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Friction Stir and Cold Metal Transfer Welding of AA7075: Experimental Investigations and Machine Learning Approaches

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Abstract

Frictions stir welding (FSW) and cold metal transfer (CMT) welding processes are ideal for joining aluminium and its alloys. FSW and CMT are clearly distinguished by their working principle, one is solid state type and other is fusion type welding process. This paper attempted to study the effectiveness of both processes on aluminium alloy. AA7075 is a heat treatable alloy and most suitable for dynamic applications owing to its exceptional characteristics. Structure and mechanical properties of the joints produced by FSW and CMT are investigated. Experimental results revealed that the performance of FSW is better than the CMT in metallurgical and mechanical aspects. The fine structure and homogenous distribution of particles in FSW joints results in strengthening mechanism unlike CMT, where the particles are uneven and coarse-grained. However, CMT can produce welds with higher speeds and can achieve performance at par with FSW. Further, machine learning techniques, polynomial regression and support vector machine are applied to derive the relationships between process parameters and strength parameters.

Keywords: Friction Stir Welding, Cold Metal Transfer Welding, AA7075, Microstructures, Mechanical Properties, Machine Learning Techniques.

1. Introduction

Aluminium (Al) alloys known for its exceptional characteristics like light weight, high strength to weight ratio, excellent corrosion resistance and fracture toughness. Among these alloys, 7xxx series are heat treatable and found in many of the applications like automotive, aerospace, ship building, construction and defence. Fabrication of Al alloys, particularly fusion welding of AA7075 is difficult due to the challenges posed by the solidification cracks, excessive heat generation, fusion defects and porosity formation (Bahemmat, et al.2012; Fuller et al.2010, Aissani et al.2010). AA7075 is based on Al-Zn-Mg-Cu alloy that can improve the strength after heat-treatment. This unique characteristic of AA7075 allows it use in military and aircraft components (Feng, et al. 2010).

Friction stir welding is a solid state type of welding process developed by The Welding Institute (TWI) particularly for joining of Al alloys (Thomas, 1991). The process uses frictional heat generated at the faying surfaces for joining work pieces. The resultant weld is formed by the solid state diffusion and material deformation rather than melting and solidification (Dawes and Thomas, 1995; Ellis and Strangwood, 1995; Dawes and Thomas, 1996). Fusion welding of Al alloys seemed to be a challenging task for the welders since very recently. Resistance welding of Al alloys needs extensive surface preparation due to the presence of surface oxide layer and is not recommendable. The problem of surface oxide layer of Al alloys is not an issue for friction stir welding and usually no prior preparation methods are needed for welding. In the recent years, many manufacturers came up with solutions for fusion welding of Al alloys such as pulsed MIG/MAG, TIG and CMT.

The problems associated with fusion welding of Al alloys arise from its relatively low melting point (~650°C). However, the amount of thermal energy required for welding aluminium is same as that of welding steel this is because of aluminium high thermal conductivity and heat of fusion (Mathers, 2002). In addition to this, problems like weld bead cracks, residual stresses and distortion are typically observed in final weld due to solidification and high value of thermal coefficient. Pulsed-MIG welding is the commonly used for welding aluminium, where controlled material transfer of one droplet per pulse is detached. However, this process is not feasible when welding thin Al alloy parts and leads to frequent burn through and fusion problems. To effectively address this challenge, cold metal transfer welding was developed which is perfect for welding aluminium and its alloys (Pickin and Young, 2006).

Cold metal transfer is the modified version of conventional MIG/MAG process. It was invented by the Fronius International. CMT incorporates the wire-feed motion and high frequency digital control system that not controls the arc stability but also the heat transfer. The electrode-wire consistently moves towards the work piece and retracts back to the specified arc length setting. The material transfer takes place during short-circuit of the wire electrode to the base metal with no thermal energy inputted by the arc (Kumar, et al., 2016). Literature reports revealed better performance of Al welds produced by CMT in terms of mechanical and metallurgical properties (Pickin, et al., 2011; Feng, et al.,2009; Elrefaey, 2015; Selvi et al., 2018). The main concern of friction stir welding of AA7075 is its speed of operation in spite of the defect free welds. This can be overcome by the CMT welding due to its flexibility and simplicity.

