvement in properties due to refined grain structure. Chandrashekar et al [29] investigated friction stir welded Al-Mg/Al₂O₃ composites for their mechanical wear and corrosion properties. They have used response surface methodology for optimizing the effect of input parameters on responses such as tensile strength, Young’s modulus, and micro hardness with a statistical confidence level of 95%

The different SPD procedures on aluminum based alloys increase structural and mechanical characteristics, according to the literature. Due to a large gap in fundamental understandings, it is worthwhile to focus some research activities on service and multifunctional characteristics (like thermal stability, electrical conductivity, wear and corrosion resistance, and so on) of fine grain structured aluminium alloys. The goal of this study is to see how process factors affect RCS cycles and how consecutive annealing affects the mechanical properties and wear characteristics of processed Al 2024 sheets.

2. Details of the experiment

2.1. Material’s chemical composition
In three thicknesses of 1, 1.5, and 2 mm, commercially available Al-2024 alloy containing 4.2% Cu, 1.6% Mg, 0.60% Mn, 0.25% Si, 0.30% Fe, 0.1% Cr, 0.10% Zn and 0.15% others with the remainder as aluminium was used.

2.2. RCS processing and annealing
The Repetitive Corrugation and Straightening (RCS) technique is applied to the as received sheets in two stages: (a) continuous corrugation and (b) straightening of a sheet, described in figure 2. As stated in table 1, RCS was carried out according to the design of experiments (DOE). Process parameters such as number of passes, temperature and thickness were considered in this study. The strengthening effects, including grain refinement influence the high strength in ultra fine grained alloys [30]. In RCS, a sheet is subjected to number of passes,
repetitively bent and straightened, introduces a large plastic strain which leads to grain refinement. It induces more homogeneous microstructure in the metal and mechanical properties will be influenced by the grain refinement. Another influencing parameter is process temperature. An increase in deformation temperature leads to softening and a deterioration in the mechanical properties [31]. The RCS processed sheets are subjected up to 30 min duration of successive annealing at different annealing temperatures, such as 150 °C, 250 °C, and 350 °C, before being furnace cooled to see the effects of these parameters on the processed sheets to determine the various properties. The work strategy for the current investigation is depicted in detail in figure 3.

2.3. Response surface methodology (RSM) based experiments
In recent years, statistical methods such as the Taguchi approach and Response Surface Methodology have been used to assess the performance of trials. The face centered central composite design of RSM, which is utilized in the design of experiments, is used for the plan of experiments in this study. RSM clearly predicts the significance of interactions and square terms, as well as the influence of each parameter on the response; this methodology can describe the response in terms of important parameters, their interactions, and square terms, in which the Taguchi method does not give. In addition, RSM’s 3D surfaces can aid in visualizing the influence of parameters on reaction throughout the whole range provided. RCS equipment has the capacity to satisfy pressure or load requirements, as well as process parameters, in order to create fine grain structured and defect-free components.

2.4. Recording the responses
Twenty-seven experiments were conducted using the design matrix shown in table 2. Tensile specimen was made from RCS treated specimens before and after successive annealing in the rolling direction using wire EDM.
cutting in accordance with ASTM-E8. A universal Testing Machine (UTM) with a capacity of 50 KN was used to conduct the tensile tests (Model: WDW-100-UTM-50KN). The features of the test specimen are shown in figure 4. Dry sliding wear tests on a sheet manufactured with optimal settings based on the results of tensile strength, as shown in table 3, and trail runs (L27 orthogonal array), as shown in table 4, test specimen is shown in figure 5, were conducted using a Pin-on disc wear testing machine (Model: TR-20LE, Make: DUCOM). Microstructures were recorded using a scanning electron microscope (Model: VEGA3 TESCAN).

