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List of Acronyms

FSE - Friction stir extrusion

TWI - The Welding Institute

IPM - Inch per minute

SCR - Southwire continuous rod

ORNL - Oak Ridge National Laboratory

RPM - Rotation per minute

HIP - Hot isostatic pressing

PM - Powder metallurgy

BTU - British thermal unit

ITP – Industrial Technology Program

EXECUTIVE SUMMARY

This project has successfully demonstrated the feasibility and potential commercial viability of a highly energy efficient solid-state materials synthesizing process – friction stir extrusion (FSE) – to produce next generation highly functional electric cables for electricity delivery infrastructure and expand to other markets and applications. Specifically the project has determined the process and materials parameters for producing extruded product forms by direct conversion of recyclable materials, nano particle dispersed and strengthened bulk materials from chips or other recyclable feedstock metals or scraps through mechanical alloying and thermo mechanical processing in a single step using frictional heat. It also successfully explored the production of nano engineered bulk materials with unique functional properties, such as electrical conductivity, mechanical strength, and wear resistance.

The novelty of FSE is that it utilizes the intrinsic frictional heating and extensive plastic deformation inherent in the process to stir, mechanically alloy, consolidate and convert powders, chips and other recyclable feedstock metals in to usable product form of highly engineered materials in a single step. Since FSE is a solid-state metal conversion process, it eliminates the energy intensive melting and casting steps in current metal material synthesis process, thereby significantly reducing energy consumption.

The project team consisted of Southwire Company, Oak Ridge National Laboratory, and TWI. Significant breakthrough has been achieved in the development of friction stir extrusion process. Up to 15 feet long aluminum alloy 6061 wires were successfully extruded. The length of the extruded wires was limited by the size in the cartridge used in the project. Process parameters were further optimized for die design, plunge forces, and rotational speed. Other aluminum alloys including 6082, 5052, and 1350 were successfully extruded. Both slugs and metal chips were used as feed stock material. A comparative analysis of the wires produced through regular melting, casting and drawing vs. friction stir extrusion revealed that the mechanical/electrical properties of the extruded products were similar. Microstructural analysis showed that the samples contained both fine and coarse grains, leading to the conclusion that further optimization of the process is necessary to get a homogeneous structure.

The friction stir process also has the potential to produce new alloys by coextruding different alloys. For example, aluminum alloys 5052/1350 and 6061/1350 were successfully coextruded. A feasibility study to extrude aluminum alloys 6201 and 1350 with nano Al_2O_3 (alumina) particles, respectively, was carried out. Microstructural examination showed that the distribution of nano particles was relatively uniform. Further work is needed to optimize the process.

An energy analysis was carried out to compare the energy consumption in the conventional melting and casting process vs. friction stir extrusion. The analysis included both theoretical calculations and actual experiment measurement of the actual energy usage of the FSE process. It was concluded that the energy savings of FSE is tremendous - FSE uses less than 15% of the energy of conventional metal casting process for Al alloys. Successful development and commercialization of this process could potentially save up to 2.5 trillion BTU/year by 2020 and also lead to a reduction in greenhouse gas emission. For example, the conversion of recyclable aluminum requires the usage of chemicals (Chlorine). The friction stir process eliminates the usage of chlorine reducing its environmental impact. Manufacturing cost-reduction and other economic benefits are also significant.

Two product lines have been identified for commercialization: (1) bare overhead cables in the utility markets and (2) metal clad cables in the building wire market. Southwire, one of the largest manufacturer of cable in North America, is already a major supplier of these product lines. Hence, Southwire is well positioned to take the products from friction stir extrusion process to the market. In order to successfully commercialize these products the process needs to be continuous and scaled up. Several modifications to the laboratory set up are being considered and will be investigated by ORNL and Southwire.

1 Introduction

Friction Stir Extrusion (FSE) is a novel energy-efficient solid-state material synthesis and recycling technology capable of producing large quantity of bulk nano-engineered materials with tailored, mechanical, and physical properties. The novelty of FSE is that it utilizes the frictional heating and extensive plastic deformation inherent to the process to stir, consolidate, mechanically alloy, and convert the powders, chips, and other recyclable feedstock materials directly into useable product forms of highly engineered materials in a single step (see Figure 1). Fundamentally, FSE shares the same deformation and metallurgical bonding principles as in the revolutionary friction stir welding process. Being a solid-state process, FSE eliminates the energy intensive melting and solidification steps, which are necessary in the conventional metal synthesis processes. Therefore, FSE is highly energy-efficient, practically zero emissions, and economically competitive. It represents a potentially transformational and pervasive sustainable manufacturing technology for metal recycling and synthesis.

