Development of Al/Steel Resistance Spot Weld for Industrial Applications

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Abstract

Resistance spot welding is a common subject taught to engineering students learning about manufacturing processes. Teaching welding to students can often pose quite a challenge, because of the wide variety of uncertainties. In this paper 6061 Aluminum (Al) and 1008 Carbon Steel (CS) were welded together using Resistance Spot Welding for two groups: one with a Silicon Carbide powder (SiC) added as a coating and one without the powder. Welding often causes metals to change in composition, which can lead to a decline in physical properties, including strength and corrosion resistance. Even more so when the welded pieces are dissimilar metals. In this paper it was found that the corrosion resistance of the welded joint in acidic environments (1% HCl at 35, 45, and 55 Celsius) increased when the SiC powder was added. It was also found that the tensile strength of the welded joint increased in the samples that the powder was used in. If Engineering students understand the changes to metals that welding can produce, they can make educated decisions about how to prevent any negative consequences such as failure of materials.

Introduction

As the supply of usable materials depletes, one of the goals of the manufacturer is to elongate the life of products. One of the factors that influences the lifespan of products is corrosion. Corrosion and its negative effects are often discussed in education, but processes to prevent or reduce corrosion are rarely integrated into laboratory classes. A good understanding of corrosion-prevention techniques is critical for being prepared for careers in the manufacturing industry and its related fields. Corrosion causes significant reduction in mechanical properties and can lead to premature failure in parts. Corrosion is electrochemical oxidation where the metal reacts with an oxidant, such as oxygen. Metals, in their pure form, are chemically unstable and easily react with highly electronegative elements, like oxygen, and make metallic bonds, which creates intermetallic compounds (IMC) on the surface of the material, more commonly known as rust. Preceding studies have determined that the majority of the IMC's that grow are $FeAl_3$ and Fe_2Al_5 [1]. These IMCs tend to be very brittle and can reduce the overall strength of the material. When these IMC's grow within the metals, the joint strength reduces [2].

During the resistance spot welding process, the extreme temperatures cause the materials to have increased rates of corrosion at the welded nugget. Like other materials that have been welded, the joint is the weakest spot, and corrosion caused by oxidation only makes it weaker. For corrosion to occur, three conditions must be met: There must be (1) an anode and a cathode (something to give and something to receive electrons), (2) electrical or physical contact between the anode and the cathode, and (3) and electrolytic path for ionic conduction. When two dissimilar metals, such as Aluminum and Carbon Steel, are welded together, it enhances the effects of corrosion because the differences in electronegativities provide optimal conditions for oxidation by using the metals as an anode and a cathode. If corrosion is to be avoided, one of the given circumstances must be prevented. Oftentimes coating, such as paints, are applied to metals to protect the surface from the oxidizing atmosphere. However, most paints aren't made to withstand welding temperatures and would not remain effective at preventing the instantaneous corrosion that occurs during the Resistance Spot Welding process. Also, the electrical resistivity of steel is 5 times that of Aluminum, and Aluminum conducts heat much faster than Steel. Because of these very different properties, challenges often arise when welding the two metals together.

The use of Silicon Carbide (SiC) in the spot-welding process is effective in preventing corrosion because it has a high melting point (2827°C), good oxidation resistance, high hardness, competitive wear resistance, low thermal expansion coefficient, good chemical resistance, and desirable thermal conduction. Silicon Carbide is a ceramic, so it naturally has much better corrosion resistance than the metals. Previous studies have characterized the relationship between the heat-affected zone and the maximum tensile shear load [3]. Previous studies have also shown that the use of SiC powder has led to increased hardness and tensile strength in welded steel joints [4]. However, this study will focus on the use of SiC powder in welding dissimilar metals. Its low thermal expansion coefficient allows for the bond to be much stronger because it reduces cracking/fracturing in the welded materials. It also prevents some of the IMC's from forming, thereby allowing the material to retain many of its mechanical properties. SiC is very cost-effective and prolongs the life of welded materials, so it is a practical material to use when teaching corrosion-prevention techniques to engineering students that can be applied to the real world. The experiments from this paper can help students better understand corrosion by allowing them to perform their own experiments and observing how corrosion is caused and how it can be prevented.