In this present study, effectiveness of friction stir welding and cold metal transfer welding of AA7075 is measured. The results were compared with respect to the joint strength and microstructures at the weld interface. Machine learning techniques such as polynomial regression and support vector machines were applied to predict the tensile strength and hardness of FSW and CMT welded AA7075 joints.

2. Materials and Methods

Experimentation was performed on the AA7075 plate with 6 mm thickness. The chemical composition of the material and the filler wire, ER5356 used for CMT welding (Fronius, Austria) is provided in Table 1. Fixed arc length of 1 mm is maintained throughout the experimentation. Joints were produced by the FSW process without a filler metal. The FSW tool made of H-13 steel with square shape was used (Fig. 1 and Fig. 2). The length and width of square tool is 5.7 mm and 6 mm respectively. A total of 27 experiments were performed for each welding process. Fig 3 reveals the friction stir welding setup. The selection of process parameters was based on the trial and error and manual inspection of optimal welds. The process parameters and their ranges are specified in Table 2 & 3 Fig 4 reveals the friction Stir welding AA7075 samples and Fig 5 exhibits the cold metal transfer welding.

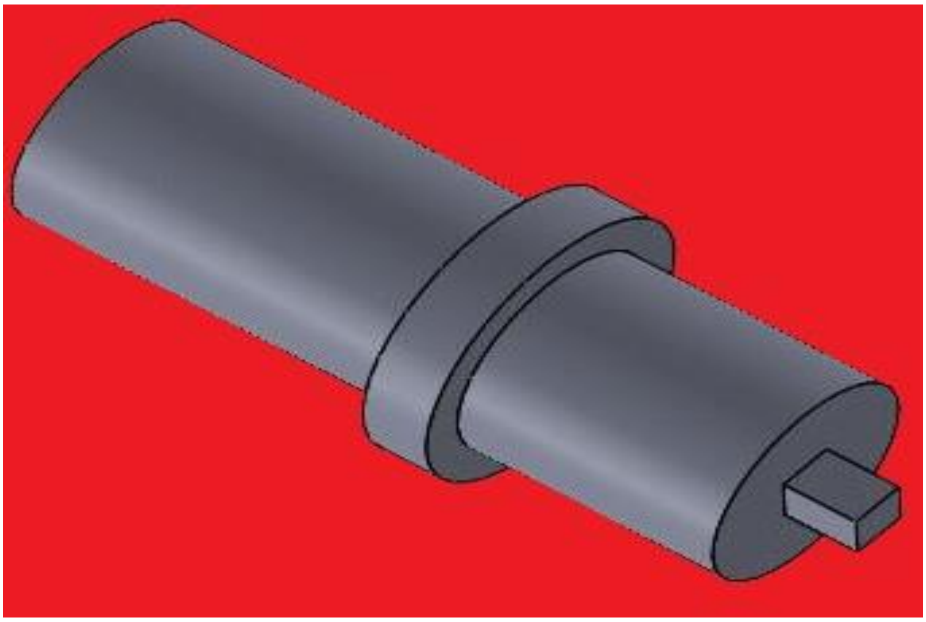

Figure 1. FSW tool profile

Figure 2. FSW tool

Figure 3. Friction stir welding setup

Figure 4. Friction Stir welding AA7075 samples

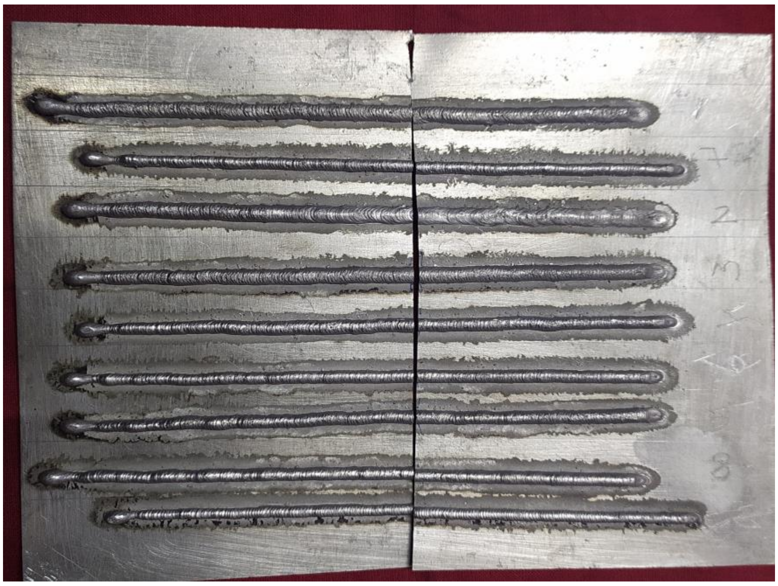

Figure 5. Cold Metal Transfer Welding

Table 1. Chemical composition in wt% of base and filler metals

Material	Zn	Mg	Cu	Fe	Si	Ti	Cr	Mn	Al
AA7075	5.5-6.1	2.2-2.6	1.2-2.0	0.5	0.36	0.24	0.18-0.28	0.03	Bal.
ER5356	0.1	4.5	0.1	0.4	0.25	0.06	0.05	0.05	Bal.

Table 2. CMT process parameters

Parameters	Range
Welding current (A)	120, 130, 140
Welding speed (mm/min)	500, 600, 700
Flow rate (L/min)	12, 15 ,18

Table 3. FSW process parameters

Parameters	Range
Rotational speed (RPM)	900, 1100, 1300