The goal of this project was to develop the technological basis and demonstrate the commercial viability of FSE technology to produce the next generation highly functional electric cables for electricity delivery infrastructure (a multi-billion dollar market). Specific focus of this project was to (1) establish the process and material parameters to synthesize novel alloys such as nano-engineered materials with enhanced mechanical, physical, and/or functional properties through the unique mechanical alloying capability of FSE, (2) verifying the expected major energy, environmental, and economic benefits of FSE technology for both the early stage “showcase” electric cable market and the anticipated pervasive future multi-market applications across several industry sectors and material systems for metal recycling and sustainable manufacturing.

Aluminum recycling is chosen as a showcase material for the first large-scale commercialization, based on a number of considerations. First, aluminum alloys are easy to work with; the relatively low process temperature (300 to 450 C) and low process load do not pose major problems to tool materials and machine design for the FSE process. Secondly, aluminum is highly recyclable and represents a very large market (second largest metal processing market behind the steel). The primary markets that will have significant positive impact for this new technology initially include all the secondary recycling aluminum industry.

Figure 1 Friction stir extrusion process principle in batch mode operation.

2 Results and Discussion

2.1 Experimental Details

In order to demonstrate the capability of the friction stir extrusion (FSE) process, various aluminum alloys in the form of recyclable machined chips, and solid slugs, were investigated in this project, including 6061, 6082, 5052 and 1350. Figure 2 shows examples of the plunger and the die used in this work. Cast and machined extrusion sample, a solid plug, is illustrated in Figure 3 (a), with a diameter of 1 inch and 3.75 inch in height. For the optimization of the FSE process, trials with different parameters were made in the extrusion of 6061 alloy, such as plunge rates from 0.25 to 3.0 ipm, rotation speeds between 400 and 600 rpm, and plunge distances from 0.5 to 3.3 inch, as listed in Table 1.

Co-synthesis of different alloys was conducted as well by co-extrusion of two Al alloys, e.g., 5052/1350, and 6061/1350. As shown in Figure 3 (b), co-extrusion sample was specially designed with four 1350 wires (an electric conductor grade pure Al) with a diameter of 0.125 inch and length of 3.75 inch inserted into the either 5052 or 6061 solid plug.

New aluminum based nano materials for wire and cable products were synthesized through feeding different volume fractions of nano-particles (2.5%, 5%, and 10%) into the four channels machined on the solid plugs of aluminum alloys 6061, 6201 and 1350, respectively, as shown in Figure 3 (c). Process parameters for the feasibility trials in alloys 6201 and 1350 are listed in Table 2 and Table 3, respectively. The log is 3.15 inch long, and the four channels are 2.765 inch in length and 0.256 inch in diameter.

Characterizations of the extruded wires were conducted for mechanical and metallurgical properties.

2.2 Test, Results and Discussion

2.2.1 Development of Process Parameters

Figure 4 shows various samples of wires successfully extruded with optimized parameters, including recycling of a single material, nano-particle strengthened, and co-synthesis of different Al alloys. The results of trials made for extrusion of various Al alloys, co-extrusion, and nano-particle incorporation are marked in the comments of Table 1 – Table 3.

By the development of process parameters, die design and system configuration, several continuous lengths of 6061 alloy were successfully extruded with length range up to 16 ft in a single charge with the parameters in run 6061-117 (Table 1). Both slugs and machined chips were used as feedstock. 12 ft of wires on other different 6xxx aluminum alloys were successfully extruded as well at a rate of 110 ft/min. The wires showed a smooth surface finish with some minor defects, as shown in Figure 5. It would be noted the length of the wires have been limited by the volume of the feedstock in the cartridge so far, because of the discontinuous nature of the batch mode operation in our feasibility study. *Making the process continuous thought innovative process concepts will be one of the primary objectives of future work.*

Process development on co-extrusion of 5052/1350 and 6061/1350 aluminum alloys was completed. 6061/1350 wires of up to 20 ft were successfully co-extruded. As shown in Figure 6, the co-extruded wire exhibit good bending property. 5052/1350 wires of up to 20 inches were co-extruded as well.

Initial feasibility study of nano-particle incorporation into aluminum alloys 6201 and 1350 was successful. Aluminum alloy 6201 with alumina nano particles were extruded (See Figure 7). For 1350 alloy, the third trial (1350-5AlO-3) with 5% of Al_2O_3 was able to produce a 5 ft (1.5m) long wire (Table 3). Figure 8 shows the 5ft long wire. Rough finish is obviously seen, due to a large particulate inclusion. Further process modification/improvement is needed to get better 1350/ Al_2O_3 wire quality.

