

## Chapter 2

# Introduction to Electrically Assisted Forming

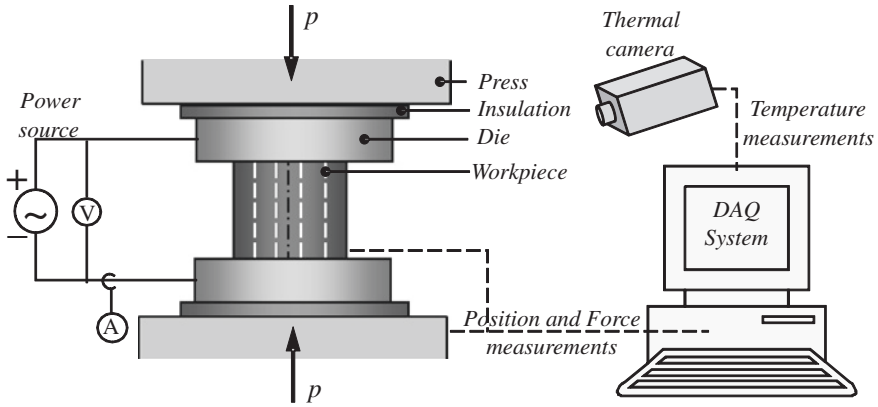
### 2.1 Electrically Assisted Forming

Electrically assisted forming (EAF) is a recently introduced metal-forming technique capable of enhancing a metal's formability during deformation and reducing springback after deformation. In this technique, electricity is applied to a metal blank while it is deformed, without stopping the deformation. Electrically assisted manufacturing (EAM) is a general term used for the technique of applying electricity to any manufacturing process. EAF is a specific type of EAM, where electricity is applied to metal-forming processes (i.e., bulk deformation or sheet metal forming). A schematic of an EAF (forging) test setup can be seen in Fig. 2.1. The key components of the test setup include a controllable power supply to generate the electricity, a DAQ system to collect mechanical data, a thermal camera to collect thermal data, and insulation to isolate the die/workpiece and machinery from the applied electricity.

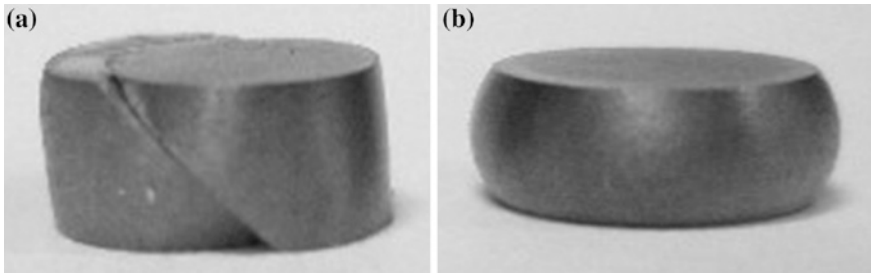
The multiple benefits generated from the applied electricity are collectively known as the electroplastic effect. The three main benefits of the electroplastic effect are as follows:

- A reduction in the flow stress required to continue plastic deformation
- Increased achievable part deformation prior to failure
- Reduction/elimination of springback effects in formed parts

Figure 2.2 illustrates the electroplastic effect, by showing EAF's ability to transform strong and brittle Ti-6Al-4 V into a highly formable material. In Part *a*, a specimen compressed under conventional conditions, with no applied electricity, is shown. After a minimal amount of deformation, the HCP material failed due to brittle shear fracture. Part *b* shows a specimen compressed under EAF conditions, where the electricity was applied for the duration of the forging operation. Due to EAF, the part was able to be completely formed to its desired height without failure.



