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Electrically Assisted Forming

Modeling and Control

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Abstract

This book encompasses a compilation of work by the authors on the manufacturing technique, Electrically Assisted Forming (EAF), whereby an electric current is passed through a metal during the forming process. The importance of improved metal deformation within manufacturing is described, and the need for novel enhanced metal forming techniques is presented. EAF has shown promising experimental forming results on many lightweight metals, and within this book, macro-scale compression and tension modeling is presented. Bringing the technique even further towards industrialization, strategies for controlling the applied electric current during EAF are described. Furthermore, the sensitivities and impacts of EAF on intrinsic and extrinsic material properties are covered. Concluding the text, an explanation on designing an Electrically Assisted manufacturing process is presented, and real-world potential EAF applications are introduced.

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The authors would like to recognize the academic institutions and local companies that have supported the research included in this book:

- **Penn State—Erie, The Behrend College** is where the benefits of EAF where experimentally proven on many lightweight metals and using various forming methods.
- **Clemson University—International Center for Automotive Research (CU-ICAR)** is where further EAF development took place, by way of creating EAF models, introducing an EAF control strategy, and explaining the formability-enhancing mechanisms of EAF.
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- **Ionic Technologies Inc.** has heat treated or hardened many fixtures for the EAF research.
- **Fuchs Lubricants** has provided several of the top metal forming lubricants to be used in comparison studies with EAF.
- **Koyo Bearings** has provided testing instrumentation and has supported with material testing.

Contents

Abbreviations

AISI	American Iron and Steel Institute
AO	Analog Output
APF	Atomic Packing Factor
ASTM	American Society for Testing and Materials
BCC	Body-Centered Cubic
CAE	Computer-Aided Engineering
CAFE	Corporate Average Fuel Economy
CCD	Constant Current Density
CGA	Circle Grid Analysis
CI	Confidence Interval
cRIO	CompactRIO
DOT	Department of Transportation
EA	Electrically Assisted
EAF	Electrically Assisted Forming
EA-Forging	Electrically Assisted Forging
EAM	Electrically Assisted Manufacturing
EDM	Electrical Discharge Machining
EEC	Electroplastic Effect Coefficient
EPA	Environmental Protection Agency
FCC	Face-Centered Cubic
FE	Finite Element
FEA	Finite Element Analysis
FFT	Fast Fourier Transform
FLC	Forming Limit Curve
FLD	Forming Limit Diagram
FLIR	Forward-Looking Infrared
GBS	Grain Boundary Sliding
GHG	Greenhouse Gas
GUI	Graphical User Interface
HCP	Hexagonal Close Packed
IF	Incremental Forming

LDH	Limiting Dome Height
LVDT	Linear Variable Differential Transformer
MBC	Model-Based Control
NCCD	Non-Constant Current Density
NI	National Instruments
OEM	Original Equipment Manufacturer
PID	Proportional-Integral-Derivative
PLC	Portevin–Le Chatelier
PS	Parameter Set
SCR	Silicon Controlled Rectifier
SMDI	Steel Market Development Institute
SPF	Superplastic Forming
TWB	Tailor Welded Blank
UHSS	Ultra-High Strength Steel

About the Authors

Dr. Wesley A. Salandro is from Latrobe, Pennsylvania, where he grew up as an industrial mechanic and machinist. In 2009, Salandro received a B.S. in Mechanical Engineering from the Pennsylvania State University. During this time, Salandro began experimentally researching Electrically Assisted Manufacturing (EAM). In 2012, Salandro received a Ph.D. in Automotive Engineering from the Clemson University—International Center for Automotive Research (CU-ICAR), where he was named the *2012 CU-ICAR Outstanding Ph.D. Student*. Dr. Salandro's graduate research consists of modeling and predicting energy-assisted manufacturing processes. Wes has authored over 15 technical publications on manufacturing process modeling, experimentation, and design. Wes has received several international recognitions for his works, including the *2012 Institution of Mechanical Engineers (IMechE) SAGE Best Paper Prize*, as well as the *2012 IMechE George Stephenson Gold Medal*.
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Dr. Joshua J. Jones is currently employed with Koyo Bearings North America as a senior process development engineer in their metal forming group. Prior to joining Koyo, he received his Ph.D. degree in Automotive Engineering from Clemson University in 2012 and his B.S. in Mechanical Engineering from The Pennsylvania State University. During his time at Clemson and Penn State, his primary research focus was on the modeling and control of Electrically Assisted Manufacturing (EAM). He has five journal articles, eight conference publications, and numerous presentations at technical conferences on this topic. He received first place at the 2010 NAMRI/SME Student Research Presentation Contest for presenting modeling work for Electrically Assisted Forming.