Table 1 Trials with varying process parameters, including rotation speed (rpm), plunge distance (inch), and plunge rate (ipm) for process optimization in 6061 aluminum alloy.

Filename Run #	RPM	Plunge Dist. In.	Plunge Rate IPM	Tool ID	Comments
6061-104	600	0.5 / 2.5	1.0 / 2.5	-	The extruded samples broke into short pieces.
6061-105	400	0.5 / 2.5	1.0 / 2.5	-	Aborted experiment due to Z servo error
6061-106	500	3	3	-	Aborted experiment because Force Control limit was exceeded.
6061-107	600	3	3	-	14"-16" wires were extruded.
6061-108	600	3	1	-	~8" wires were extruded.
6061-109	600	3	0.75	-	8-9" wires were extruded.
6061-110	600	3	0.25	-	No sustained extrusion.
6061-111	600	3	0.75	-	Extrusion of wires was discontinuous.
6061-112	600	3	0.75	-	12" and 6" wires were extruded.
6061-113	600	0.75 / 2.5	0.75 / 3.0	-	3ft wires were extruded with fine grains in both transverse and longitudinal directions (TD and LD).
6061-114	600	0.75 / 2.5	0.75 / 3.0	A	Short wires were extruded.
6061-115	600	0.75 / 2.5	0.75 / 3.0	B	6ft wires were extruded.
6061-116	600	0.7 / 2.6	0.75 / 3.0	B	Short wires were extruded.
6061-117	600	0.7 / 2.6	0.75 / 3.0	A	~16ft long wire was extruded containing coarse grains with fine grains dispersed at boundaries.
6061-118	600	0.7 / 2.6	0.75 / 3.0	A	Up to 10 ft long wire was extruded containing coarse grains in both TD and LD.
6061-119	600	0.7 / 2.6	1.0 / 3.0	B	4 ft long wire was extruded.
6061-120EM	600	0.7 / 2.6	0.75 / 3.0	A	Short wires were extruded.
6061-121EM	600	0.7 / 2.6	0.75 / 3.0	B	Long pc wire with fine grains at 0.75ipm, and ~40" wire with coarse grains at 3ipm were obtained.
6061-122	600	0.7 / 2.6	0.75 / 2.0	A	Using machined chips, 8" and 10" wires were obtained.
6061-123	600	1.0 / 2.3	0.75 / 3.5	A	Test failed.
6061-124	600	1.0 / 1.0 / 1.3	0.75 / 3.0	A	Using machined chips, 8" and 10" wires were obtained.
6061-125	600	3.3	0.75	A	30"-40" long wires with fine grains at start and end at 0.75ipm were obtained.

Table 2 Alloy 6201 trial extrusions containing different volume fractions of Al_2O_3 nano powders.

Filename Run #	RPM	Axial force, KN	Axial force rate, mm/sec*	Result 3mm dia. wire length	Comments
6201-2.5AlO-1	600	300	25.0	Zero	Failed trial. No extrusion.
6201-2.5AlO-2	600	300	6.0 up to 25.0	Zero	Failed trial.
6201-5AlO-3	600	300	6.0	2x100mm	Minimal extrusion.
6201-5AlO-4	600	300	8.0	500mm and chips	Same as above.
6201-2.5AlO-5	600	300	10.0 up to 25.0	Initial 400mm & secondary 150mm	Metallurgical examination shows powder distribution, but maybe oxide.
6201-2.5AlO-6	600	300	6.0	Initial 250mm and series of 50mm lengths	Initial extrusion produces rough surface, then shorter smooth lengths.
6201-10AlO-7	600	300	10.0 up to 25.0	50mm long chips	Encountered die problems.
6201-5AlO-8	600	200	15.0	700mm	Discontinuous extrusion.
6201-5AlO-9	600	200	15.0	Small chips	Same as above.
6201-2.5AlO-10	600	300	15.0	500mm	Encountered die problems.
6201-2.5AlO-11	600	300	15.0	chips	Minimum extrusion.

Table 3 Alloy 1350 trial extrusions containing different volume fractions of Al_2O_3 nano powders.

