Impact of speed of traverse during joining of CDA101 plates by FSW process

B. Yokesh Kumar¹ and P. Sevvel²*

¹ Assistant Professor, Department of Mechanical Engineering, Chennai Institute of Technology, Kundrathur – 600 069, Tamil Nadu, India. Ph: +91 9791345675
² Professor, Department of Mechanical Engineering, S.A. Engineering College, Chennai – 600 077, Tamil Nadu, India. Mobile: +91 9445048418

Email ID: ¹yokeshkumarb@citchennai.net; ²drsevvel@saec.ac.in

Abstract:

An experimental investigation was carried out to comprehend the impact of speed of traverse of tool on tensile strength and micro-structural peculiarities of attained joints during friction stir welding of Cu alloy namely CDA 101 flat plates, with other parameters namely spinning speed of tool (1100 rpm) and downward force (6kN) being constant. A tool with cylindrical tapered pin geometry was made to traverse at distinctive speeds from 20 mm/min to 45 mm/min. It was observed that, the CDA 101 joints fabricated at 20 mm/min was found to be entirely free flaws, with joints fabricated at other speeds of tool traverse possessing several weld flaws. Grains in the center of the zone of stir of the joints obtained at 20 mm/min was uniformly distributed and homogeneous, due to the experience of the exemplary volume of frictional heat and sufficient amount of stirring force. Highest tensile strength of 200.65 MPa (nearly 85.38% of base metal) was exhibited by joint attained at 20 mm/min.

Keywords: Speed of tool traverse, CDA 101 Cu alloy, Zone of stir, Friction stir welding, Tensile Strength, Micro-structural characteristics.

* Corresponding author: Tel.: +91 94450 48418 ; E-mail address: drsevvel@saec.ac.in

1. Introduction

Alloys of Copper have the immense capability for usage in a variety of industrial sectors including marine systems, construction, transportation, for encapsulating material wastages especially nuclear wastes etc and this usage is possible mainly because of their
superior thermal and electrical conductivities, a unique combination of ductility and strength, exemplary resistance to corrosion etc [1–5]

Even though there exists an everlasting demand for the alloys of copper (Cu) in several industrial sectors, the usage of these alloys are restricted due to the difficulty in welding them [6–9]. Fusion-based joining techniques are not suitable for copper, as the existence of pernicious and eruptive constituents such as zinc (present in the alloys of Cu) and other oxides (adherent in nature) deteriorate the quality of weld [10–13]. In addition to this, the peculiar characteristic features of alloys of Cu namely, larger level of thermal diffusivity, elevated oxidation rate, etc also hinder the successful welding of alloys of Cu by fusion-based joining techniques [14, 15].

Comparatively unique and advanced solid condition of welding methodology namely friction stir welding (FSW), in which a non-esculent welding tool accomplishes both the heat (due to friction) and mechanical deformation concurrently, seems to be suitable for joining alloys of Cu [16–18]. Reasons for preferring the process of FSW for joining Cu are that the higher amount of input of heat required for joining alloys of Cu can be easily met by employing the FSW process. In addition to this, this solid-state category of welding (i.e., FSW) makes it possible to attain superior high strength joints free from cracks, porosity and with reduced levels of residual stresses [19–22].

The process of FSW have been proved to be an effective joining method for almost all the alloys of aluminium (which could not be welded by employing conventional joining techniques) ranging from 7XXX alloy series to 2XXX series and several alloys of magnesium [23–31]. For example, FSW of 7 series Al alloy namely 7075-T6 Al alloy was carried out by Wen et al [25]. During that experimental attempt, he investigated the micro-structural and nano-mechanical characterization of the fabricated 7075-T6 Al alloy joints by adopting the technique namely nano-indentation, and a correlation was framed between the micro-hardness and nano-hardness. The analysis of the experimental observations revealed, employment of the FSW process has led to the refinement of the grains appreciably and the nano-hardness of each & every zone of the friction stir welded joint exhibited indentation size impact and the nano-mechanical demeanor was proved to be impacted by the precipitation in the interior of the grains. Likewise, Patel et al. [27] made an experimentation to attain very fine grains in 6.35 mm thickness Mg alloys using copper and steel as backing plates by employing stationary shoulder based friction stir technique. Uniform fine grains were obtained during the usage of steel type backing plates in the
bottom, middle and top regions of the zone of stir and were in the size of 4.12, 4.75 and 4.98 μm respectively. At the same time, copper type backing plates produced very fine grains in the lower region (0.96 μm in size) and fine grains (4.1 μm in size) in the upper portion of stir zone. The attainment of very fine grains has contributed for the reasonable improvement in the hardness of the parent metal by nearly 80% and its tensile strength by nearly 24%.

Apart from joining similar alloys of Al, FSW was also proved to be very much effective in welding together dissimilar alloys of Al. For instance, the experimental work carried out by Shunmugasundaram [29] investigated in a detailed manner the optimization of the parameters during joining of dissimilar alloys of Al, namely AA6063& AA5052 by FSW process. The major reason for carrying out the joining of these dissimilar alloys of Al is, AA6063 possesses superior strength, whereas, AA5052 is non-heat-treatable in nature and possesses desirable weldability, thereby the fabricated joint will possess extraordinary properties. In this work, the parameters of FSW process were optimized by employing Taguchi-based L9 orthogonal array. The parameters taken into consideration included the speed of tool spinning, rate of traversing, and the angle of tool tilt and the optimization of these parameters were aimed towards the maximization of the strength (tensile) of the dissimilar joint. Close and detailed observation of the experimental recordings proved the spinning speed of the tool has a more dominating part in impacting the strength (tensile) of the fabricated joint when compared with that of the other parameters namely the rate of traversing and the angle of tool tilt.