**Fig. 2.1** Schematic of an EAF test setup [1]. During EAF, electricity is applied to a metal while it is deformed, thus increasing the overall formability of the metal and producing the electroplastic effect



**Fig. 2.2** EAF formability improvement (Ti-G5) [1]. EAF increases the achievable amount of part displacement before failure. **a** Conventional forming of a Ti-G5 slug led to almost instantaneous shear failure, **b** EAF forming of the same material enabled the slug to be deformed to its desired distance

However, like all processing techniques, EAF has some disadvantages and challenges that exist within the process and its implementation toward industrial use. First, in order for the electricity to reach the part, there must be some type of electrical applicator in contact with the conductive workpiece at all times. For manufacturing processes where the workpiece is stationary, like forging or stamping, this can be done rather easily. Conversely, when implementing the EAF technique on manufacturing processes with workpieces of relative motion, like friction welding two workpieces together, an applicator system which is in continuous contact with the workpiece while not becoming entangled in the part must first be designed. In addition, since the workpiece is subjected to electrical flow, all personnel and machine components should be insulated from the electricity. It must be noted that extreme caution should always be used when working with electricity. Isolating the electricity, however, can prove to be a challenging task in some cases, since most machinery components are comprised of conductive metals and the common insulating

materials (e.g., nylons, rubbers, ceramics, or plastics) cannot withstand the mechanical demands placed on these components (i.e., too soft or too brittle). Outweighing these issues, in most cases, are the energy reduction benefits, decreased flow stress, increased ductility, and reduced springback, that can be accomplished using the EAF method. Some tooling designs devised to overcome issues with electric current integration to the forming process are described in Chap. 10.

## 2.2 EAF Literature Review

Research investigating how electricity affects materials can be traced back to the mid-twentieth century in Russia. Toward the later part of this century, this research slowly began in the United States. Now, there are an increased number of universities and national laboratories which have begun to focus on some portion of the EAF technique. An in-depth explanation into the history of EAF research will be provided below.

In 1959, Machlin et al. [2] examined electricity's effect on group 1A salts (NaCl), determining that an applied electric current significantly affected the material's ductility, flow stress, and yield strength. Later, Nabarro [3] discussed electricity's effect on metals as part of his book in 1967. In 1969, Troitskii et al. [4] studied how electrons influence dislocation motion and reproduction in different alloys of zinc, tin, lead, and indium, concluding that pulsed electricity could lower the flow stress within the materials. Years later, in 1982, Klimov et al. [5] explained that the effects on a metal's structure from electricity are unrelated to those caused by Joule heating. Moving forward, in 1988, a microstructure analysis was conducted by Xu et al. [6], and it was discovered that a continuous electric current in titanium materials caused the recrystallization rate and the grain size of the materials to increase. Next, Chen et al. [7, 8] developed a relationship between electric flow and the formation of intermetallic compounds (Sn/Cu and Sn/Ni systems). Afterward, in 2000, Conrad et al. [9–11] determined that very high-current density/short-duration electrical pulses can affect the plasticity and phase transformations of metals and ceramics. In 2005, Heigel et al. [12] examined the microstructural alterations in Al 6061 resulting from direct current.

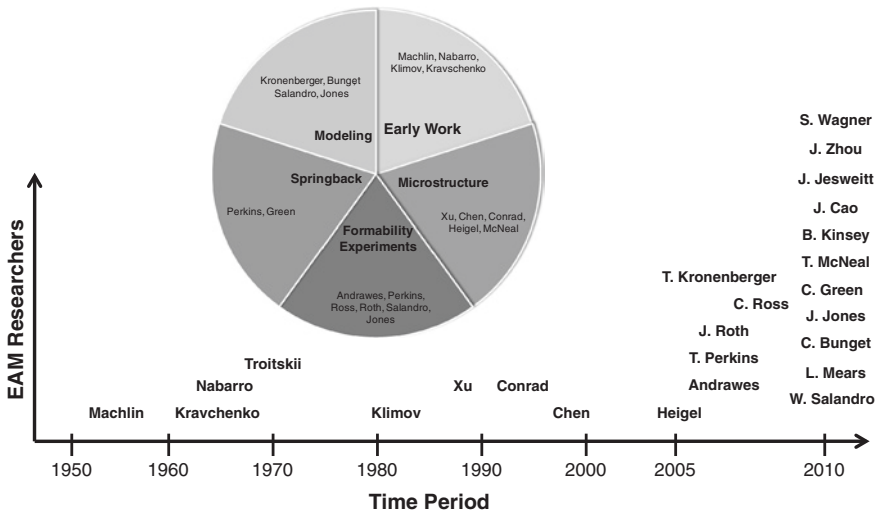
Within the past few years, much experimental research has been performed to establish how electricity affects the mechanical behavior of different metallic alloys. In 2007, Andrawes et al. [13] was able to conclude that electrical current can significantly reduce the energy needed for uniaxial tensile deformation of Al 6061-T6511 without greatly heating the workpiece. Perkins et al. [14] studied the effects of a continuously applied electric current on various alloys undergoing an upsetting process and found that the electricity increased the amount of allowable compressive deformation prior to fracture and lowered the required compressive forces. Again in 2007, Ross et al. [15] examined the application of a continuously supplied electric current on tensile specimens, only to conclude that, although deformation forces were reduced, the achievable elongation was decreased, leading to premature failure.