Engineering students will also study the strength of certain materials, so it is important to know how joining processes, such as welding, affect the strength, and how it can be improved. The gradual evolution of the fine grains caused by the addition of the SiC powder plays a crucial role in the improvement of the strength of the material. The SiC is the main contributor to the strength of the Al-Fe-SiC composite because it allows for the transfer of the external load from the Al matrix to the SiC particles. Excellent bonding between the metals and the SiC also increases the tensile strength of the composite. The mechanism for its increase in tensile strength is its ability to act as an impediment to dislocation motion in the crystal structure of the materials. It also initially increases the number of dislocations in the soft Al matrix, which increases its strength and hardness.

Oftentimes in engineering laboratory classes, students will measure the hardness of certain materials using various instruments, such as the Micro Vickers hardness tester. Hardness is a material's resistance to indentation or scratching. The goal of these experiments is to determine the effects of a certain manufacturing process, such as heat treatment or welding, on the hardness of the material. Ordinarily, ceramics have a much higher hardness than metals, so the addition of the SiC ceramic powder will allow for a weld with a higher hardness.

Materials and Experimentation:

Pieces of 2 mm thick 6061 Aluminum (Al) and 0.8 mm thick 1008 Carbon Steel (Fe) were welded together using a Resistance Spot Welder (RSW). Two different types of samples were prepared, one with the Silicon Carbide (SiC) powder between the two pieces, and one without the powder. The pieces were single-lap joint welded with an overlapping cross section of

35.8 by 26.3 mm as seen in Fig. 1. The welder that was used was a model 1-24-20 ACME Rocker Arm Resistance Spot Welder, which can be seen in Fig. 2a, and the specifications and information can be seen in Fig. 2b. The welding controller was an Enron EN1000-B and was set on schedule No. 12, as seen in Fig. 3. All the welding was done with a clamping force of 2kN, with a current of 12kA, for 1.5 seconds. This type of welder, or one of similar specifications, can be found in most educational manufacturing laboratories, and the operation of the machine is very beginner friendly, so instructors can even guide students to operate the welder themselves. Once the machine was set up and ready for use, the Al and Fe were held together using pliers to ensure they would not slip when the electrodes clamped together. This process can be seen in Fig. 4. Keeping the pieces lined up with one another is very important and requires a great deal of precision, so it should be performed by the instructor. The nugget that formed from the welding process was then examined and measured. Spot welding experiments can cause injury, so all students must understand all hazards and how to avoid them.

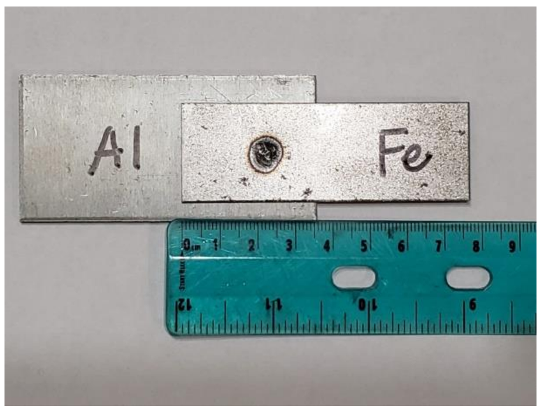

Figure 1: Aluminum (Al) and Carbon Steel (CS) Spot Welded together in a single Lap Joint.