Filename Run #	RPM	Axial force applied, KN	Axial force rate, mm/sec*	Result 3mm dia. wire length	Comments
1350-2.5AlO-1	600	250	6.0	100mm lengths	Initial trial.
1350-2.5AlO-2	600	300	25.0	100mm lengths	Initial trial.
1350-5AlO-3	600	300	15.0	1.5m	Rough external features on the wire.
1350-2.5AlO-4	600	300	15.0	1.4m	Wire with smooth surface was produced.
1350-2.5AlO-5	600	300	15.0	800mm in 100mm lengths	Smooth wires were produced with powder randomly distributed.
1350-2.5AlO-6	600	300	15.0	1.5m	Wire produced with powder distributed at various locations along length.
1350-2.5AlO-7	600	200	15.0	Chips as 45mm lengths	Smooth wires were produced. Powder expelled at 45mm intervals from extrusion
1350-5AlO-8	600	300	15.0	400mm	Smooth wire with powder at approx. every 30mm was produced.

2.2.2 Mechanical Property

Table 4 compares the mechanical testing results of 6061 wires produced with different process parameters, indicating conditions used in Run No. 117 in Table 1 yields the maximum strength and elongation. Table 5 shows the tensile properties of several different Al alloys produced by FSE, under the as-produced conditions. Excellent properties were obtained compared to the values reported in literature [1]. For example, the *as-produced* 6061 samples have properties very close to the T4 designation by solution heat-treatment and natural aging. Therefore, it can be concluded that the mechanical properties of 6061, 6082, 5052, and 1350 wires produced by the new friction process, such as tensile strength, yield and elongation, were comparable to those specified in the Aluminum standards [1].

2.2.3 Microstructure Characterizations

For the 6061 wires extruded with different process parameters, as illustrated in Figure 9, microstructural characterization revealed fine grain as well as coarse grain structure. The grain sizes can be manipulated by controlling the temperature and extent of deformation during FSE. For instance, the process of friction extrusion can be fine-tuned to achieve a homogeneous microstructure.

As mentioned earlier, FSE opens new and exciting opportunities to synthesize completely new materials. The very high straining rate and the extensive materials flow/deformation of FSE in a wide temperature range between 0.3 and 0.8 T_m (melting temperature of material), which is not easily attainable in other thermo-mechanical deformation processes. The co-extruded wires exhibit very unique microstructural features, which potentially opens exciting avenues for new products. As shown in Figure 10, two different Al alloys, A15052 and 1350 (an electric conductor grade pure Al), was co-synthesized via FSE to form a dual phase microstructure.

Furthermore, high volume fraction of nano-particles (up to 10% volume fraction so far) was mechanically alloyed into the matrix of Al alloys with uniform distribution through FSE, as shown in Figure 11 – Figure 13, which is impossible by the conventional casting process. Distribution of the nano particles is relatively uniform. Further work is needed to optimize the parameters to have much finer and uniform distribution of nano particles.

Figure 2 The tool for friction stir extrusion: (a) plunger, and (b) top view of the die (cartridge).

Figure 3 (a) Solid 6061 sample. Southwire cast and machined the samples to size. (b) 5052 sample with 1350 wire for co-extrusion trials. Similar samples were created with 6061 and 1350 wire. (c) Samples drilled and filled with nano-particles. Holes are closed with aluminum caps.

Figure 4 Various Al wires produced in the concept study of FSE.

Figure 5 Wires of 6082, 6061, 5052 and 1350 alloys produced by friction stir extrusion.

Figure 6 Examples of co-extruded 6061/1350 wires.

Figure 7 Al6201 wires containing nano alumina particles.

Figure 8 Extruded 1350 wire with addition of 5% Al₂O₃ particles.

Figure 9 Optical microstructure of recycled Al6061 wires via FSE with different process parameters.

11-0865-07

Co-Ext-01 5052 + 1350
3.0 ipm Transverse

200X 20μm

Figure 10 (a) and (b) show the unique dual-phase microstructure of co-extruded 5052/1350 wires along transverse and longitudinal directions, respectively.

(a)

(b)

Figure 11 Optical metallography of (a) as polished Al 6201 without addition of nano particles, and (b) Al 6201 with 2.5% of Al_2O_3 .

Figure 12 Longitudinal microphotograph of the 1350 wire with 4% Al₂O₃ particles.

Figure 13 Uniform distribution of clusters of nano-sized (20nm average) Al₂O₃ particles in the matrix of 6061.

Table 4 Results of mechanical testing from 6061 wires.