The problem of decreased elongation in EAF-tensile processes was overcome in 2008, when Roth et al. [16] achieved elongation increases of nearly 400 % by applying square wave pulsed (rather than continuous) current to Al 5754 tensile specimens. Following this, Salandro et al. [17] examined the effect of pulsed electricity on three different heat treatments of two 5xxx Aluminum Alloys (5052 and 5083). Moreover, in 2009, Salandro et al. [18] discovered a linear relationship between current density and pulse duration in Mg AZ31B-O tensile specimens that could be used to reliably achieve intended elongations for a variety of pulsing conditions. Research by McNeal et al. [19] examined microstructural alterations in the same Mg AZ31B-O tensile specimens. Green et al. [20] determined that springback in Al 6111 sheet specimens could be completely eliminated with a single high-current, short-duration electrical pulse. From work by Jones and Roth [21], achievable compressive displacements of the same Mg alloy were increased by over 400 %, and the electricity even led to strain weakening effects. Additionally, in 2009, Salandro and Roth [22] found that, by applying electric pulses to Al 5052 while undergoing highly localized channel formation, the achievable channel depth could be increased while reducing the required machine forces. Siopis et al. [23] examined how different microstructure properties affect the effectiveness of EAF in micro-extrusion experiments. Specifically, it was concluded that a finer-grained material, with more grain boundaries, enhanced the electroplastic effect, whereas a larger-grained material, with fewer grain boundaries, lessened the effect. Another work by Siopis et al. [24] determined that the effectiveness of EAF increased as the dislocation density within the metal also increased, as a result of cold-working prior to EAF experiments. A work by Dzialo et al. [25] examined the effect of current density and zinc content during electrical-assisted forming of copper alloys. A more in-depth overview of the development of EAF can be found in [26]. Additionally, several recent EAF patents were found as a part of the EAF literature review [27–31].

Overall, the effort and number of researchers studying EAF in the USA have increased tremendously since Roth began experimentally analyzing EAF in the mid-2000s. Shown in Fig. 2.3 is a timeline displaying both the researchers and universities that are involved in some type of EAF research (note the exponentially increasing trend).

### ***2.2.1 EAF Theory and Modeling***

Due to the lack of knowledge about the electroplastic effect, past researchers have been unsuccessful in accurately modeling and predicting EAF effects for process control. However, from the previous work in this field, a multi-part postulated theory can be explained. At the microstructure level, metals are held together by metallic bonds, consisting of clouds of electrons, which surround ion cores containing protons and neutrons. Because of this, it is realistic that the application of electricity (i.e., the application of flowing electrons) to any metal will have noticeable effects. Specifically, when electricity is applied to a metal during



**Fig. 2.3** EAF research timeline. The number of researchers and universities investing time and money into different aspects of EAF research has increased exponentially over the past decade

deformation, a few phenomena occur simultaneously, thus transforming the material into an easier-to-deform state, known as the electroplastic effect. This effect has been attributed to the following aspects:

- *Localized atomic-level resistive heating effects* that are enhanced by the resistivity of the material (i.e., electrons scatter off of interfacial defects within the lattice, such as voids, impurities, grain boundaries) [16]. It is important to remember that this heating occurs on the atomic level (within the metal's lattice), and although this contributes toward the overall heating of the workpiece, this temperature increase is not the same as the bulk temperature increase that is witnessed at the part's surface (known as global or bulk heating). Specifically, the bulk temperature of a metal is the result of all the atomic-level heating locations. This effect expands the local lattice and allows for easier dislocation motion (i.e., plastic deformation) by way of enhanced diffusion. The resistive heating effects are dependent upon resistivity; hence, a material with a greater resistance will experience larger amounts of localized resistive heating and will potentially achieve greater formability benefits when the EAF technique is applied.
- *Direct dislocation–electron interaction* takes place when the flowing electrons impact the dislocation lines, assisting in “pushing” the dislocation lines and further enhancing plastic deformation and material ductility [32]. Kravchenko [33], in his explanation of electroplasticity, succinctly stated this effect when he explained that, if there is an electric current flowing and the electrons are traveling at a faster rate than the dislocations within the lattice, the energy from the electrons is transferred to the dislocations, thus making the plastic flow easier. The overall impact of this effect can be significant or minimal, depending on the