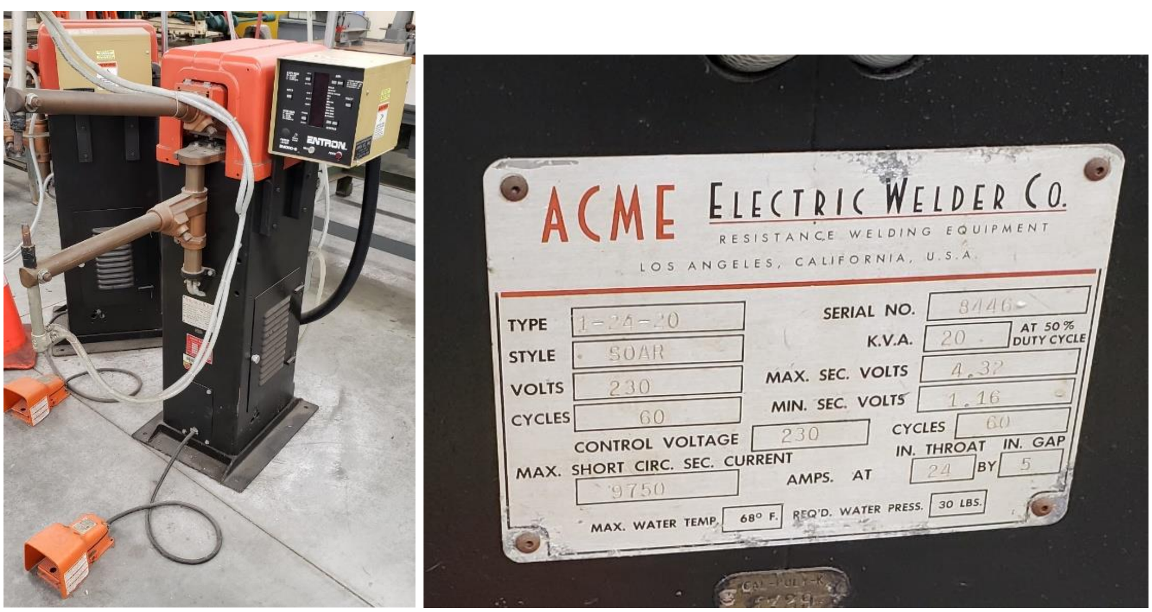

Figure 2: (a) rocker arm resistance spot welder and (b) the schematics for the welder.

Figure 3: The welder controller set to program 12.

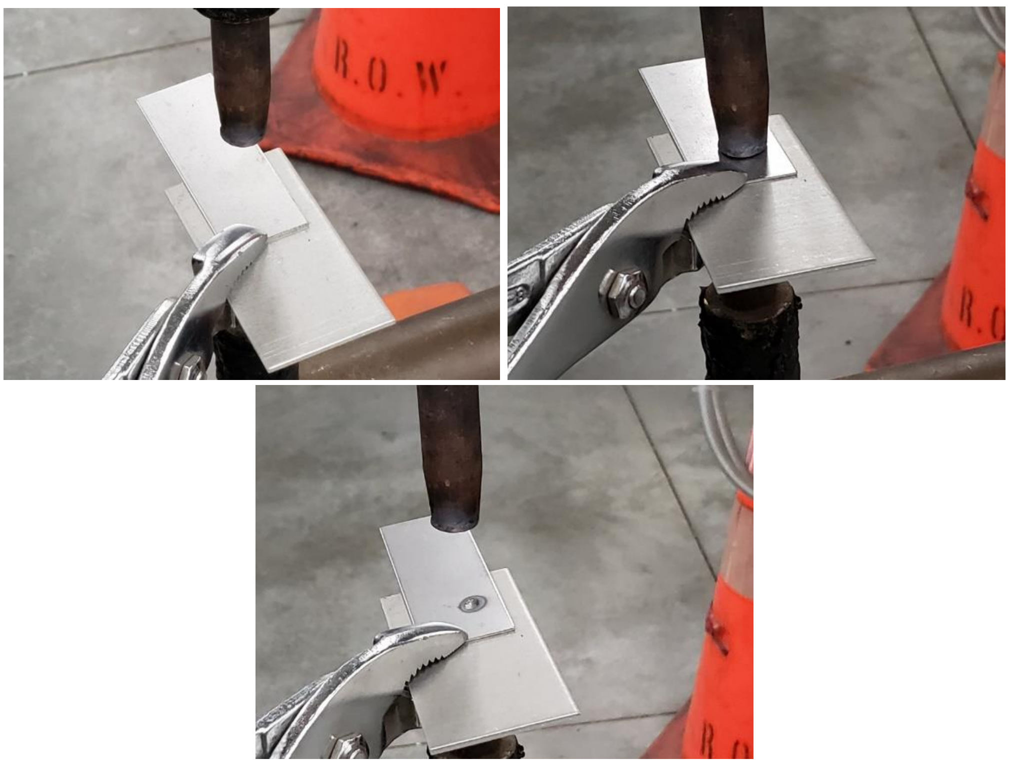

Figure 4: Holding the metal pieces with locking pliers during the resistance spot welding process.