Welding speed (mm/min)	40, 50, 60
Axial force (kN)	3, 5, 7

The metallographic specimens were prepared from the each joint to obtain microstructures and scanning electron microscopy (SEM) images. Further, specimens were sectioned as per ASTM standard for evaluating tensile strength and micro hardness of the welds. Metallographic specimens sectioned, polished and then etched for 120 s (Keller's reagent). The microstructural images of as-received (Fig.6) and weld zone were obtained by using optical microscopy (OM) at the weld interfaces and inspected for any porosity formation. The micro hardness values were recorded the Vickers micro-hardness machine setup. The tensile strength values of as-received work piece and weld joints were evaluated.

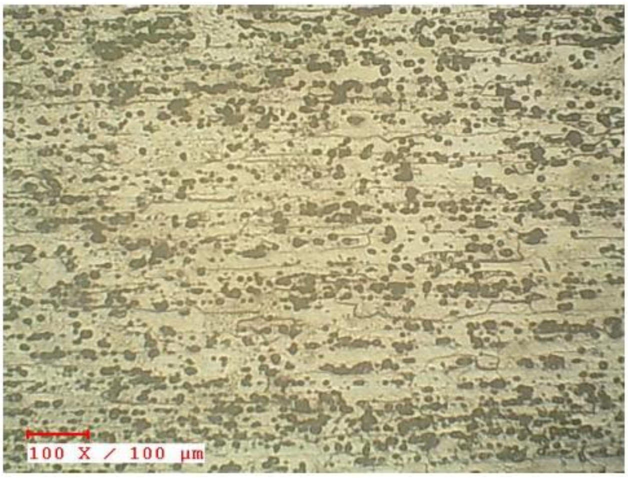

Figure 6. Microstructure of AA7075 (as-received)

3. Results and Discussions

3.1. Structure Properties

The microstructural investigations of friction stir (Fig. 7a) and cold metal transfer welding (Fig. 7b) of AA7075 was established. The CMT weld microstructure was characterized by the coarse-grained structure and the porosity formation was observed. Whereas the microstructures of FSW joints revealed considerable structure refinement at the weld zone unlike fusion welding. In fusion welding, grain coarsening takes place due to the collective recrystallization. The fine structure of FSW joints associated with the dynamic recrystallization i.e., nucleation. Structure refinement and dislocation densities of FSW joints are apparently due to the extensive heat generated by the plastic deformation and dynamic recrystallization respectively. On the other hand, welds produced by CMT have no trace of cracks in fusion zone. However, presence of extensive porosity is observed and the similar results were reported in literature (İpekoğlu and Çam, 2019). This may be attributed to the presence of surface oxide layers and insufficient cleaning prior welding as well as the high solidification rates post welding.