direction of the flowing electrons and the direction of deformation. This aims to explain why the temperature of an EAF test, where electricity is applied during deformation, is less than a stationary electrical test, where the electricity is applied when no deformation takes place. In the EAF test, some of the energy is used to assist plastic deformation, instead of fully contributing toward resistive heating.

- The *addition of excess electrons* to the metal's microstructure is an important aspect. Since the electron clouds control how strongly a metal is bonded and essentially act as the "glue" which holds a metal together, the excess electrons (obtained from applying the electricity) will assist in breaking and reforming bonds by reducing the bond strength between electrons. As the metallic bonds are able to break and reform easier, the ductility of the metal is improved; hence, it becomes more workable [34].

Figure 2.4 displays a schematic describing the three main pillars of the electroplastic effect explaining the EAF theory.

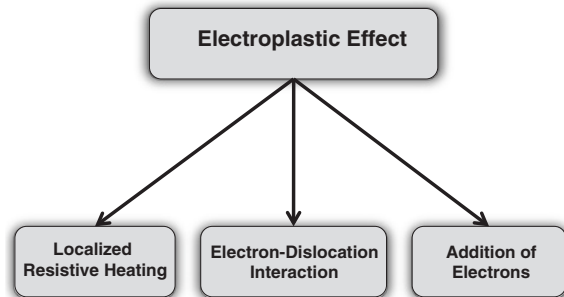
As previously stated, there have been several unsuccessful attempts at modeling EAF; however, these attempts have helped to bring a better understanding to EAF. In [36], a finite element (FE) model, capable of accurately predicting resistive heating and isothermal forming effects, was considerably unsuccessful in simulating material behavior in an EAF compression test, as shown in Fig. 2.5.

Additionally, in [37], isothermal compression tests were run at temperatures above the maximum temperature reached during EAF tests, concluding that the isothermal tests accounted for about only 10 % of the formability improvement witnessed in the EAF tests (Fig. 2.6). While these works helped to disprove the common misbelief that EAF's effect is due solely to temperature, they emphasize the fact that the EAF theory is not fundamentally understood and EAF effects cannot be effectively predicted.

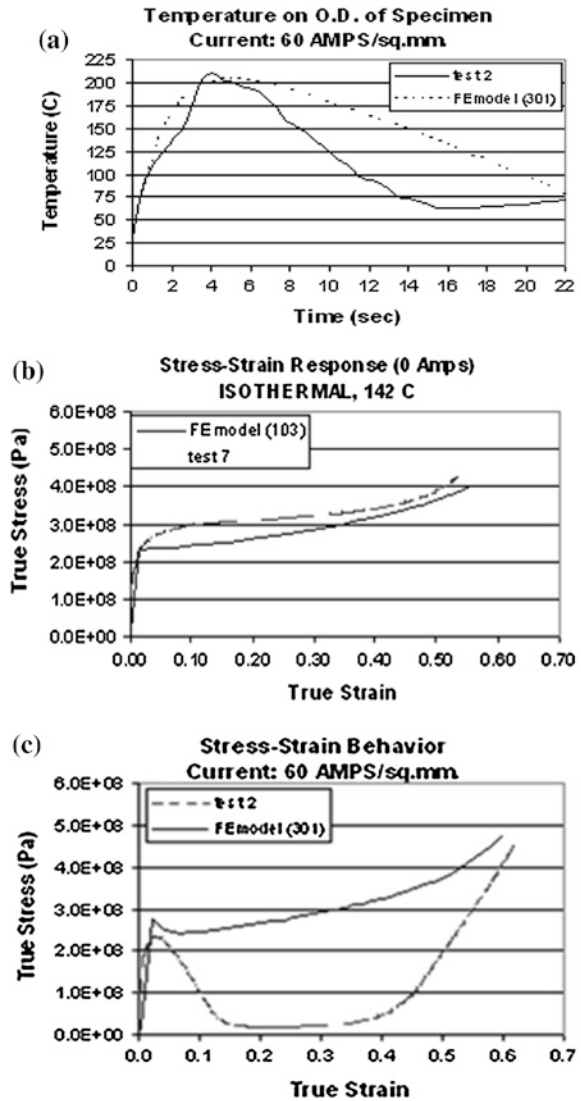
### 2.2.2 Significant EAF Modeling Variables from Experimentation