Before any destructive tests were performed, the specimens were examined around the area of the weld nugget to determine the effects of coating on the formation of the IMC's. The diameters of the discolored zones were measured using a caliper. Many engineering classes study the effects of heat treating and welding of metals. This study can help students understand the mechanical properties that result from the resistance spot welding process and how they can be improved. The hardness of the specimens was also determined using a Vickers Hardness tester on the Aluminum side where the electrodes clamped the pieces. This hardness tester is very easy to operate, so, with appropriate demonstration and guidance from an instructor, students can operate this machine themselves. The Vicker's Hardness tester used 200g of force for 10 seconds that created an indentation, which yielded a microhardness number. Five different tests were performed at varying intervals and the average microhardness number was then found. The

Vickers Hardness tester is mostly safe to use, but it can cause injury if a student gets pinched in the tester, so anyone who operates the tester must understand how to handle the machine safely. After the samples were thoroughly examined, a tensile test was performed with an Instron Tensile Tester as seen in Fig. 5. Most engineering labs have adequate tensile testers that are versatile and easy to operate. The specimens were put in the clamps that can be seen in Fig. 6. They were inserted into the clamps far enough so that they would not be pulled out by friction. The pieces were pulled in tension until the weld broke, and the maximum strength was recorded. To ensure a safe experiment, all students must understand how to properly use the Tensile Tester and how to practice safety measures, like keeping hands and other body parts clear of the machine while it is in use.

Figure 5: Tensile Tester used to determine the tensile strength of the welded pieces.

Figure 6: Clamps used to hold the pieces and pull them apart.

Additional samples that hadn't been broken from the tensile experiment were subjected to temperatures ranging from 250°C-600°C and the mass was recorded for each sample before and after heating. The mechanism of the loss of mass of the samples is corrosion. To heat the sample, they were placed in a furnace where the temperature could be controlled, until the weight of the sample stabilized. The mass of the samples was measured with a Sartorius 2004 MP1 scale, which can be seen in Fig. 7. Next, different samples that hadn't been broken from the tensile test were immersed in an acidic solution of 1% Hydrochloric Acid (HCl) at 35, 45, and 55°C for 30 hours and the weight losses were measured before the experiment and every 5 hours until completion. This particular test requires the use of HCl and, even though its concentration is only 1%, the solution should still only be handled by the instructor. Students can perform the weighing operations, but they should not handle the HCl solution.

Figure 7: Scale used to measure mass of the samples for the thermal and acidic corrosion tests.

Results and Discussion

Fig. 8 shows the pieces after they have been welded together. The largest measurable diameter of the discolored zone is 10 mm. This is the region that was clamped between the electrodes during the spot-welding process. The visible discolorations were not melted together, like the interior nugget was, but they were affected by the heat that was created from by the resistance spot welder. Fig. 1 shows the lap joint that was created from the spot-welding process. The figure shows that they overlap a significant amount, which allows for a strong connection. It is important to understand the different types of joints that can be created by welding or fastening and the factors that govern the strength of the joints. In many engineering courses, students learn about the mechanics of joints as well as methods used to improve the strength of such joints. It is also important for engineers to understand how welding can affect the mechanical properties of metals. Most lectures on mechanics and manufacturing processes cover the impact of welding on metals, however it is important to examine this more closely in engineering laboratories. Making informed decisions on the manufacturing process of materials is a crucial part of the education of engineering students.

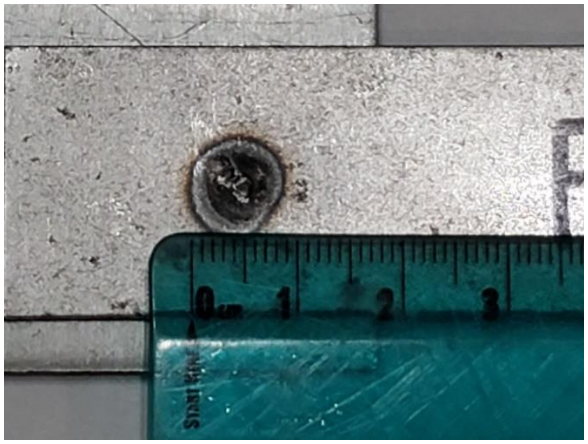

Figure 8: close-up of the clamped region of the metal pieces on the Steel side.