Although the process of FSW was successfully employed for joining a wide variety of similar and dissimilar alloys of aluminium, only very few researchers [32–35] have made investigational attempts to join alloys of Cu by employing the FSW process. For example, an effort was put forward by Nagabharam et al. [32] to understand the impact of some parameters of FSW namely, the geometry of tool pin, speed of traversing, and speed of spinning. In this experimental effort, tools with 2 distinctive geometry of pin (namely straight square and straight cylindrical) were employed at 2 distinctive traversing and spinning speeds. The validation of the experimental efforts revealed Cu weldment fabricated at tool spinning speed of 910 rpm, 30 mm/min traversing speed during the employment of tool possessing square pin geometry exhibited desirable values of tensile strength when compared with that of the other Cu joints.
Hwang et al [34] investigated the thermal characters of the friction stir welded C11000 (pure copper) joints by employing thermocouples (K-type) at distinctive locations on the surface of the plates to be welded and these thermocouples were used to record the peak temperatures being developed during the process of joining. The peak temperatures of the desirable quality joints were found to be in the range of 460\(^\circ\)C to 530\(^\circ\)C. Careful observations of the recorded data also showed surfaces of the plates kept on the side of advancement have experienced higher temperatures when compared with that of the plate surfaces on the side of retraction. The percentage of elongation exhibited by the flawless joints was nearly 3 times larger than that of the elongation of the parent metal, namely C11000.

Even though research works investigating the impacts of parameters during the FSW of pure copper were found to be carried out by few researchers, no investigational works have been accomplished to investigate the impact of the speed of traverse during FSW of alloys of copper. Significance of the speed of traverse (i.e., feed rate), its impact on the evolution of micro-structural characteristics and joint quality, and the inadequacy of research conclusions available with respect to FSW of alloys of copper have motivated the authors to perform this research investigation.

2. Procedure for Experimentation

Alloy of copper namely CDA 101 is the material of research in this experimentation and 6mm thick flat plates (with a length of 150 mm and 50 mm width) of this CDA 101 alloy were butt joined using the FSW process. The composition of this material of experimental research is described in Table 1.

The tensile strength of experimented metal was 235 MPa along with strength of yield of 193 MPa and elongation is 18%. Flat plates of this base metal (CDA 101 alloy) was butt welded at right angles to the direction of rolling as seen in the Figure 1 (b), by employing an idiosyncratically developed, pseudo-automatic category friction stir welding machine, which can travel in three distinctive axes (namely 400 mm vertically, 510 mm longitudinally and 400 mm horizontally) and is fitted with a 810 mm X 400 mm size work table. The photograph of this machine is shown in Figure 1(a). Moreover, the employed FSW machine also encompasses an exclusive fabricated work holding platform so as to hold work pieces possessing a maximum width of 75 mm and the maximum length of 250 mm.
The employed tool possessed a 20mm diameter shoulder for a length of 40mm, followed by a 30 mm broad main shoulder for a 35 mm length possessing a cylindrically tapered pin profile for a length of 5.85 mm. The photograph of this tool is displayed in Figure 1(c). The tool used for carrying out the FSW in this experimental work was made out of M42 grade high-speed steel. The preeminent reason for employing M42 grade HSS to fabricate tool in this work is, this grade of HSS contains additionally 8% of cobalt (when compared to other Grades of HSS) and incorporation of this cobalt has significantly raised the resistance of heat of this alloy leading to extraordinary red hardness properties, thereby permitting reduced welding & machining periods[36, 37].

Another unique feature of this tool fabricated using M42 grade HSS is, it can last longer than M35, M2 grades of HSS [38, 39]. The entire set of experimental investigations were carried out by employing a constant downward force of 6kN and the tool was made to spin at a consistent speed of 1100 rpm and the tool was made to traverse at 6 distinctive rates including 20, 25, 30, 35, 40 and 45 mm/min.

3. Experimental Inferences and Deliberations

3.1. Characterization of Macrostructures

Table 2 illustrates in detail the macro-structural images of the friction stir welded CDA 101 flat plates obtained by employing 6 distinctive speeds of traverse of the tool.

From this table, it can be visualized that, the macrostructure of the CDA 101 flat plate joints fabricated at lower speeds of traverse of the tool (i.e., at 20 mm/min) observes to be free from flaws. At the same time, with an upswing in the speed of traverse of the tool, (i.e., from 25 mm/min to 45 mm/min) with other adopted parameters remaining constant (namely 1100 rpm and 6kN), the intensity of the flaws and irregularities seems to get intensified. For example, the joint obtained during 25 mm/min is found to be present with a weld flaw namely galling of surface, followed by tunneling flaws in CDA 101 joints fabricated at 30 and 35 mm/min. Likewise, joints attained at 40 and 45 mm/min speeds of traverse of the tool were found to possess porosities.