Specific wear rate \( \text{mm}^3 \text{Nm}^{-1} \) can be calculated by using following relation,

\[
\text{Specific Wear rate} = \frac{\text{Volume loss}}{\text{Sliding distance x Force}}
\]

Volume loss (mm\(^3\)) is computed in the following manner

\[
\text{Volume loss} = \frac{\text{Mass loss \times 1000}}{\text{Density}}
\]

Mass loss in gm, can be calculated by weight difference,

\[
\text{Mass loss} = (w_1 - w_2) \text{ in gm}
\]

Where, ‘\( w_1 \)’ weight of the specimen before test, gm

‘\( w_2 \)’ is weight of the specimen after test, gm

Density is gm cm\(^{-3}\)

3. Findings and discussions

3.1. Tensile strength

The tensile properties of the source metal and RCS treated sheet samples were tested which were processed with different parameters according to the design of experiments indicated in table 2. The tensile characteristics RCS treated sheets samples were compared to the ultimate tensile strength of the material before it was annealed. The process parameters have a significant impact on ultimate tensile strength, according to the findings. Prior to annealing, specimen number 7 (\( t = 2 \text{ mm}, n = 2 \) at room temperature) had the maximum tensile strength of 138 MPa. Strength was raised by 18.11 percent (113 MPa) in contrast to the lowest. Specimen number 6 (\( t = 1.5 \text{ mm},\)
n = 6 at room temperature) exhibited the lowest strength of 113 MPa. The formation of dislocations and grain accumulations causes an increase in strength during the initial passes. Increased number of passes results in improved strength without sacrificing ductility and due to higher strain imparted and formation of stable sub-grains. However, when the numbers of passes were further increased, larger stresses were imparted in the material and sub grains with low-angle boundaries converted to stable grains with high-angle boundaries, resulting in a loss of strength and hardness [31]. Because of anisotropy in mechanical behaviour at higher passes, similar results are also seen [24]. High density, non-uniform dislocation distribution and non-equilibrium nature of high and low-angle grain boundaries are seen in ultra fine grains and nanostructured materials treated using the SPD method [32].

In comparison to the remainder of the annealing temperatures, specimen number 7 showed maximum UTS of 143 MPa after successive annealing at 150 °C. UTS at 150 °C (143 MPa) is raised by a minor amount of 3.49 percent compared to UTS before annealing (138 MPa) and found to decrease with additional improvement in annealing temperature attributing to improved ductility owing to recovery and recrystallization process in the material. In contrast to all the combinations processed during the investigation, the highest UTS was observed
for annealing temperature of 150 °C, sheet treated with parameters such as thickness 2 mm and with 2 passes. In table 5, the values of UTS in all circumstances are reported. Comparative values were seen in figures 6(a)–(d) under different annealing temperatures.

3.1.1. Fractography
Figures 7(a)–(d) shows the scanning electron micrographs of tensile fractured surfaces of RCS processed AA2024 specimens. All of the tensile specimens had shear ductile fractures, which resulted in dimples and a grey
fibrous appearance. In comparison to previous studies [20], the results were found to be consistent. Small and elongated dimples are associated with an increase in the number of passes, indicating that shear ductile fracture is the cause of failure. The fracture tending to elongated voids is affected by shear stress, which causes the fracture surface to create either elliptical or parabolic depressions.

3.2. Wear characteristics

Ultimate tensile strength of RCS sheet processed considering two passes, annealed at 150 °C of thickness 2 mm found to be maximum (143 MPa) compared to other combinations, considered as an optimum parameters. Sheet processed in the above stated configuration was evaluated for wear studies as per design of experiments.
presented in table 4. At room temperature, RCS processed samples were put through a dry sliding wear test using a pin on disc wear testing machine with varied process parameters. The specimen’s weight loss, wear rate, and frictional force were all monitored on a regular basis. In all of the experiments, the findings of particular wear rate are tabulated and reported in table 6.

3.2.1. Worn surface morphology
The worn surface morphology of the RCS processed sheets are shown in figures 8(a)–(d). As the applied force rises, the adhesive wear increases, and material must be connected to the disc owing to an increase in contact area between the sliding surfaces. The welding trend indicates an increase in surface delamination, which revealed evidence of adhesive wear. As a result, the wear process may be determined using a combination of adhesion wear and plastic deformation bands [20]. On the worn surface, adhesion regions with plastic deformation bands in the direction of sliding and delamination areas were detected.