Sample number ¹	DIAMETER (INCHES)	ULTIMATE TENSILE STRENGTH (PSI)	YIELD STRENGTH (PSI)	ELONGATION (%)	%IACS
#113 a	0.1230	35,580	17,569.6	15.00	41.51
#113b	0.1230	23,188	17,526.0	2.00*	
#117a	0.1230	36,008	18,178.3	18.00	43.52
#117b	0.1230	36,096	18,495.9	17.00	
#118a	0.1230	32,002	15,303.0	14.00	43.10
#118b	0.1230	31,667	14,979.8	13.00	

1. Sample numbers are tracked through the Filename Run column listed under Table 1.

* Surface defect

Table 5 Summary of tensile properties of different Al alloys after FSE, in as-produced conditions.

Material	Processing	Wire Diameter (mm)	Ultimate tensile strength (ksi)	Yield strength (ksi)	elongation%	Electric conductivity, %IACS
6061	FSE	3.0	34.5	17.1	15.0	43.2
6082	FSE	3.0	36.8	19.3	17.0	43.1
5052	FSE	2.9	23.0	11.0	17.0	34.1
1350	FSE	3.0	10.9	4.9	14.0	61.8
6061-T4	Ref		33.0	19.0	20.0	62.0
1350-O	Ref		12.0	4.0		54.0

3 Benefits Assessment

3.1 Technological Benefits

The innovation in FSE is a direct solid-state metal conversion that enables (1) metal recycling with greatly improved energy efficiency, and (2) synthesis of nano-engineered bulk materials with enhanced mechanical strength and other unique functional properties. FSE is an original approach, which is a dramatic departure from current practices, for sustainable manufacturing with the following unique advantages:

- Since melting and solidification is eliminated, FSE is suitable for synthesis of high-performance structural and functional materials that rely on mechanical alloying principles. This includes both nano-particle engineering materials, and completely new materials with unique microstructures through purposely blending different feedstock materials (co-synthesizing), as shown in our feasibility study. This suggests that FSE can potentially produce novel materials such as light weight metal composites (Al or Mg based), nano engineered oxide dispersion strengthened alloys, which can be used in transportation, power grid and nuclear energy systems. It can also be used in the production of titanium (Ti) and Ti based composites. These are the materials of the future in DOE ITP programs, and strategically important to U.S. industry and the national economy.
- FSE in principle can be readily developed into a continuous process that is scalable for high-volume production of bulk nano-engineered materials. Current techniques such as powder metallurgy (PM) + hot isostatic pressing (HIP) process are not easily scalable.
- FSE is not limited to produce wires or rods. Other shapes can potentially be produced with proper design of the die and related process conditions.

FSE can be deployed as a metal recycling process with much lower energy consumption, operational cost and equipment cost. This could help the US metal producing industry gain a competitive advantage in material recycling, a strategically important resource to the US industry and economy. The ability of dispersion strengthening and co-synthesizing by the FSE technology lessens the compositional restrictions in alloy design. It is therefore possible to develop recycling friendly alloys to ease the requirement for metal sorting [2].

Since FSE has the potential to recycle and convert a variety of industrial metals and produce unique advanced materials it offers significant energy, economic and market benefits as discussed below.

3.2 Economic and Energy Benefits

Energy Benefits

An energy analysis was carried out to compare the energy utilization in the conventional melting and casting process vs. friction stir extrusion. The analysis included both theoretical calculations and actual experiment measurement of the actual energy usage of the FSE process. It was concluded that the energy savings of FSE is tremendous - *FSE uses less than 15% of the energy of conventional metal casting process for Al alloys*. It should be noted that, to avoid ambiguities and difficult-to-guess assumptions in the energy and environmental benefits analysis, existing technologies typically using 100% scrap metals as input charges are chosen as the current baseline technology for comparison [3-6]. As such, the energy and environmental benefit analysis for FSE technology would be expected to be conservative. Even so, our analysis reveals the enormous potential benefits of the new technology.

The increased environmental concerns, limited natural resources, and the tremendous energy incentives of the FSE technology over the conventional aluminum recycling technology are the economic driving forces favoring the commercialization of FSE in aluminum recycling. FSE has the potential to recycle and synthesize a variety of industrial metals such as aluminum, magnesium, titanium, and steel. The energy and environment analysis primarily focused on aluminum alloys. Because of their sheer amount of

tonnages in recycling in the U.S., the widespread applications of FSE to Al are expected to have highest energy, economic, and environmental impact. From technology development and readiness point of view, Al alloys would be among the first group of materials that FSE technology can be applied commercially and in large quantity. This is also in line with the business interests of the Southwire Company, the leading organization of the project.