3.2. Characterization of Macrostructures

In order to gain a better understanding of the impact of the speed of traverse of the employed tool during the welding of flat plates of CDA 101 by FSW process, careful examinations of the respective joints microstructure are inevitable. The photographic image of the microstructures of the metal of investigation and CDA 101 friction stir
welded joints fabricated at 6 distinctive speeds of traverse of the tool are illustrated in Figure 2 (a – g).

It can be seen in Fig.2 (a), that the microstructure of the metal of investigation, i.e., CDA 101 possesses enormous sized grains with sporadic boundaries. The matrix of the metal also exhibits the occupancy of coupled areas together with lines of assimilation. Careful observation of the microstructures of the friction stir welded CDA 101 joints, i.e., Fig.2 (b – g) divulges us that, the process of friction stir welding has impacted the microstructural characteristic aspect of this CDA 101 alloy and have exceedingly refined the arrangement, distribution of the grains and their size, especially in the region of the stir of the fabricated joints.

At the same time, it can be observed, there exists a legitimate volume of difference in the size of the refined grains present in the region of the stir of all the CDA 101 joints fabricated at 20 mm/min to 45 mm/min, when compared with that of their parent metal. This was principally due to the employment of the FSW process for joining the flat plates of alloy of CDA 101. Because of the employment of the FSW process, the generous volume of frictional heat generated has paved the path to the refinement of grains in an adorable manner and have also led to the recrystallization of the grains, their distribution in a unique and compatible manner as proven by Patel et al. [40].

At the same time, there exists a difference in the size of the grains due to the employment of 6 distinctive speeds of traverse of the tool. For example, the grains found in the region of the stir of the joint fabricated at speed of traverse of the tool of 30 mm/min (Fig. 2d) & 35 mm/min (Fig. 2e) were found to be smaller in size when compared with that of the grains present in the joints fabricated at 40 mm/min (Fig. 2f) and 45 mm/min (Fig. 2g).

Likewise, the grains present in the region of the stir of the joint fabricated at speed of traverse of tool of 20 mm/min (Fig. 2b) & 25 mm/min (Fig. 2c) are smaller in size when compared with that of the grains present in the joints fabricated at 30 mm/min (Fig. 2d) and 35 mm/min (Fig. 2e). Thus, it can be understood that the joints fabricated at smaller speeds of tool traverse are found to possess fine sized, completely refined smaller sized uniaxial grains when compared with that of the joints fabricated at greater speeds of tool traverse [41, 42]. In better words, the size of the grains seems to increase with the increase in the speed of tool traverse.

This increase in the size of the grains with the increase in the tool’s speed of
traverse happens due to the fact mentioned by Patel et al. [43] that, a high speed of traverse of the tool will eventually lead to a decline in deformation degree of friction stir welded joints [44]. The general proven principle of recrystallization as mentioned by Wang et al. [45] states that the reduced deformation degree during the employment of FSW for joining will result in a raise in the size of the recrystallized grains. This escalation in the size of the grains will be usually associated with various weld deformities including surface galling, tunneling flaws, porosities, etc [46, 47]. Table 2 reveals us the same fact, as it can be seen in this table that, the joints fabricated at higher speeds of traverse of tool were found to possess above mentioned defects and at the same time, the joints fabricated at a lower speed of traverse of the tool (i.e., 20 mm/min) were completely free from defects.

3.3. Scrutiny of SEM Images

To have a better understanding of the evolution of microstructures that has occurred in the friction stir welded CDA 101 flat plates, it becomes in evitable to compare the SEM images of the various zones of the joints fabricated at lower and higher speeds of traverse of the tool, namely at 20 mm/min and at 45 mm/min. Fig. 3(a) depicts the SEM image of the metal of investigation namely alloy of Copper i.e., CDA 101 flat plate. This image reveals us the presence of enormous sized grains with sporadic boundaries.

Matrix of Cu metal also exhibits the occupancy of coupled areas together with lines of assimilation. SEM images of the zones being influenced by frictional heat (HAZ) of the joints fabricated at 20 mm/min and 45 mm/min are depicted in Fig. 3(b) and 3(c) respectively. By comparing these two figures, we can understand that, the grains of the both the joints in the zone being influenced by heat have grown to some observable extent. At the same time, in both of the joints fabricated at 20 and 45 mm/min, we cannot observe any drastic change in the size of the grains when compared with that of their parent metal, which concedes us the fact that, the change in the speeds of traverse of the tool has only a meager impact on influencing the size of the grains in the HAZ.

Fig. 3(d) & (e) portrays the SEM images of the zones being affected thermomechanically (TMAZ) of the joints fabricated at 20 mm/min and 45 mm/min. The size of the grains in the TMAZ of the joint fabricated at 20mm/min seems to be smaller when compared with that of the grains in the TMAZ of joints at 45mm/min. This helps us to understand us that, the grains in the TMAZ of the joint fabricated at reduced speeds of traverse of the tool have experienced sufficient amount of frictional heat and archetypal
volume of stirring action by the shoulder of the tool for a longer period when compared with that of the joint attained at 45 mm/min, which eventually have played an inevitable role in reducing the size of the grains in the TMAZ [48, 49].