For the tensile test, the strength of the weld increased significantly when the SiC particles were added to the materials prior to welding. The regular Al-Fe sample had a tensile strength of 266.8 MPa, while the Al-Fe-SiC composite had a tensile strength of 310.28 MPa. This means that Adding SiC powder to as a coating resulted in a percent increase of 16.3%. Previous studies have shown that mechanism for failing is caused by cracks growing around the interfacial region and traveling around the Aluminum zone near the interface of the pieces and partially into the IMC layer [5]. The addition of the SiC creates a strong composite where the SiC particles effectively reinforce the metal matrix, especially the softer Aluminum. Previous studies have shown, using a Scanning Electron Microscope (SEM), that the size of the particles in the welded nugget are much smaller for the samples with SiC powder than the samples without the powder [4,6]. The finer grains in the Al-Fe-SiC composites impeded the formation of new dislocations in the materials, causing the strength of the material to increase. This is the same mechanism for the increase in hardness. In most engineering laboratories, an SEM will not be used for more basic labs, but many classes teach about the use and purpose of the SEM. However, teaching students about what they should expect to observe when using an SEM is just as important, such as grain sizes and IMC layers, and how they are expected to affect mechanical properties. Most engineering labs have tensile testers, which would allow engineering students to easily compare the tensile strength of the Al-Fe and Al-Fe-SiC composites by performing a simple tensile test on both samples.

The results of the Micro Vickers hardness tester show a significant increase in the hardness of the Aluminum. Silicon Carbide naturally has a hardness of 9.5 Mohs, which is almost as hard as diamond, which has a hardness of 10 Mohs. [7]. So, utilizing SiC powder in the interface of the Al-Fe weld would increase the hardness significantly. The micro hardness number was found for both the sample with the SiC powder and without the powder on the Aluminum piece after welding in 5 different random locations around the weld. The result of averaging these 5 different numbers shows that the microhardness for the Al-Fe sample was 90 and the Al-Fe-SiC sample was 101, which is a percent increase of 12.2%. Previous studies that examined the effects of SiC powder on the hardness show that the hardness of the material increases as the average size of the powder decreases [8]. Most engineering laboratory classes will examine the effects of heat treatment on the hardness of a metal. Engineering lecture classes investigate mechanical properties such as hardness and discuss the effects of grain structures and sizes on the hardness. It is important for engineering students to understand the different actions they can take to affect mechanical properties, such as the addition of Silicon Carbide powders to increase the hardness of welded pieces. This research will help illustrate in engineering classes the effects on the hardness of the addition of coatings between two dissimilar metals that are spot welded together.

The results of the thermal test weight loss experiments can be seen in Table 1. The data is illustrated in Fig. 9. Both specimens have an increase of weight loss as the temperature increases, showing how corrosion increases as temperature increases. However, it can be seen from the data that the Al-Fe samples have a much greater weight loss than the Al-Fe-SiC samples at every data point. It only takes a temperature of 350°C for the weight of the Al-Fe sample to start decreasing, while it takes a temperature of 400°C for the weight of the Al-Fe-SiC sample to begin to decrease. At the maximum temperature that was tested, 600°C, Table 1 shows that the Al-Fe has a weight loss of 22.34 $(g*cm^{-2})*10^{-5}$, while the Al-Fe-SiC only has a weight loss of 16.78 $(g*cm^{-2})*10^{-5}$. It has been determined from previous research that SiC has high thermal shock resistance up to around 450°C at which point it begins decreasing in weight [7]. This is supported by the results of this experiment. It can be seen in Table 1 and Fig. 9 that the weight loss remains relatively low until around 450°C, at which point it begins increasing sharply. However, its Thermal Shock Resistance properties are still superior to most materials; it is only second to Si_3N_4 which has a Thermal Shock Resistance temperature of around 600°C. When performing heat treatments, it is easy to disregard effects on the materials such as corrosion from thermal tests, however it is a very crucial aspect in the processing of materials. Engineering students must understand how heat treatments affect welded materials so they can make the best choices possible when deciding how to process materials and the best way to do this is to study these topics in engineering lecture and laboratory classes.