The projected energy savings as determined using the Energy Savings Calculation Tool (an Excel Spreadsheet based tool developed by DOE Office of Industry Technology Office) for FSE technology are remarkable. The estimates are that the total secondary aluminum in the world market was about 16.7 million Metric Tons in 2011. If the FSE technology is accepted globally for the secondary aluminum market, there is an opportunity for tremendous energy savings. See energy calculation in reference [7]. By 2025, the projected total primary energy reduction is 10 trillion Btu (TBtu) for steel and 2.5 TBtu for aluminum. By 2035, the combined total primary energy reduction is over 95 TBtu (76 TBtu for steel and 19 TBtu for aluminum). Note that all these energy savings are achieved in the steel and aluminum making process, without accounting for other derivative energy savings.

Environmental Benefits

The Energy Savings Calculation Tool also provided the environmental benefits associated with the application of the new technology. By 2035, the total emission reductions include 2,300 tons of CO₂, 17,000 tons of SO₂, and 14,400 tons of NO_x. In addition, by eliminating melting, the new technology is essentially emission free during the operations, whereas the current technology does have significant emission of oxide particulates and metal particulates associated with the molten metal oxidation process during operation, which was not captured in the Energy Savings Calculation Tool.

Economic Viability

The outlook of the economic viability of the new technology is also very positive. While scaling up the new technology to meet the market demands would mean construction and fabrication of large scale electrical/hydraulic equipment, the steel and aluminum industry and the U.S. manufacturing are well experienced for construction and fabrication of such types of equipment construction as they have done in the past to build steel mills and aluminum mills. Therefore, technological feasibility in equipment construction is considered to be high. This is particularly true for conversion of aluminum alloys.

The Energy Savings Calculation Tool also revealed significant financial savings associated with the application of the FSE technology due to low energy cost. The laboratory trials indicated that the operating cost of the FSE technology would be ~20% of the current melting and casting technologies for the secondary aluminum production. At this time, since the scale-up data is not available, it is difficult to estimate the return on investment. By 2035, the net economic benefit (from the production operations) would reach over \$100 million dollar for the aluminum industry and over \$420 million dollars for the steel industry, annually. In addition, part of the current steel and aluminum making infrastructure can be used for the new technology. This further reduced the financial burdens for adopting the new technology. While it is very difficult, at this stage, to have good estimates on the capital investment required to construct equipment for the new technology, the huge financial net gains from the operation side of the business would certainly offset, if not completely cover, a significant portion of the construction cost.

Finally, our commercialization strategy, discussed below, would help further ease the barrier for introduction of FSE to the market, through targeting the early-stage applications (nano engineered bulk materials and Al recycling) where the FSE technology can be developed and matured quickly and the cost of entrance and market competition are low or non-existent. This will help build the momentum and market acceptance of the new technology.

4 Commercialization

4.1 Potential Markets and Commercialization Strategy

The FSE process has the potential to be an energy-efficient material-producing method for a very broad range of materials and applications. Some of the applications are inherently more difficult and complicated than the others, if one considers the differences in capital investment requirements, the ease with which the FSE technology can be applied, and the market size and needs.

The nano-engineered materials will be the first targeted application and commercialization of the FSE technology. This is consistent with the business interest of Southwire, and the technical and economic impact of the technology, and the anticipated cost of commercialization. The nano-engineered mechanically alloyed materials would be a relatively small, niche market, which offers a number of advantages from future commercialization point of view. For example, it is expected that pilot productions can be done for certain applications where the size and quantity of the parts allow for batch mode operation with laboratory type of equipment. This would ease the transition from R&D to production, and avoid huge capital investment needs to build large complex equipment for high-volume mass production situations. Due to the relatively low volume demand, the quality of the feedstock materials is easy to control (no need to deal with scrap materials, at least in the early production stage. However, it should be noted that properly sorting out scrap materials is needed for both the FSE technology and the today's recycling technology).

Choosing aluminum recycling as a showcase material for the first large scale commercialization is based on a number of considerations. First, aluminum alloys are easy to work with; the relatively low process temperature (300 to 450 C) and low process load do not pose major problems to tool materials and machine design for the FSE process. We can use aluminum to further advance the understanding of the process and explore different process innovations. Secondly, aluminum is highly recyclable and represents a very large market (second largest metal processing market behind the steel). Southwire Company, the leading organization of this project, is very interested in future commercialization of this technology for aluminum recycling. Finally, the technology development and experience gained from commercialization of nano-engineered mechanically alloyed materials (tool material development) and aluminum recycling (large scale production) would ease the market entry barrier for steel recycling, the largest energy saving potential for the proposed technology.