The previous experimental works on EAF highlight the important material- and process-related parameters for EAF. The following lists of important variables are

**Fig. 2.4** EAF research theory summary [35]. From the previous research performed on EAF, the three effects listed above are theorized to produce the electroplastic effect in metals

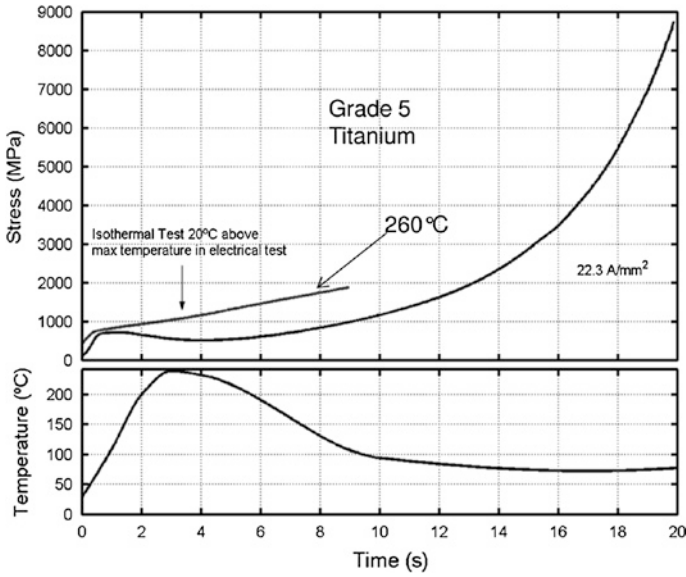


**Fig. 2.5** FEA modeling of EAF [36]. In previous research, generic FEA modeling of EAF proved unsuccessful. **a** The FEA program was capable of predicting resistive heating temperature profiles, **b** the FEA model proved capable of predicting a stress–strain profile for an isothermal test, **c** the FEA model, which accounted solely for resistive heating, was shown to be highly inaccurate when trying to predict an EAF stress–strain profile



derived from the experimental works on EAF, as well as from conversations with experts in related fields who have shared their opinions on the electroplastic effect.

The material properties of importance to an EAF process are as follows: 1 thermal conductivity ( $k$ ), 2 density ( $\rho$ ), 3 specific heat ( $C_p$ ), 4 heat transfer coefficient ( $h$ ), 5 starting strength coefficient of the material ( $C$ ), 6 strain hardening exponent of the material ( $n$ ), 7 resistivity ( $r$ ), and 8 the initial grain structure of the metal. Each of the material-based properties is significant when modeling any heat

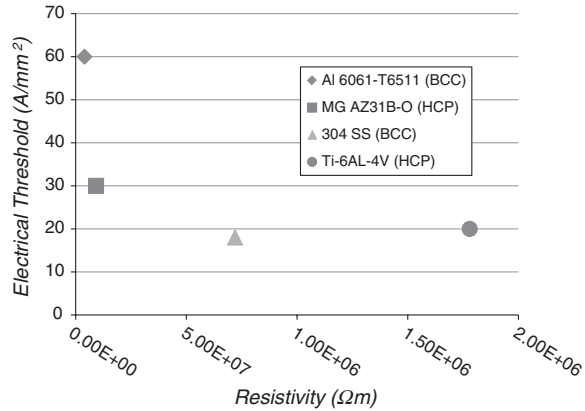


**Fig. 2.6** Experimental EAF modeling [37]. A previous research work proved that the stress–strain profiles for an EAF test, and an isothermal test run at the maximum temperature reached during the EAF test, were considerably different. Additionally, this confirmed that the effects of EAF were not solely contributable to resistive heating or thermal softening

transfer or thermodynamic phenomenon, or performing any mechanical modeling [35]. The effects/relations of these inputs are described below:

- The thermal conductivity ( $k$ ), density ( $\rho$ ), specific heat ( $C_p$ ), heat transfer coefficient ( $h$ ), and resistivity ( $r$ ) all affect the heat transfer and ultimately the stress–strain characteristics of the EAF process. Additionally, each of these variables change as a function of temperature, so depending on the temperatures reached during an EAF process, these variables could have weighted effects. These intrinsic properties are not only important for the workpiece, but it is also critical to know these properties for the forming dies as well.
- The strength coefficient ( $C$ ) and strain hardening exponent ( $n$ ) are intrinsic properties that determine the magnitude and shape of the forming load profile of an EAF test (and any forming test in general). Further, both are affected by the temperature of the workpiece and forming dies in the process. Any type of metal deformation modeling would need to include the effects of both the strength coefficient and strain hardening exponent at a minimum.
- The initial grain structure (i.e., grain size, grain direction) of a material can affect the heating and mechanical characteristics of a workpiece during EAF. The grain size dictates how often moving dislocations must pass through grain boundaries which cause dislocation pile-ups and can limit achievable deformation. In addition, the applied electrons must also pass through the grain boundaries and the grain size (dictating the number of boundaries) will potentially cause the workpiece to become hotter (more boundaries) or cooler (less boundaries).

**Fig. 2.7** Electrical threshold versus material resistivity comparison for several lightweight metals [35]. The figure depicts that, as the material resistivity is increased, the electrical threshold decreases



- The resistivity has a direct correlation with the electrical threshold current density, as seen in Fig. 2.7. For the same die speed, metals with a higher resistivity require a lower electrical threshold to produce significant formability improvements. This could be related to the first part of the electrical theory, where the flowing electrons scatter off of the lattice obstacles and cause localized atomic heating. A material with a higher resistivity will have a greater number of lattice obstacles and will result in a greater amount of localized heating around these obstacles, which ultimately lowers the electrical thresholds of these metals.

The process-related variables to be presented are as follows: (1) initial dimensions of the workpiece ( $r_o$  and  $h_o$ ), (2) deformation speed (i.e., die speed), (3) current density (current per normal area), (4) applied voltage (V), (5) workpiece/die contact area, (6) electrical application method, and (7) initial percent cold work. These additional effects are detailed below:

- The initial dimensions of the workpiece determine the magnitude of current needed for EAF. It was determined that the electroplastic improvements are a function of current density and not current magnitude, so the current density will determine the appropriate current magnitude to use.
- The deformation speed is important because the EAF technique is strain rate-dependent, and therefore, the electrical application parameters (starting current density) must be adjusted if the die speed is increased or decreased.
- The current density and applied voltage make up the applied electrical power to the process. In an EA-forging process where the electricity is applied continuously, these variables must be adjusted to produce a desired amount of electrical power.
- The effect of the actual contact area between the workpiece and die was not previously explored experimentally; however, since the dies and workpiece are separate parts, are composed of different materials, and must both transfer electricity during the EAF process, this variable is to be explored. Additionally, the roughness between surfaces is a widely studied topic in the field of electrical connectors.

- Electricity can be applied to a deformation process in many ways. The work by Ross et al. [15] showed that the electricity must be applied differently for compressive and tensile processes.
- The percent cold work within a metal generally determines the dislocation density within that metal. As the dislocation density is increased, there are more dislocation pile-ups and the achievable deformation can become limited. It is theorized that the flowing electrons directly affect the dislocations within the metal's lattice.

### 2.2.3 Relation to Crystal Structure and Resistivity

As seen in the work by Perkins et al., for a specific die speed, each material has a specific electrical threshold (i.e., a current density where significant formability improvements due to the applied electrical power are observed) [14]. Table 2.1 shows several lightweight material properties (crystalline structure and resistivity), along with the electrical thresholds, which were experimentally determined using data from works by Perkins et al. [14] and Jones and Roth [21]. Figure 2.7 shows the relationship between the material resistivity and the electrical threshold current density. The calculated electrical thresholds for each of these materials are from [14] and [21], where the specimens were deformed at 25.4 mm/min. It can be noted that, as the material resistivity is increased, the electrical threshold current density decreases (see Fig. 2.7). This supports the theory of localized heating from electrons scattering off of lattice obstacles and allowing the lattice to expand easier. Also noted in the figure are the crystalline structures of the specific materials. It can be seen that, for these four metals, there is not a relation between the crystalline structure and the electrical threshold.