Table 1: Weight loss of the two samples at different temperatures.

Temperature (°C)	Weight Loss $(g*cm^{-2})*10^{-5}$	
	Al-Fe	Al-Fe-SiC
250	0	0
300	0	0
350	6.2	0
400	15.2	1.55
450	17.9	7.22
550	19.2	12.18
600	22.34	16.78

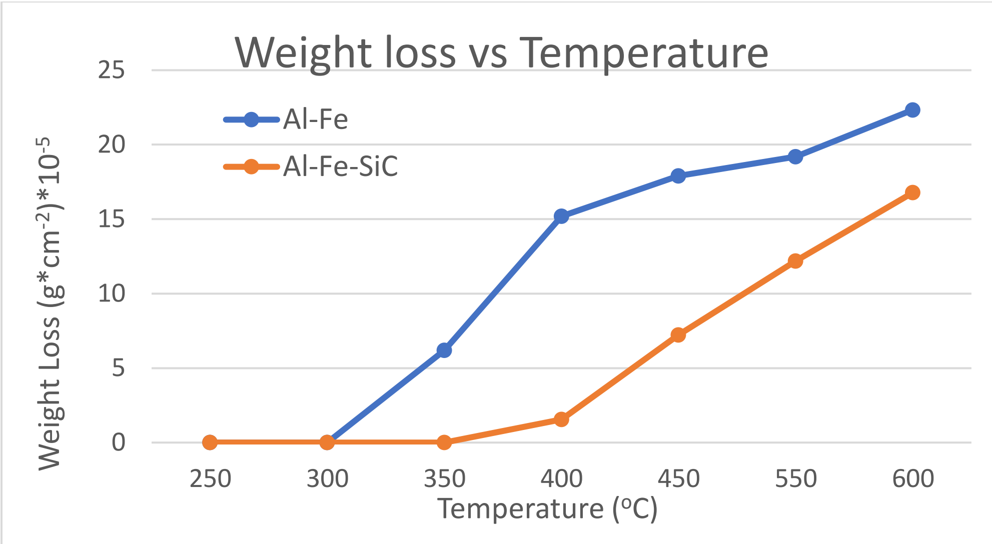

Figure 9: Graph of the weight loss vs. temperature for the two samples.

The results of the HCl provide a similar result. Tables 2, 3, and 4 show the results of immersing the samples in a 1% HCl solution for 30 hours at 35, 45, and 55ºC. Figs. 10, 11, and 12 show the data trends for both samples as the time increases. It should be noted that the weigh losses for the Al-Fe-SiC samples seem to level off once the time reaches around 20 hours. The Al-Fe-SiC at 35ºC levels off at around 37 $(g*cm^{-2})*10^{-5}$ at 20 hours and the sample at 45ºC levels off at around 40 $(g*cm^{-2})*10^{-5}$ at 20 hours. The Al-Fe-SiC sample, however, does not level off at 20 hours. It increases from 44 to 51 to 59 $(g*cm^{-2})*10^{-5}$ as the time goes from 20-30 hours. This means that it would take longer than 30 hours for the weight loss to level off, because the higher temperatures cause the composite to be less stable, thus inducing more corrosion. The high resistance to corrosion of the Al-Fe-SiC composite is attributed to the fact that SiC is extremely chemically stable, only becoming susceptible to corrosion to certain chemicals or oxidation at high temperatures of around 900ºC [8]. Silicon Carbide has also been attributed to prevent Galvanic Corrosion when added to form metal/ceramic bonds [9]. The presence of SiC in the Al-Fe-SiC composite has been shown to decrease the potential difference gradient between the two metals, which reduces the Galvanic Corrosion [10]. Reducing the potential difference between the Steel and the Aluminum (the anode and the cathode) decreases the rate of corrosion in the presence of strong electrolytic mediums such as HCl.