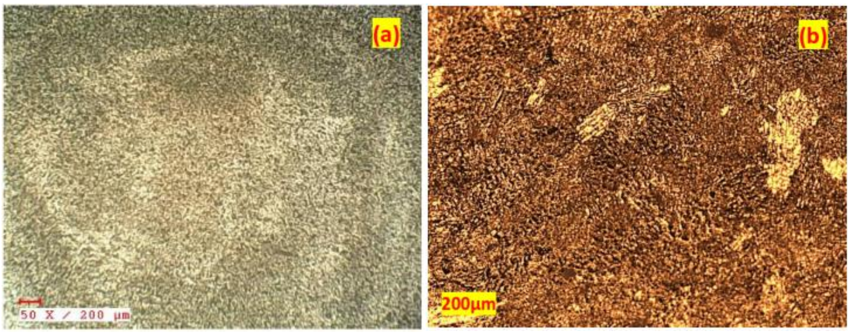

Figure 7. Weld microstructures of AA7075 (a) FSW process (b) CMT welding

The microstructure of base metal, AA7075 is shown in Fig. 6. From the figure, it can be clearly seen inhomogeneous distribution of Si and Fe-rich coarse-grained particles. The major alloying elements are Mg_2Si, Al_7Cu_2Fe and $Al_{12}Fe_3Si$ which are randomly oriented in the alpha Al matrix (İpekoğlu, et al., 2018). Along with these particles, finely grained homogeneous distributed $MgZn_2$ precipitates are also present which is the factor of strengthening in T6 temper condition of AA7075. These strengthening precipitates are typically very fine and extraordinarily small so that they are not visible under any microscopy techniques.

In Fig. 3b, the presence of dendritic structures can be observed in the fusion zone results after the solidification. Intermetallic compounds also can be observed in the fusion zone, this may be attributed to the low melting of filler wire. In heat affected zone of CMT welds, the structure refinement and coarsening of alpha grains of the strengthening particles took place.

3.2. Weld Joint Strength

The detailed studies on microstructures along with analytical evaluation assist in understanding the mechanical behaviour of the weldments. The mechanical properties are mainly dependent on the induced local stresses (τ) and deformation localization zones. The formation of local residual stresses (τ) and their interactions, magnitudes and extent with structural properties of the joins can be determined by the following equation (Markashova, 2012).

$$\tau = \frac{Gbh\rho}{[\pi(1-\nu)]} \qquad \text{Equ… 1}$$

Where *G, b, h, p, v* are the shear modulus, Burger's vector, foil thickness, dislocation density and Poison's ratio. The increased residual stresses (τ) leads to the cracks initiation and propagation.

3.2.1 Hardness

Hardness of all the samples was measured using Vickers hardness setup. In case of FSW, distinctive soft zones occurred along the joint interface. The higher welding speeds for a fixed tool rotational speed results in less softened zones. The welds with higher welding speeds showed a relative increase of hardness in nugget region with respect to their heat affected zones. This variation may be attributed to different levels of process parameters that result in various thermal histories. Another reason for increased hardness at the nugget zone is due to the direct impact of FSW tool that leads to severe plastic deformation and dynamic recrystallization, which generates sufficient heat for material diffusion. All the tested welds followed W-shape profile of hardness values.

On the other hand, CMT welds suffered the loss of hardness in the fusion zone. According to the literature reports, this is the common phenomenon in fusion welded age-hardened aluminium alloys ((Pakdil, et al., 2011; Çam and Koçak, 2007). This declining phenomenon of hardness in fusion zone and heat affected zone is due to the coarsening of particles and formation of dendrites. The base plate AA7075-T6 used in this study, which is artificially aged and tempered. The high hardness of base plate, 175 HV comes from the homogeneous distribution of fine grains of strengthening precipitates in alpha matrix. The hardness profile of CMT weld is deviated from the typical profile exhibited by FSW joints of AA7075. The variations of hardness of base metal, FSW and CMT welds are shown in Fig. 8. The low hardness is usually observed in the heat affected zones lies on both sides of nugget region. The loss of hardness in nugget region is regained by the precipitation and plastic deformation by the FSW tool.