Apart from this, it can be observed that in both the Cu alloy joints (i.e., CDA 101 flat plate joints), the zone being affected thermo mechanically are not as apparent as observed in the case of friction stir welded joints of alloys of aluminium or magnesium [50]. This is due to the reason that, no stirred or lengthened grains contiguous to the zone of stir can be noticed. The SEM images of the zone of stir of the CDA 101 flat plate joints fabricated at 20 mm/min and 45 mm/min are portrayed in Fig. 3(f) & (g) respectively. By correlating all these SEM images, we can see that the size of the grains in the TMAZ is tinier than in the HAZ, but larger than those in the zone of stir. The size of the grains in the zone of stir in the joint attained at 20 mm/min is very much smaller when compared with grains attained at 45 mm/min. Moreover, the grains at the center of the zone of stir of the joints obtained at 20 mm/min traverse speed of tool is very finer, uniaxially distributed, equally spaced and homogeneous, due to the experience of exemplary volume of heat and enormous stirring action exerted by shoulder & pin of the tool for sufficient period [51].

Even though the size of the grains of the joint attained at 45mm/min is smaller when compared to that of the grains in its base metal, it is noticeable that, they are not finer and equally distributed when compared with that of the grains attained at 20 mm/min. This is mainly due to the reason, the employment of higher speeds of traverse of the tool (i.e., 45 mm/min) have subjected these grains to experience frictional heat and stirring action for a shorter period of time and this in turn have led to these grain size variations & their distributions. These variations in grain size and their distributions have eventually led to the welding defect namely porosities in the joints fabricated at 45 mm/min. These facts proves us, speed of traverse of the tool has an undeniable impact in dominating the micro-structural characteristic features of attained joints of Cu alloy, namely CDA 101.

3.4. Determination of the mechanical strength

Fig. 4 shows the graphical comparison of the tensile strength of the CDA 101 alloy weldments attained at varying speeds of traverse of the tool. It can be observed, the tensile strength falls with the upswing in speed of traverse of tool. Tensile strength of the joint
attained at 20 mm/min seems to have the highest value, i.e., 200.65 MPa (nearly 85.38% of the tensile strength of the metal of investigation) and the lowest value of strength is exhibited by joint fabricated at 45mm/min traversing speed, namely 147.56 MPa.

Fig. 5 depicts the locations of fracture of the CDA 101 Cu alloy joints fabricated at distinctive speeds of traverse of the tool. Careful observation of photograph of fractured tensile specimen of CDA 101 Cu alloy joints, we can visualize, reasonable necking prevails around region of fracture for CDA 101 Cu alloy joint attained at 20 mm/min, revealing us, macro-plastic type of deformation have occurred in that joint during conduction of test for tensile, as mentioned by Sejani et al. [52]. At the same time, this type of necking cannot be observed in other joints when being subjected to tensile load test. Moreover, the joint fabricated at 20 mm/min have encountered its fracture on the side of retraction (RS) and all other joints have encountered their fracture towards their side of advancement (AS). To be more specific regarding the exact position of the exact location of the fracture mechanism, it can be stated that, the path of the fracture of the joint (attained at 20 mm/min) have occurred along the thermo mechanically affected (TMAZ) regions, heat influenced regions (HAZ). But for all other joints, the fractures have occurred at the cavity of their defect [53].

3.5. Deliberations on SEM Fractography

SEM tensile fractographic images of the joint attained at 20 mm/min is illustrated in the Fig. 6 (a) along with two highlighted portions namely 1, 2 and enlarged SEM images of these two highlighted regions are being displayed as Fig. 6 (b) & (c). From Fig. 6(a), it can be visualized that, the fractured sample of the CDA 101 Cu alloy joint possesses a fracture morphology which is ductile in nature. This ductile type of fracture morphologies usually occur due to amalgamation of micro voids present in its parent metal [40, 45], which is positive indication that, FSW have resulted in sound quality weldment. This fracture surface has been partitioned into two regions and marked as 1 & 2, and the magnified SEM images of these two regions are depicted in the Fig. 6(b) & (c).

Careful observations of the enlarged SEM images of these two marked regions reveals us that, the ridges and hole like portions present in the Fig.6(a), can be identified as dimples. These dimples are found to be present in a river like pattern along with presence of very tiny void like structures, which indirectly confirms us the higher ductility of the CDA 101 Cu alloy joint. Correlating the presence of smaller sized grains and their
uniform distribution in the zone of stir of the CDA 101 Cu alloy joint fabricated at 20 mm/min and the joint’s corresponding exhibited tensile strength of 200.65 MPa (almost 85% of the parent metal) declares us that, generation of these exquisite sized grains in the zone of stir resulted purely by the impact of low speed of traverse of tool (20 mm/min) have made the joint entirely free from flaws, thus providing the required ideal amount of resistance for deformation during tensile test, resulting in amalgamation of the micro voids of the parent metal, leading to ductile nature of fracture morphology.