Table 2: Weight loss of the two samples in the 1% HCl different times at 35°C

HCl (35°C)		
Time (hr)	Weight loss ($g*cm^{-2}$) $*10^{-5}$	
	Al-Fe	Al-Fe-SiC
0	0	0
5	59	22
10	51	20
15	60	31
20	61	37
25	69	36
30	85	37

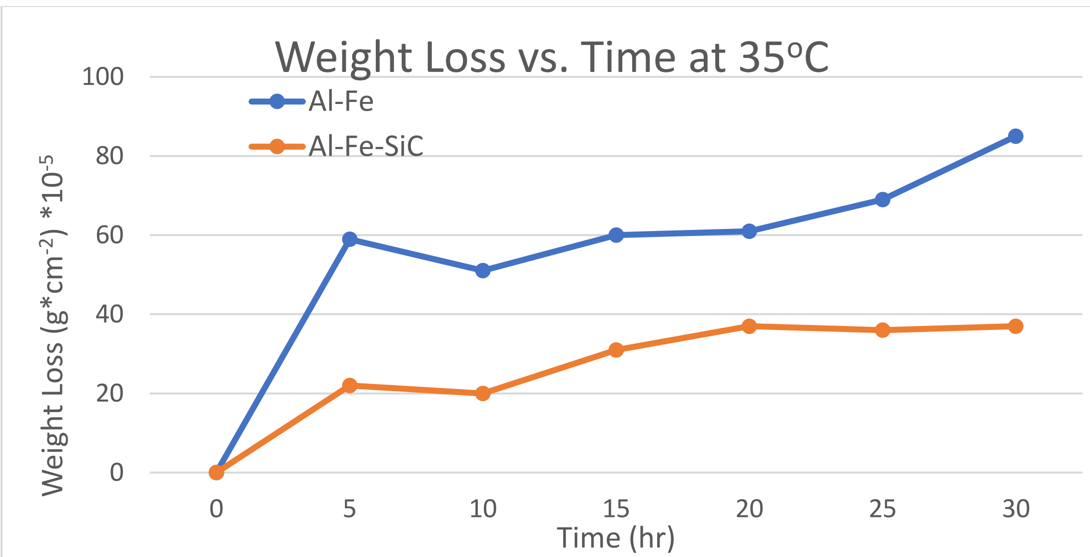

Figure 10: Graph of the weight loss vs. time for the two samples at 35°C.

Table 3: Weight loss of the two samples in the 1% HCl different times at 45°C

HCl (45°C)		
Time (hr)	Weight loss ($g*cm^{-2}$) $*10^{-5}$	
	Al-Fe	Al-Fe-SiC
0	0	0
5	63	24
10	62	20
15	69	33
20	89	39
25	78	40
30	92	39

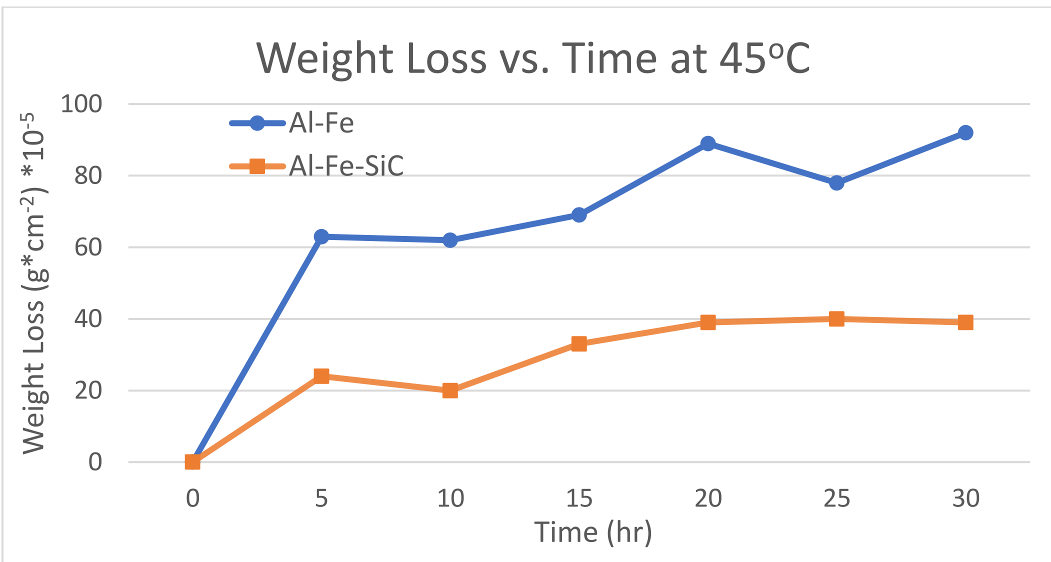

Figure 11: Graph of the weight loss vs. time for the two samples at 45°C.