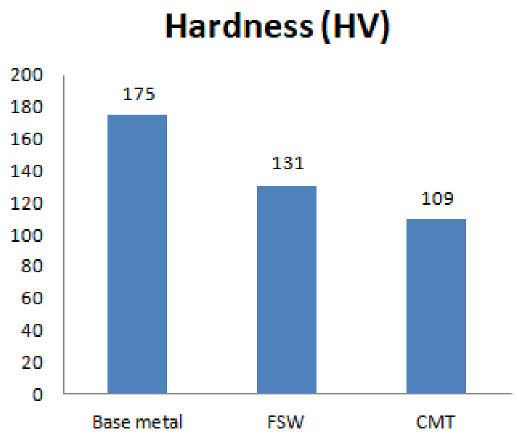

Figure 8. Hardness values (maximum value obtained) of base metal, friction stir and cold metal transfer welded AA7075

This fall of hardness is also observed in CMT welded heat affected zones but it is not as significant as it occurred in the conventional fusion welding processes and FSW process. The hardness profile of CMT is in similar fashion to electron beam and laser welding of AA7075, low heat was inputted in both the cases.

3.2.2 Tensile Strength

Tensile tests of FSW and CMT joints have been carried out to understand the effects of process parameters on joint strength at heat affected zones, nugget zone (FSW) and fusion zone (CMT). The joint strength performance with regard to tensile strength can be calculated as follows.

$$\text{Performance (\%)} = \frac{\text{Tensile strength of joint}}{\text{Tensile strength of base metal}} \text{ x } 100 \qquad \text{Equ.....2}$$

It is observed that the fall of tensile strength values irrespective of the FSW tool rotational speeds. This phenomenon is due to the eradication of strengthening precipitates from the nugget zone and thermo-mechanically affected zone (TMAZ). The highest value of tensile strength recorded is 358.4 MPa for FSW joints, which is almost 40% less than the base metal strength. Fig. 9 shows the variations of tensile strength of base metal, friction stir and cold metal transfer welded AA7075.

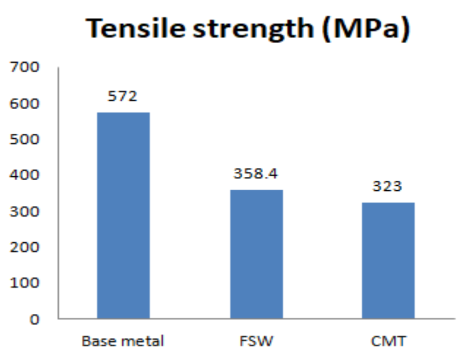

Figure 9. Tensile strength (maximum value obtained) of base material, friction stir and cold metal transfer welded AA7075

The highest tensile strength recorded for CMT is 323 MPa which is 56% of that of base metal strength. The low tensile strength of CMT welds can be explained with the fact that the extensive porosity formation with increase in welding speeds. The amount of porosity formation is comparatively less for low welding speeds. As discussed earlier, the degree of pores is based on the inadequate surface preparation. Presence of surface oxides on Al alloys is a serious limiting factor for fusion welding. The amount of heat supplied by the fusion welding process has great influence on the joint strength. Higher heat inputs produce larger softening regions which in turn decreases precipitates and strengthening particles. CMT is known for its low heat input, which is around 0.1 kJ/mm is far lower than the MIG and TIG welding process, that uses 4-5 kJ/mm (Elrefaey, 2015). Because of low heat input of CMT, loss of alloying elements and strengthening particles are greatly reduced and the overall performance of CMT is quite better than MIG and TIG process.