4. Conclusions

In this experimental work, during the joining of flat plates of Cu alloy namely CDA 101, by employing the process of FSW, a detailed investigation was carried out to understand the impact of the speed of traverse of tool (with cylindrically tapered pin geometry) on the micro-structural characteristics and mechanical properties of the obtained joints, with other parameters namely speed of spinning of tool (1100 rpm) and downward force (6kN) being constant. The derived outcomes are mentioned below:

- CDA 101 Cu alloy joints fabricated at speed of tool traverse of 20 mm/min was observed to be entirely defect free and the joints fabricated at other speeds of tool traverse (25 to 45 mm/min) was found to be present with several weld flaws including surface galling, porosities, tunneling flaws etc.
- There existed a legitimate volume of difference in the size of the refined grains present in the region of stir of all the CDA 101 joints fabricated at 20 mm/min to 45 mm/min, when compared with that of their parent metal.
- CDA 101 Cu alloy joints fabricated at smaller speeds of tool traverse (especially at 20 mm/min) are found to possess fine sized, completely refined smaller sized uniaxial grains when compared with that of the joints fabricated at greater speeds of tool traverse.
- Grains at the centre of zone of stir of the joints obtained at 20 mm/min traverse speed of tool is finer in size, uniaxially distributed, equally spaced and homogeneous, due to the experience of exemplary volume of frictional heat and enormous stirring force & action exerted by shoulder & pin of the tool for sufficient period.
• Reasonable necking has prevailed around the region of fracture for the CDA 101 Cu alloy joint attained at 20 mm/min, revealing us that, macro-plastic type of deformation have occurred in that joint during the conduction of test for tensile

• SEM tensile fractographic images of the joint attained at 20 mm/min reveals us that, occurred fracture morphology is ductile in nature and have resulted due to amalgamation of micro voids, positively indicating us that, employment of FSW for joining of CDA 101 Cu alloy have resulted in sound quality weldment.

• Tensile strength has fallen with the upswing in speed of traverse of tool. Tensile strength of the joint attained at 20 mm/min exhibited the highest value, i.e., 200.65 MPa (nearly 85.38% of the tensile strength of the metal of investigation) and the lowest value of strength is exhibited by joint fabricated at 45mm/min traversing speed, namely 147.56 MPa

References:

1. Heng Zhang, Ke Xin Jiao, Jian Liang Zhang, et al. “Experimental and numerical investigations of interface characteristics of copper/steel composite prepared by explosive welding”, Materials & Design, 154, pp. 140-152 (2018)

2. Sathiyaraj, S., Venkatesan, S., Ashokkumar, S., et al. “Wire electrical discharge machining (WEDM) analysis into MRR and SR on copper alloy”, Materials Today Proceedings, 33(1), pp. 1079-1084 (2020)

3. Dhanesh Babu, S.D., Sevvel, P., Senthil Kumar, R., et al. “Development of Thermo Mechanical Model for Prediction of Temperature Diffusion in Different FSW Tool Pin Geometries During Joining of AZ80A Mg Alloys”, Journal of Inorganic and Organometallic Polymers and Materials, 66(12), 2021

4. Cassidy Silbernagel, Leonidas Gargalis, Ian Ashcroft, et al. “Electrical resistivity of pure copper processed by medium-powered laser powder bed fusion additive manufacturing for use in electromagnetic applications”, Additive Manufacturing, 29, pp. 100831 (2019)

5. Zohreh Dahaghin, Hassan Zavvar Mousavi, Maryam Sajjadi, et al. “Determination and pre concentration of trace amounts of Cd(II), Cu(II), Ni(II), Zn(II), and Pb(II) ions by functionalized magnetic nanosorbent and optimization using a Box-Behnken design and detection of them by a flame atomic absorption spectrometer”, Scientia Iranica, 25(6), pp. 3275-3287 (2018)
6. Dhanesh Babu, S.D., Sevvel, P., and Senthil Kumar, R. “Simulation of heat transfer and analysis of impact of tool pin geometry and tool speed during friction stir welding of AZ80A Mg alloy plates”, *Journal of Mechanical Science and Technology*, **34 (10)**, pp. 4239–4250 (2020)

7. Wenhe Feng, Jiang Guo, Wenjin Yan, *et al.* “Deep channel fabrication on copper by multi-scan underwater laser machining”, *Optics & Laser Technology*, **111**, pp. 653-663 (2019)

8. Yao Liu, Songlin Cai, Fengguang Xu, *et al.* “Enhancing strength without compromising ductility in copper by combining extrusion machining and heat treatment”, *Journal of Materials Processing Technology*, **267**, pp.52-60 (2019)

9. Sathish T., Sevvel P., Sudharsan, P., *et al.* “Investigation and optimization of laser welding process parameters for AA7068 aluminium alloy butt joint”, *Materials Today: Proceedings*, **37**, pp. 1672–1677 (2021)

10. Ganachari, V.S., Chate, U.N., Waghmode, L.Y., *et al.* “A Comparative Performance Study of Dry and Near Dry EDM Processes in Machining of Spring Steel Material”, *Materials Today Proceedings*, **18(7)**, pp. 5247-5257 (2019)

11. Han Wang, Yukui Wang, Guanxin Chi, *et al.* “Simulation Study on Surface Drag Reduction Performance of Beryllium Copper Alloy by EDM”, *Procedia CIRP*, **95**, pp. 244-249 (2020)