3.3. Response surface methodology (RSM)
3.3.1. Effect of process parameters on the response specific wear rate
figures 9(a)–(c) depicts the influence of process parameters on the output response specific wear rate (SWR). According to the contour surface plots, the average specific wear rate for a load of 9.81 N, a sliding distance of 2000 m and a sliding velocity of 2 m s\(^{-1}\) is around 2.163 \(\times\) \(10^{-4}\) mm\(^3\) Nm\(^{-1}\) (figures 9(a)). The average SWR increases to 7.813 \(\times\) \(10^{-4}\) mm\(^3\) Nm\(^{-1}\) when the load is raised to 19.62 N for the same sliding distance. Similarly, the average specific wear rate for a sliding distance of 2000 m and a sliding velocity of 1.45 m s\(^{-1}\) is around 2.889 \(\times\) \(10^{-4}\) mm\(^3\) Nm\(^{-1}\) (figure 9(b)). The average SWR increases to 6.270 \(\times\) \(10^{-4}\) mm\(^3\) Nm\(^{-1}\) when the sliding velocity is raised to 2.66 m s\(^{-1}\) for the same sliding distance. Similarly, the average specific wear rate with a sliding velocity of 1.45 m s\(^{-1}\) and a load of 9.81 N is around 1.467 \(\times\) \(10^{-4}\) mm\(^3\) Nm\(^{-1}\) (figure 9(c)). The average specific wear rate increases to 8.826 \(\times\) \(10^{-4}\) mm\(^3\) Nm\(^{-1}\) when the load is raised to 19.62 N for the same sliding velocity [33–35]. The Response surface plots of SWR for three input variables (Load, SD and SV) of the RCS treated AA 2024 alloy are shown in figures 10(a)–(c).
Figure 8. Worn surface of the wear test specimen surface tested under (a) 4000 m at 2.66 m s\(^{-1}\) under 19.62N (b) 6000 m at 1.45 m s\(^{-1}\) under 9.815 N (c) 6000 m at 2.66 m s\(^{-1}\) under 14.715N (d) 2000 m at 2.66 m s\(^{-1}\) under 19.62N.

Table 6. Specific wear rate of RCS processed sheet with varying wear parameters as per DOE.

| Trail Runs | Sliding Distance, m | Load, N  | Sliding Velocity, m s\(^{-1}\) | Friction Force, N | Coefficient of Friction \(\mu = F/N\) | Specific Wear Rate (SWR) (mm\(^3\)Nm\(^{-1}\)) \(\times 10^{-4}\) |
|------------|---------------------|---------|-------------------------------|------------------|-----------------------------------|---------------------------------|
| 1          | 2000                | 9.81    | 1.45                          | 4.22             | 0.430                             | 1.564                           |
| 2          | 2000                | 9.81    | 2                             | 5.33             | 0.543                             | 2.183                           |
| 3          | 2000                | 9.81    | 2.66                          | 4.93             | 0.503                             | 2.742                           |
| 4          | 2000                | 14.715  | 1.45                          | 4.87             | 0.331                             | 2.201                           |
| 5          | 2000                | 14.715  | 2                             | 7.79             | 0.529                             | 4.497                           |
| 6          | 2000                | 14.715  | 2.66                          | 8.26             | 0.561                             | 7.269                           |
| 7          | 2000                | 19.62   | 1.45                          | 10.82            | 0.551                             | 4.903                           |
| 8          | 2000                | 19.62   | 2                             | 9.01             | 0.459                             | 6.189                           |
| 9          | 2000                | 19.62   | 2.66                          | 11.23            | 0.572                             | 8.812                           |
| 10         | 4000                | 9.81    | 1.45                          | 3.3              | 0.336                             | 1.829                           |
| 11         | 4000                | 9.81    | 2                             | 5.34             | 0.544                             | 2.163                           |
| 12         | 4000                | 9.81    | 2.66                          | 3.72             | 0.379                             | 2.703                           |
| 13         | 4000                | 14.715  | 1.45                          | 8.47             | 0.576                             | 4.822                           |
| 14         | 4000                | 14.715  | 2                             | 6.91             | 0.470                             | 5.969                           |
| 15         | 4000                | 14.715  | 2.66                          | 6.95             | 0.472                             | 8.281                           |
| 16         | 4000                | 19.62   | 1.45                          | 6.46             | 0.329                             | 5.512                           |
| 17         | 4000                | 19.62   | 2                             | 8.18             | 0.417                             | 8.355                           |
| 18         | 4000                | 19.62   | 2.66                          | 10.26            | 0.523                             | 12.223                          |
| 19         | 6000                | 9.81    | 1.45                          | 3.65             | 0.372                             | 1.019                           |
| 20         | 6000                | 9.81    | 2                             | 4.98             | 0.508                             | 3.399                           |
| 21         | 6000                | 9.81    | 2.66                          | 4.84             | 0.493                             | 4.390                           |
| 22         | 6000                | 14.715  | 1.45                          | 6.22             | 0.423                             | 2.278                           |
| 23         | 6000                | 14.715  | 2                             | 5.8              | 0.394                             | 4.749                           |
| 24         | 6000                | 14.715  | 2.66                          | 5.9              | 0.401                             | 6.578                           |
| 25         | 6000                | 19.62   | 1.45                          | 5.73             | 0.292                             | 3.071                           |
| 26         | 6000                | 19.62   | 2                             | 7.46             | 0.380                             | 9.144                           |
| 27         | 6000                | 19.62   | 2.66                          | 6.25             | 0.319                             | 10.351                          |
From table 7 shows the experimental and the predicted values for specific wear rate (typical). The objective is to minimize the wear rate and hence it is Smaller-the-Better type characteristic.