Ti alloys present another potential market, due to the window-of-opportunity by the recent development on alternative low-cost Ti production in the U.S. Ti and its alloys are widely used in the energy intensive industries for their superior corrosion resistance and high-temperature strength. However, Ti is very expensive to produce in large quantities due to its high cost, energy intensive extraction process. In the US, there are several concerted large-scale R&D initiatives (including DOE's ITP office) to develop and commercialize alternative, low-cost Ti production methods. The proposed direct solid-state material conversion process would be a very attractive method to consolidate the Ti powders produced by the alternative Ti extraction process [8].

The Mg alloy is another market for potential application of FSE. There have been heightened interests in the U.S. automotive industry to use Mg alloys to reduce the vehicle weight for improved fuel efficiency. The relatively low ductility of Mg alloys is a pressing issue, as it would negatively influence the crashworthiness of the vehicle. Recent studies [9] have shown that nano-particle strengthened Mg casting alloys have much improved ductility and strengthen. FSE may be used to produce nano-particle strengthened stock materials for further processing (rolling and forming) to produce the body parts and engine components for energy efficient vehicles. In addition, Mg alloys due to their lightweight are a promising candidate material for use in windmills. This is another growing market as the nation embraces emission free alternative energy sources.

4.2 Position and Roles of Southwire Company in Technology Commercialization

Southwire Company is well positioned in marketing and commercializing this technology in the Al and Cu metal recycling and production. Southwire Company is a large producer of copper and aluminum, building and utility wire. From cables for power generation plants, overhead conductors for the transmission of electricity, and cables for the secondary distribution of electricity, our products are found across the product chain for electrical power grids. Electrical utility companies form the core of our customer base in the utility markets. Southwire is not only the supplier of wire and cable products but has been at the forefront of technology innovation. In the last several years alone, Southwire has successfully developed and commercialized the next generation of overhead cables. Southwire continues to collaborate with ORNL in the development and commercialization of high temperature superconducting cables.

Transmission of electric power is the ability to move energy from the point of generation to the point of usage. The ability to transmit electric power efficiently not only affects the cost of electricity, but also influences the reliability of the systems to move power within regions. As the electric power industry restructures the way it processes and transmits electricity in part in response to next generation of smart electric grids to accommodate the alternative electric energy generation from solar, wind and thermo-hydro sources, the need to dynamically adapt to the new market forces and world events underscore the need to evolve new engineering materials for more efficient electricity transmission. It is the consensus at Southwire that a carefully planned strategy of new materials development to increase current carrying capacity of transmission lines can turn the potential changes outlined above into opportunities for technological innovation and commercial application. Therefore the need to develop low cost, green energy solutions continues to grow to adequately accommodate the United States increasing demand for power. Research carried out by numerous independent research organizations has pointed to the need to modify and upgrade existing power transmission grids to meet increased national power needs while maintaining an environmentally friendly, cost efficient system. The estimates from several agencies indicates that there will be an increase of at least 20% demand for electricity in the next ten years while the transmission lines increase is expected to accommodate only about 6%. In addition economic development and business expansion requires increased and reliable power transmission. Therefore it becomes critical to increase the power carrying capacity of existing transmission lines to offset the increase in the electricity demand. Southwire strongly believes that the development of nano-engineered materials could partially address these requirements of higher power transmission lines. The current generation of overhead conductors consist of a core that is basically used as a strength element in the conductor overhead conductors. The primary purpose of the core is to provide support to the conductor that carries electric current. It is important to note that current carrying capacity for a conductor is directly proportional to the cross sectional area of the conductor. Therefore if there is an increase in the total conductor area without concomitant increases in the area of the composite conductor then the current carrying capacity of the core/conductor composite can be dramatically increased without altering the overall dimensions of the conductor. Since FSE has the potential to generate new materials with higher mechanical and electrical properties, which would increase the current carrying capacity of transmission cables. Southwire will leverage its years of expertise in the field of Utility Wire and Cable to develop and commercialize these nano-engineered products.

Southwire is a technology leader in the continuous casting of copper and aluminum wire rod with its Southwire Continuous Rod[®] (SCR) process. Southwire operates the world's largest SCR copper rod facility in Carrollton, Georgia, where every day we produce over 2,000,000 pounds of pure copper rod. Additionally, Southwire operates three SCR aluminum rod mills at its facility in Hawesville, Kentucky, where more than 1,000,000 pounds of the highest quality rod are cast each day. Not only do we use our SCR systems in our own wire-making business, we sell our SCR systems to other manufacturers globally. As a result of our innovation and technology leadership, 50% of the world's copper rod is processed through a Southwire Continuous Rod system. More than 80 systems operate in such countries as India, Japan, Russia, South Africa and the United Kingdom.