12. Stephan Thangaiah, I.S., Sevvel, P., Satheesh, C., *et al.* “Experimental Study on the Role of Tool Geometry in determining the Strength & Soundness of Wrought AZ80a Mg Alloy Joints During FSW Process”, *FME Transactions*, **46(4)**, pp. 612–622 (2018)

13. Asghar Azizi, Behrooz Bayati, and Mohammad Karamoozian. “A comprehensive study of the leaching behavior and dissolution kinetics of copper oxide ore in sulfuric acid lixiviant”, *Scientia Iranica*, **25(3)**, pp. 1412-1422 (2018)

14. Uhlmann, E., Kuche, Y., Polte, J., *et al.* “Influence of cutting edge micro-geometry in micro-milling of copper alloys with reduced lead content”, *Procedia CIRP*, **77**, pp. 662–665 (2018)

15. Mojtaba Bagherzadeh, Hamed Mahmoudi, Mojtaba Amini, *et al.* “SBA-15-Supported Copper (II) Complex: An Efficient Heterogeneous Catalyst for Azide-Alkyne Cycloaddition in Water”, *Scientia Iranica*, **25(3)**, pp. 1335-1343 (2018)
16. Büttner, H., Vieira, G., Hajri, M., et al. “A comparison between micro milling pure copper and tungsten reinforced copper for electrodes in EDM applications”, Precision Engineering, 60, pp. 326-339 (2019)
17. Satheesh, C., Sevvel, P., and Senthil Kumar, R. “Experimental Identification of Optimized Process Parameters for FSW of AZ91C Mg Alloy Using Quadratic Regression Models”, Strojinski Vestnik / Journal of Mechanical Engineering, 66(12), pp. 736–751 (2020)
18. Boitsov, A.G., Pleshakov, A.S., Siluyanova, M.V., et al. “Friction Stir Welding of M1 Copper Alloy in the Production of Power Equipment”, Russian Engineering Research, 40 (3), pp. 249–252 (2020)
19. Saravanan C., Saravanan K., Sathish Kumar G., et al. “Investigation and evaluation of mechanical Behaviour of Al-TiC alloy”, Materials Today: Proceedings, 37, pp.1203–1207 (2021)
20. Gihad Karrar, Alexander Galloway, Athanasios Toumpis, et al. “Microstructural characterisation and mechanical properties of dissimilar AA5083-copper joints produced by friction stir welding”, Journal of Materials Research and Technology, 9(5), pp. 11968–11979 (2020)
21. Boitsov, A.G., Siluyanova, M.V., and Kuritsyna, V.V. “Electric-discharge milling of small airplane-engine components”, Russian Engineering Research, 38 (7) pp. 552–556 (2018)
22. Memduh Kurtulmus, and Alper Kiraz. “Artificial Neural Network Modelling for Polyethylene FSSW Parameters”, Scientia Iranica, 25(3), pp. 1266-1271 (2018)
23. Jafar langari, and Farhad Kolahan. “The effect of friction stir welding parameters on the microstructure, defects, and mechanical properties of AA7075-T651 joints”, Scientia Iranica, 26(4), pp. 2418-2430 (2019)
24. Li, W.Y., Niu, P.L., Yan, S.R., et al. “Improving microstructural and tensile properties of AZ31B magnesium alloy joints by stationary shoulder friction stir welding”, Journal of Manufacturing Processes,37, pp.159–167 (2019).
25. Wen Wang, Shengnan Yuan, Ke Qiao, et al. “Microstructure and nanomechanical behavior of friction stir welded joint of 7055 aluminum alloy”, Journal of Manufacturing Processes, 61, pp. 311–321(2021)
26. Zhang, H.J., Sun, S.L., Liu, H.J., et al. “Characteristic and mechanism of nugget performance evolution with rotation speed for high-rotation-speed friction stir
welded 6061 aluminum alloy”, *Journal of Manufacturing Processes*, **60**, pp. 544–552 (2020)

27. Vivek Patel, Wenya Li, Xichang Liu, *et al.* “Tailoring grain refinement through thickness in magnesium alloy via stationary shoulder friction stir processing and copper backing plate”, Materials Science and Engineering: A, **784**, 139322 (2020)

28. Sevvel, P., and Satheesh, C. “Role of tool rotational speed in influencing microstructural evolution, residual-stress formation and tensile properties of friction-stir welded AZ80A Mg alloy”, *Materiali in tehnologije*, **52 (5)**, pp. 607–614 (2018)

29. Shunmugasundaram, M., Praveen Kumar, A., Ponraj Sankar, L., *et al.* “Optimization of process parameters of friction stir welded dissimilar AA6063 and AA5052 aluminum alloys by Taguchi technique”, *Materials Today: Proceedings*, **27 (2)**, pp. 871-876 (2020)

30. Sevvel, P., Dhanesh Babu, S.D., and Senthil Kumar, R. “Peak Temperature Correlation and Temperature Distribution during Joining of AZ80A Mg Alloy by FSW – A Numerical and Experimental Investigation”, *Strojniški vestnik - Journal of Mechanical Engineering*, **66 (6)**, pp. 395-407 (2020)

31. Devang Sejani, Wenya Li and Vivek Patel “Stationary shoulder friction stir welding – low heat input joining technique: a review in comparison with conventional FSW and bobbin tool FSW”, *Critical Reviews in Solid State and Materials Sciences*, (2021)