4. Conclusions

The aluminium alloy 2024 was successfully treated using a technique called repeated corrugation and straightening, followed by annealing. The following are the conclusions:

1. RCS approach has shown to be a valuable tool in the refining of grains, as well as the enhancement of mechanical characteristics of Al2024 samples and the impact of successive annealing.
2. Sheet thickness and number of passes are the two most important parameters that influence tensile strength. The tensile strength increases by 8%–18% when the temperature was kept constant and the number of passes increased.

Figure 10. (a)–(c) Response surface plot of Specific Wear Rate for three factors (Load, Sliding distance and Sliding velocity) of the RCS processed AA2024 alloy
3. The influence of successive annealing on the mechanical characteristics of the treated material has been demonstrated. The annealing temperature of 150 °C was shown to improve UTS. Then, when the annealing temperature was raised, the strength steadily dropped.

4. Wear characterization was carried out on the sheet treated using improved RCS process settings and three primary significant elements that impact the particular wear rate, as well as the wear behaviour of the RCS processed AA2024 alloy, were taken into account.

5. Experimental results of wear test and RSM plots confirms that the average SWR increases when the load is raised for the constant sliding distance and sliding velocity. Similarly, the average SWR increases when the sliding velocity is raised under the under sliding distance.

6. Fractography of broken surfaces in a tensile sample reveals a ductile fracture mechanism.

Data availability statement
All data that support the findings of this study are included within the article (and any supplementary files).

Conflicts of interest
The authors declare no conflicts of interest.

ORCID iDs
Y J Manjunath  https://orcid.org/0000-0003-1455-7443
A Chandrashekar  https://orcid.org/0000-0003-3813-9385
Abdul Razak Kaladgi  https://orcid.org/0000-0001-7985-2502
V Mohanavel  https://orcid.org/0000-0002-3111-4305
Asif Azfal  https://orcid.org/0000-0003-2961-6186
M C Manjunatha  https://orcid.org/0000-0003-2242-8481

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Table 7. Results of experiment and predicted values for the specific wear rate.

| Material  | Parameters | Experimental value | Predicted value | Variation |
|-----------|------------|--------------------|----------------|-----------|
| AA 2024   | SD = 4000 m| 2.163              | 2.163          | 0.00      |
|           | Load = 9.81N| 8.355              | 7.813          | 6.487     |
|           | SV = 1.45, 2, and 2.66 m s⁻¹ | 5.969              | 5.012          | 16.03     |
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