3.3.Statistical Analysis

Predictive modelling is an important application of regression analysis. Regression analysis is the basic of statistical analysis and yet it is so powerful method till date. The regression modelling can be performed through modelling, estimation and hypothesis testing. The present study investigates the polynomial regression and support vector machine models for prediction of tensile strength and hardness values of FSW and CMT joints. The data is normalized for all the modelling techniques to eliminate the magnitude differences. The experimental data is randomly selected for training and testing purposes and 20% of the data is separated for testing alone.

3.3.1. Performance Parameters

Performance parameters are significant for any model. These parameters change according to the machine learning task. For regression analysis, the model performance is commonly estimated from the root mean squared error RMSE (smaller value) and coefficient of determination, R-Squared (should be close to one) (Dinesh,et al.,2019; Rajkumar,et al.,2020; Yokeswaran, et al.,2019; Yokeswaran,et al.,2018; Rajkumar,et al.,2020; Sureshkumar,et al.,2019).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(Predicted_i - Actual_i)^2}{N}} \qquad \text{Equ…. 3}$$

$$R^2 = 1 - \left(\frac{\sum_{i=1}^{N}(Predicted_i - Actual_i)^2}{\sum_{i=1}^{N}(Predicted_i)^2} \right) \qquad \text{Equ…. 4}$$

3.3.2. Models Performance

Performance parameters of any model provide the quantitative estimation. The performance can be calculated from the actual and predicted values. Table 4 & 5 provides the performance parameters of training and testing data of tensile strength for friction stir and cold metal transfer joints. A total of 27 experiments are performed by varying three process parameters (Table 2&3). The training data consists of 21 samples and testing data of 6 samples. The small amount of testing data is not recommendable for predictive modelling. However, regression models tend to perform well amid high non-linearity. Predictive modelling was performed using python scikit-learn package.

Table 4. Performance parameters of training data (Tensile strength)

Type	Performance Parameter	Polynomial Regression	Support Vector Machine
Friction stir	RMSE	19.23	11.44
	R-squared	0.55	0.74
Cold Metal Transfer	RMSE	7.56	6.52
	R-squared	0.73	0.74

Table 5. Performance parameters of testing data (Tensile strength)

Type	Performance Parameter	Polynomial Regression	Support Vector Machine
Friction Stir	RMSE	13.58	9.67
	R-squared	0.76	0.74
Cold Metal Transfer	RMSE	8.12	6.66
	R-squared	0.67	0.60

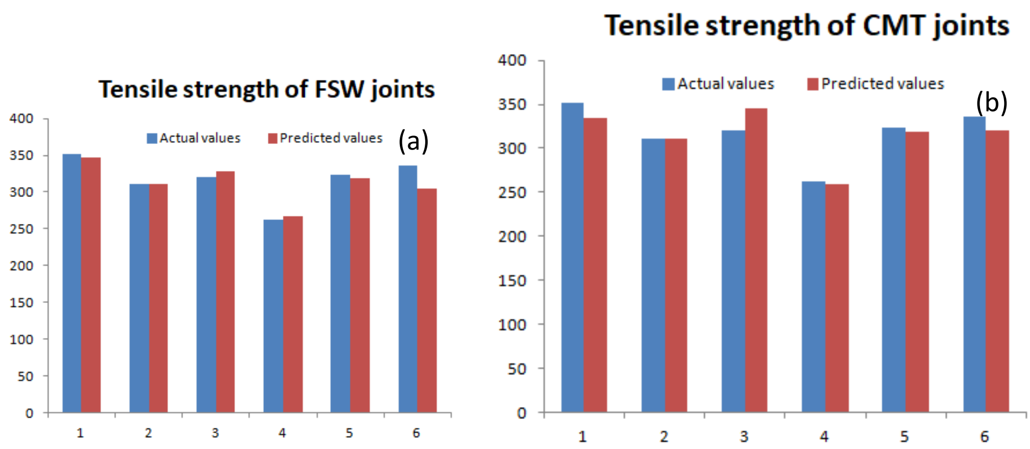

Figure 10. Actual vs predicted tensile strength values of polynomial regression model (a) Friction Stir, (b) Cold Metal Transfer Welding

Figure 10 shows the actual and predicted values of the tensile strength of FSW and CMT joints of polynomial regression model. The performance of FSW joints is better when compared to the CMT joints for polynomial regression model. The same pattern is observed for support vector machine regression model also. Under regression model, support vector machine (SVM) offer good RMSE and R-squared values over the polynomial regression. It is well known that SVM model tend to perform well on the smaller datasets when compared to other models.