32. Nagabharam, P., Srikanth Rao, D., Manoj Kumar, J., *et al.* “Investigation of Mechanical Properties of Friction Stir Welded pure Copper Plates”, *Materials Today: Proceedings*, **5**, pp. 1264–1270 (2018)

33. Xu, N., Feng, R.N., Guo, W.F. *et al.* “Effect of Zener–Hollomon Parameter on Microstructure and Mechanical Properties of Copper Subjected to Friction Stir Welding”, *Acta Metallurgica Sinica (English Letters)*, **33**, pp.319–326 (2020)

34. Y.M. Hwang, P.L. Fan, C.H. Lin, “Experimental study on Friction Stir Welding of copper metals”, *Journal of Materials Processing Technology*, **210 (12)**, pp.1667–1672 (2010)

35. Jha, K., Kumar, S., Nachiket, K. *et al.* “Friction Stir Welding (FSW) of Aged CuCrZr Alloy Plates”, *Metallurgical and Materials Transactions A*, **49**, pp.223–234 (2018)
36. Ramkumar S., Duraiselvam M., and Sevvel P. “Acoustic Emission Based Deep Learning Technique to Predict Adhesive Bond Strength of Laser Processed CFRP Composites”, *FME Transactions*, **48** (3), pp. 611–619 (2020)

37. Chai, F., Yan, F., Wang, W., *et al.* “Microstructures and Mechanical Properties of AZ91 Alloys Prepared by Multi-Pass Friction Stir Processing”, *Journal of Materials Research*, **33**, pp. 1789–1796 (2018)

38. Joshi, G.R., Badheka, V.J. “Microstructures and Properties of Copper to Stainless Steel Joints by Hybrid FSW”, *Metallography, Microstructure, and Analysis*, **6**, pp. 470–480 (2017)

39. Sevvel, P., Satheesh, C., and Senthil Kumar, R. “Generation of regression models and multi-response optimization of friction stir welding technique parameters during the fabrication of AZ80A Mg alloy joints”, *Transactions of the Canadian Society for Mechanical Engineering*, **44(2)**, pp.311-324 (2020)

40. Vivek Patel, Wenya Li, Achilles Vairis, *et al.* “Recent Development in Friction Stir Processing as a Solid-State Grain Refinement Technique: Microstructural Evolution and Property Enhancement”, *Critical Reviews in Solid State and Materials Sciences*, **44** (5), pp. 378–426 (2019)

41. Patel, P., Rana, H., Badheka, V. *et al.* “Effect of active heating and cooling on microstructure and mechanical properties of friction stir–welded dissimilar aluminium alloy and titanium butt joints”, *Welding in the World*, **64**, pp.365–378 (2020)

42. Lin, J., Zhang, D. T., Zhang, W., *et al.* “Microstructure and mechanical properties of ZK60 magnesium alloy prepared by multi-pass friction stir processing”, *Materials Science Forum*, **898**, pp.278–283 (2017).

43. Vivek Patel, Wenya Li, Xichang Liu, *et al.* “Through-thickness microstructure and mechanical properties in stationary shoulder friction stir processed AA7075”, *Materials Science and Technology*, **35** (14), pp. 1762–1769 (2019)

44. Esmaily, M., Svensson, J. E., Fajardo, S., *et al.* “Fundamentals and advances in magnesium alloy corrosion”, *Progress in Materials Science*, **89**, pp. 92–193 (2017).

45. Yunpeng Wang, Ruidong Fu, Lei Jing, *et al.* “Grain refinement and nanostructure formation in pure copper during cryogenic friction stir processing”, *Materials Science and Engineering: A*, **703**, pp. 470–476 (2017)
46. Sun T., Roy M. J., Strong D., et al. “Weld zone and residual stress development in AA7050 stationary shoulder friction stir T-joint weld”, *Journal of Materials Processing Technology*, 263, pp. 256–265 (2019).

47. Qin, D.Q., Fu, L., and Shen, Z.K. “Visualisation and numerical simulation of material flow behaviour during high-speed FSW process of 2024 aluminium alloy thin plate”, *International Journal of Advanced Manufacturing Technology*, 102, pp. 1901–1912 (2019)

48. Jaiganesh, V., and Sevvel, P. “Effect of Process Parameters in the Microstructural Characteristics and Mechanical Properties of AZ80A Mg Alloy during Friction Stir Welding”, *Transactions of the Indian Institute of Metals*, 68 (S1), pp. 99–104 (2015)

49. Shahnam, A., Karimzadeh, F., Golozar, M.A., et al. “Microstructure evolution of ultra-fine-grained AZ31 B magnesium alloy produced by submerged friction stir processing”, *Journal of Materials Engineering and Performance*, 28, pp. 4593–4601 (2019)

50. Sevvel, P., Satheesh, C., and Jaiganesh, V. “Influence of tool rotational speed on microstructural characteristics of dissimilar Mg alloys during friction stir welding”, *Transactions of the Canadian Society for Mechanical Engineering*, 43(1), pp.132-141 (2019)

51. Gao, J., Zhang, S., Jin, H. et al. “Fabrication of Al7075/PI composites base on FSW technology”, *International Journal of Advanced Manufacturing Technology*, 104, pp.4377–4386 (2019)