In summary, Southwire Company has the vested business interests, significant market share in Al and Cu metal production for electricity cable, resources, technical capability for the future commercialization of the FSE technology.

5 Conclusions

FSE is a unique metal processing technology because it bypasses the melting step and does not use the conventional solidification mechanisms. The work done under this program has clearly demonstrated the viability of friction stir extrusion for metal recycling and synthesizing bulk advanced materials incorporating nano particles. We have also demonstrated that FSE has the potential to produce alloys that today cannot be processed with the conventional melting/casting technologies. We have concluded that the FSE has significant advantages in saving energy, reducing environmental footprint and the ability to get significant traction in advanced materials commercialization that could have a great impact of national significance.

Extensive work carried out on the FSE has advanced this technology beyond the conceptual stages. Significant breakthrough has been achieved in the development of friction stir extrusion process. Lengths of aluminum alloy 6061 were successfully extruded. Process parameters were further optimized for die design, plunge forces, and rotational speed to make several continuous lengths of 6061 alloy. Wire lengths up to 15 feet were accomplished. Both slugs and metal chips were used feed stock material and the length of the extruded wire was only limited by the charge in the cartridge. The capability of the process to extrude other aluminum alloy 6082, 5052, and 1350 was successful. A comparative analysis of the wires produced through regular melting, casting and drawing vs. friction stir extrusion revealed that the mechanical / electrical properties of the extruded process were comparable. Microstructural analysis using metallographic technique showed that the samples contained both fine grains and coarse grains. Further optimization of the process parameters is necessary.

The friction stir process also has the potential to produce new alloys by coextruding different alloys. Aluminum alloy 5052 and 1350 was successfully coextruded. The data looks promising for producing new alloys. Feasibility studies to extrude aluminum alloy 6201 with Al₂O₃ and alloy 1350 with Al₂O₃ was carried out, respectively. Microstructural examination showed that the distribution of nano particles was relatively uniform. Further work is needed to optimize the process and the processing parameters.

Also an energy analysis was carried out to compare the energy utilization in the conventional melting and casting process vs. friction stir extrusion. The energy and economic assessment of the FSE suggests that FSE could be developed as a revolutionary, game-changing, technology for Southwire Company's core business. Hence, Southwire is committed to continue the development of the technology for commercialization.

Patent disclosure below has been filed for both US and European Patent applications:
Zhili Feng and Venkata Kiran Manchiraju, "Providing Plastic Zone Extrusion". July 8, 2011. US Serial No. 13/178, 746.

Technical highlights in newsletters and Journal:

1. Oak Ridge National Laboratory Reporter, "Friction-stir Extrusion Seen as Key to New Materials Process at a Fraction of the Energy", July 25, 2011.
2. Advanced Materials and Processes, "New Spin of Friction-Stir", Vol. 169, No. 9, September 2011
3. Tribology & Lubrication Technology, "Tech Beat", December 2011, pp. 8-9

6 Recommendations

Based on this feasibility work, we recommend the followings:

- 1) Develop the sound technological basis and demonstrate the commercial viability of FSE technology to produce next generation highly functional electric cables for electricity delivery infrastructure (a multi-billion dollar market) at the end of this project, and to expand to two or three specifically targeted markets and applications in 5 to 7 years. Specific objectives are: (1) establishing the process and material parameters to synthesize novel alloys such as nano-engineered materials with enhanced mechanical, physical, and/or functional properties through the unique mechanical alloying capability of FSE. We believe that additional areas of research that look into using nano engineered FSE wires in an aluminum matrix would produce useful results. Without going into extensive detail it is believed that these nano engineered FSE produced composite cores would be characterized by higher strengths, lower density and lower thermal coefficients of expansion thereby not only increasing the overall capacity of the conductor but would also not be limited by the sag problems confronting the current generation of transmission lines at higher currents.
- 2) Design and construct a small-scale laboratory continuous FSE prototype system capable of producing sufficient quantity of Al alloys based nano-engineered electric cable products (first targeted application), for market testing, and verify the expected major energy, environment, and economic benefits of FSE technology for both the early stage “showcase” electric cable market and the anticipated pervasive future multi-market applications across several industry sectors and material systems for metal recycling and sustainable manufacturing.

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