**Table 2.1** Lightweight materials and respective electrical thresholds [38–41]

Material	Electrical threshold (A/mm <sup>2</sup> )	Crystalline structure	Resistivity (Ωm)	Threshold reference	Specimen size (mm)	Def. rate (mm/min)
Al 6061-T6511	60	BCC	3.99E-08	Perkins et al.	9.5 × 6.4 (dia)	25.4
Mg AZ31B-O	30	HCP	9.20E-08	Jones et al.	12 × 7.5 (dia)	25.4
304 SS	18	BCC	7.20E-07	Perkins et al.	9.5 × 6.4 (dia)	25.4
Ti-6Al-4 V	20	HCP	1.78E-06	Perkins et al.	9.5 × 6.4 (dia)	25.4

### ***2.2.4 Electroplasticity and Electromigration***

The above-described effects are shown experimentally to be due not just to bulk thermal influences. There is an effect on material flow stress that appears to be due solely to direct electrical influence, beyond what would be expected from temperature effects. This electroplasticity effect is one of the key phenomena associated with EAF, and what we attempt to describe in the modeling chapters in later chapters.

## **2.3 Broader Impacts of EAF**

The applications (or industries) which could use EAF will be discussed first, followed by potential users of the EAF thermo-mechanical predictive models.

### ***2.3.1 Automotive and Aerospace Industries***

Like other formability-enhancing manufacturing techniques, EAF is not the optimum technique to use for all metals or all part designs. Specifically, during EAF, excess electrical power needs to be supplied to the workpiece, which does not always make it the most efficient process. However, the results from using EAF are significant and it may be one of the very few techniques that allow efficient forming of particular metals. For this reason, EAF should be used to form metals and alloys which are currently not able to be formed to great lengths or require excessive heating or annealing. The EAF technique would act as a gateway for these metals to be used in industry. Two metals whose formability improves tremendously using EAF are magnesium and titanium, which are targeted by the automotive and aerospace industries, respectively.

With the rising fuel and operational costs, the automotive and aircraft industries are becoming more weight-, performance-, and efficiency-focused. One way to achieve all three variables is by lightweighting. In this technique, lighter and stronger materials are used instead of the heavier carbon steels mainly used today. Magnesium is a desirable material for the automotive industry, where it is currently used in mainly cast components due to its very low formability. On the other hand, titanium is popular for use in aerospace applications, but the manufacturers constantly struggle with the poor formability and high required forming forces of this material. Again, previous research has shown that EAF significantly improves the formability of titanium, which will increase the number of potential aerospace applications for the alloy.

### 2.3.2 *Potential Early Adopters of EAF Modeling*

Now that the main industries that could benefit from EAF have been identified, it is also important to explain how the predictive model could be used. There are two main potential “Early Adopters” that could be interested in a modeling concept for EAF.

#### 2.3.2.1 Simulation Software Companies

- These simulation software companies already produce software that is able to predict outcomes of many current manufacturing processes. They already have all of the general algorithms/methodologies needed for conventional forming. By integrating the main algorithms generated by this research into their software package, these companies would be able to sell EAF-predictive software.
- There are different applications of simulation. The main simulation applicability would be for metal forming; however, there is also the potential to simulate, or model, alternative EA processes. Such process could be EA machining, EA bending, or EA joining.

#### 2.3.2.2 Metal-Forming Companies

- The predictive model can be used for EAF process design, where the speed, electrical settings, and die design will be optimized. The Tier I and Tier II metal-forming suppliers will also be probable early adopters because the EAF technique may be their chosen formability-enhancing technique for forming Mg and Ti, as explained earlier. This is where the “heart” of metal forming is and each metal-forming supplier wants to ensure that they are not overtaken by new technology of a competitor. Of note is that the automotive/aircraft OEM’s would not be considered early adopters because they want something immediately and that is 100 % dependable. It is safer to market to the suppliers because they are more likely to work with some “growing pains” of a new manufacturing process.

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Modeling and Control

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