52. Devang Sejani, Wenya Li and Vivek Patel. “Stationary shoulder friction stir welding – low heat input joining technique: a review in comparison with conventional FSW and bobbin tool FSW”, *Critical Reviews in Solid State and Materials Sciences*, (2021)

53. Anil Kumar, K.S., Murigendrappa, S.M., and Kumar, H. “Experimental investigation on effects of varying volume fractions of SiC nanoparticle reinforcement on microstructure and mechanical properties in friction-stir-welded dissimilar joints of AA2024-T351 and AA7075-T651”, *Journal of Materials Research*, 34, pp.1229–1247 (2019)
List of Figure captions:-

Fig. 1. Photographs of (a) idiosyncratically developed, pseudo-automatic category friction stir welding machine employed in this work (b) flat plates of base metal (CDA 101 alloy) being butt welded at right angles to the direction of rolling using FSW process (c) M42 grade HSS Tool with cylindrically tapered profiled pin

Fig. 2. (a) Microstructure of the metal of investigation, i.e., CDA 101alloy; microstructure of the centre of the region of stir of CDA 101 joints attained at (b) 20 mm/min (c) 25 mm/min (d) 30 mm/min (e) 35 mm/min (f) 40 mm/min and (g) 45 mm/min

Fig. 3. SEM images of (a) metal of investigation i.e., CDA 101; HAZ of the CDA 101 joint fabricated at (b) 20 mm/min & (c) 45 mm/min; TMAZ at (d) 20 mm/min & (e) 45 mm/min; Zone of stir at (f) 20 mm/min and (g) 45 mm /min

Fig. 4. Graphical illustration of the tensile strength of the CDA 101 Cu alloy joints fabricated at distinctive speeds of traverse of the FSW tool

Fig. 5. Photographs of the fractured tensile specimen of the CDA 101 Cu alloy joints with their exact location of fracture being highlighted

Fig. 6. (a) SEM fractographic images of the tensile joints fabricated at 20 mm/min; (b) & (c) enlarged SEM images of the highlighted portions, namely 1 and 2

List of Table captions:-

Table 1 Chemical configuration of CDA101

Table 2 Macrostructure of the friction stir welded flat plates of CDA 101 at 6 distinctive speeds of traverse of the tool
List of Figures:-

Fig. 1.

Fig. 2.
Fig. 3.
Fig. 4.

Fig. 5.
**List of Table captions:-**

**Table 1 Chemical configuration of CDA101**

| Material  | Pb    | Si    | Cr   | Ni   | P    | S    | Fe   | Zn   | Cu   | less than <0.001 |
|-----------|-------|-------|------|------|------|------|------|------|------|-----------------|
| CDA 101   | <0.005| <0.005| <0.01| <0.005| <0.002| <0.015| 0.0139| Balance | Mg, Sn, Al & Mn |

**Table 2 Macrostructure of the friction stir welded flat plates of CDA 101 at 6 distinctive speeds of traverse of the tool**

| Weldment No | Speed of tool traverse | Macrostructure of the friction stir welded plates of CDA 101 |
|-------------|------------------------|------------------------------------------------------------|
| 1           | 20 mm/min              | ![Image](image1)                                             |
| 2           | 25 mm/min              | ![Image](image2)                                             |
| 3           | 30 mm/min              | ![Image](image3)                                             |
| 4           | 35 mm/min              | ![Image](image4)                                             |
| 5           | 40 mm/min              | ![Image](image5)                                             |
| 6           | 45 mm/min              | ![Image](image6)                                             |

**Author’s Biography:-**

**Mr. B. Yokesh Kumar** is currently pursuing his Doctoral degree (Ph.D.) in Mechanical Engineering, Anna University, Chennai, India. He had successfully completed his Master's Degree with 1st Class in Industrial Engineering from Anna University, Chennai, India in 2014. He has a total 7.5 years of Teaching experience. He is currently serving as Assistant Professor, Department of Mechanical Engineering in Chennai Institute of Technology, Chennai, TamilNadu, India. He has published several research
papers in the area of Friction Stir Welding in renowned International Journals indexed in Science Citation Index, Scopus etc.

Dr. P. Sevvel obtained his Ph.D. in Mechanical Engineering from Anna University, Chennai in 2016 and successfully completed his M.Tech. degree with 1st Class Distinction in Industrial Engineering from the National Institute of Technology (NIT) Trichy, India, in 2005. He has a total of more than 15 years of teaching experience. He is currently working as Professor, Department of Mechanical Engineering College in S.A. Engineering College, Chennai. He has a total of 3 ongoing funded Projects worth Rs. 46,90,107 under various schemes of DST, TNSCST He has 5 Indian PATENT GRANTS in his name. He is a Life Member of the Indian Society for Technical Education (ISTE) and a Corporate Member in The Institution of Engineers (IE), India. He has published more than 46 Research Papers in various SCI & Scopus indexed International Journals. He is currently guiding a total of 9 Research Scholars pursuing their Ph.D. in Centre for Research, Anna University. He was awarded with BEST RESEARCHER AWARD for his distinct contribution in the field of Materials Science during the 6th Annual Millennium Impact Award 2020.