Table 4: Weight loss of the two samples in the 1% HCl different times at 55°C

HCl (55°C)		
Time (hr)	Weight loss (g*cm^{-2}) *10^{-5}	
	Al-Fe	Al-Fe-SiC
0	0	0
5	67	27
10	68	22
15	69	37
20	97	44
25	102	51
30	112	59

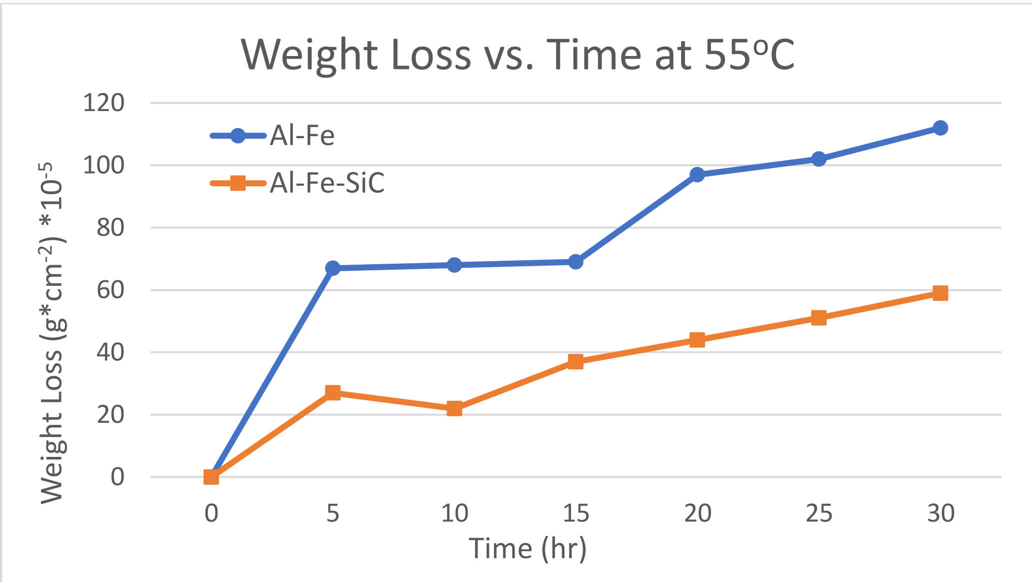

Figure 12: Graph of the weight loss vs. time for the two samples at 55°C.

Conclusions

The addition of Silicon Carbide (SiC) powder between pieces of 6061 Aluminum and 1008 Carbon Steel that will be welded together by a resistance spot welder substantially increases the mechanical properties of the composite that is formed. The tensile strength, hardness, corrosion resistance due to thermal shock, and corrosion resistance from acidic environments all improve with the addition of SiC powder. It is very important for engineering students to understand methods they can use to achieve the properties they desire in materials. Silicon Carbide powder is an effective way to increase the physical properties of metal pieces welded together. The findings of this study are as follows:

(1) The tensile strength of the Al-Fe-SiC composite shows a 16.3% increase when compared to the strength of the Al-Fe sample. This is attributed to the SiC creating a strong composite where the SiC particles effectively reinforce the metal matrix, especially the softer Aluminum. The SiC prevents the growth of cracks around the region where the pieces connect.

(2) The hardness of the Al-Fe-SiC composite shows a 12% increase from the Al-Fe sample. This is because the SiC allows for the formation of much smaller grains at the welding zone.

(3) The corrosion weight loss that was thermally accelerated from heating the samples significantly decreases with the addition of the SiC powder. SiC naturally has a very high thermal shock resistance, so the bonding of the metals to the SiC increases the thermal shock resistance of Aluminum and Steel.

(4) The composite with the addition of the SiC powder had a much higher resistance to corrosion weight loss due to exposure to an acidic environment of 1% HCl. This is attributed to the fact that SiC is extremely chemically stable. It only becomes susceptible to corrosion to certain chemicals at temperatures close to $900^{o}C$.

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