Table 6. Performance parameters of training data (Hardness)

Type	Performance Parameter	Polynomial Regression	Support Vector Machine
Friction Stir	RMSE	2.08	1.51
	R-squared	0.88	0.76
Cold Metal Transfer	RMSE	5.46	3.13
	R-squared	0.53	0.66

Table 7. Performance parameters of testing data (Hardness)

Type	Performance Parameter	Polynomial Regression	Support Vector Machine
Friction Stir	RMSE	6.03	5.24
	R-squared	0.71	0.75
Cold Metal Transfer	RMSE	7.67	5.15
	R-squared	0.45	0.53

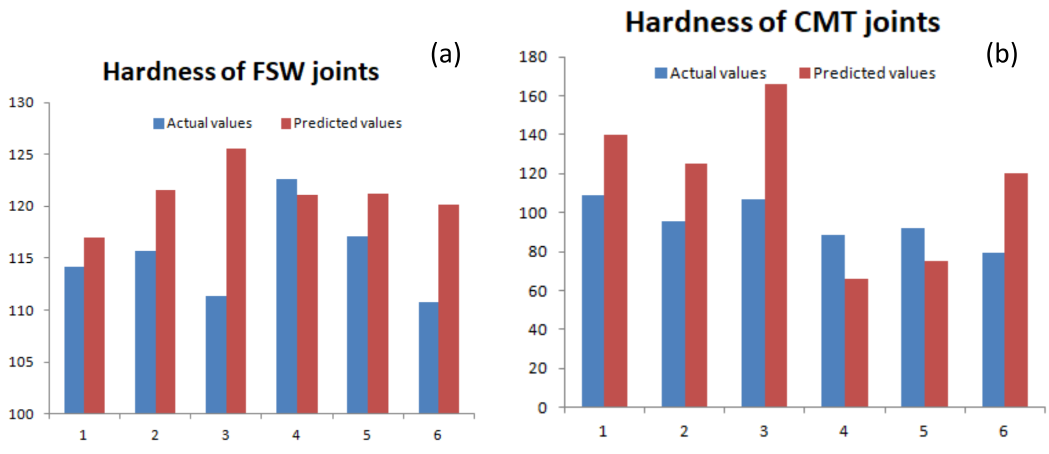

Figure 11. Actual vs predicted values of hardness of polynomial regression model (a) FSW (b) CMT

Figure 11 shows the actual and predicted hardness values of friction stir and cold metal transfer welded AA7075 joints. The performance is low when compared to the tensile strength. The SVM model performance is relatively better than the polynomial regression model. The predicted values of FSW joints are good when compared to the CMT joints in both the models.

4. Conclusions

The friction stir and cold metal transfer welding of AA7075 was successfully performed. Experimental investigations include structure and strength properties were evaluated and compared. The major conclusions can be drawn from this study are the following.

* In case of FSW, joints are characterized by the homogenous distribution of fine grains in the nugget zone which is the resultant of dynamic crystallization and severe plastic deformation.

* It is observed that the hardness and tensile strength values under FSW conditions are 75% and 60% of that of base metal.

* Under CMT, microstructures revealed coarse grain structures and loss of strengthening and precipitate elements in HAZ, extensive formation of large pores also observed. Both hardness and tensile strength values are comparatively lower than the values attained by the FSW joints.

* Predictive modelling of tensile strength and hardness values of FSW and CMT joints is performed using polynomial regression and support vector machine models. SVM tends to perform well over polynomial regression model. Under welding processes, predictions made for FSW joints are relatively good over CMT joints.

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Competing Interests

The authors declare no competing interests.

Concerns to Publish

All the authors concern to the publication of this article.

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