He also has received several scholarships and grants during his time as student from organizations such as SME, Clemson University, NSF, PA SciTech, and Penn State. Aside from EAM, other research interests include lightweight material integration, manufacturing process design, and physical process modeling/simulation.

Dr. Cristina Bunget received her B.S. in Mechanical Engineering, particularly machining and designing of machine tools, from Polytechnic University of Bucharest, Romania. After gaining practical experience from working as a design engineer in a locomotive factory, Cristina decided to continue her studies, and received M.S. and Ph.D. majored in Mechanical Engineering and minored in Mathematics from North Carolina State University. During the time spent there, she was exposed to various metal forming processes, and looked for non-conventional ways to overcome some of the challenges brought by newly emerged technologies, such as microforming and ultrasonically-assisted forming. Later, during the postdoctoral training at the International Center for Automotive Research (ICAR, part of Clemson University), her exposure enlarged by working on various projects, from machining of superalloys to metal forming applications (accumulative roll bonding on titanium sheets and Electrically Assisted forming).

Dr. Laine Mears P.E., is an Associate Professor in Automotive Engineering at Clemson University, teaching and carrying out projects at the Clemson International Center for Automotive Research. He teaches modeling and analysis of automotive manufacturing processes, and has performed research in Intelligent Machining Systems, manufacturing process design and control, and manufacturing equipment diagnostics. He is the recipient of the NSF CAREER award, SAE Teetor Educational Award, and together with Drs. Salandro and Bunget, recipient of the IMechE George Stephenson Gold Medal.

Dr. Mears has previously held industry positions with Hitachi Automotive and SKF Bearings both as Manufacturing Engineer and Engineering Manager in a high-volume precision manufacturing environment. Applicable work in industry includes: power optimization of hard machining processes, multi-spindle turning analysis and startup of a bulk deformation rolling process. Dr. Mears has a B.S. in Mechanical Engineering from Virginia Tech and M.S. and Ph.D. degrees in Mechanical Engineering from Georgia Tech. He is a member of the American Society of Mechanical Engineers and a Senior Member of both the Society of Manufacturing Engineers and the American Society for Quality. He is an ASQ Certified Quality Engineer (CQE), BMW Lean Six Sigma Black Belt, and a licensed Professional Engineer.

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Chapter 1
Deformation of Metals

Deformation of metals is one of the key manufacturing processes for adding value in secondary operations. Deformation as a process evolved soon after metal refinement in ancient times to shape tools and other functional parts. With the dawn of the second Industrial Age, the availability of localized power sources allowed for the development of more standardized automated processes for metal deformation, such as forging, stamping, drawing, and extrusion. These processes gave rise to high-value, standardized components for construction, vehicles, and consumer goods.

With the development of automated deformation processes, there came a need for analysis of process behaviors and physics, in order to understand the process limitations, feasible design regions, and "optimum" points. A number of key models have been developed over the past century to describe behavior, such as the power law and Johnson-Cook models for flow stress, forming limit diagrams for sheet metal behavior, and various shearing and punching force models. These have been augmented with improved variables that better describe material changes with environmental and process effects such as temperature and strain rate, and are used to size equipment, plan processes, and define limitations.

Two key limitations of the deformation process are achievable strain (related to ductility) and flow stress (related to material strength and strain hardening behavior). These become significant limitations to processing as more brittle, higher strength metal alloys are introduced to design. These limitations and the associated cost of higher capital investment to overcome them are the motivation for the methods described in this text.

To begin, we will describe technologies used to form metals, the mechanisms by which metals plastically deform, and details of the limitations to be addressed.

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1.1 Relevant Background on Automotive and Aerospace Industries

US-based automotive Original Equipment Manufacturers (OEM's) are an integral part of the US economy, responsible for nearly one million automotive-related jobs [1]. A key evolution in today's automotive designs is reduction of mass in order to meet more stringent legislation on allowable fuel economy and vehicle emissions for this industry (see Fig. 1.1).

Vehicle energy consumption across a given driving cycle can be described by

$$E = \int_{\text{cycle}} (P)\mathrm{d}t = m\beta_1 + \frac{1}{2}C_D\rho A_f\beta_2 + \mathrm{mg}C_r\beta_3 \tag{1.1}$$

where the power P over time t can be decomposed into mass m effects (acceleration, increasing elevation), drag effects through the drag coefficient C_D, fluid density ρ, frontal area A_f, and rolling resistance C_r effects by way of weighting coefficients β_i. This energy, and hence fuel consumption, can be reduced through a number of possible means as shown in Table 1.1.

Of these, lightweighting to reduce mass-based energy consumption is an approach that can be readily implemented and has significant and immediate effects on fuel consumption. The concept of vehicle lightweighting is currently a major focus for all US and foreign automotive manufacturing OEMs, due to the

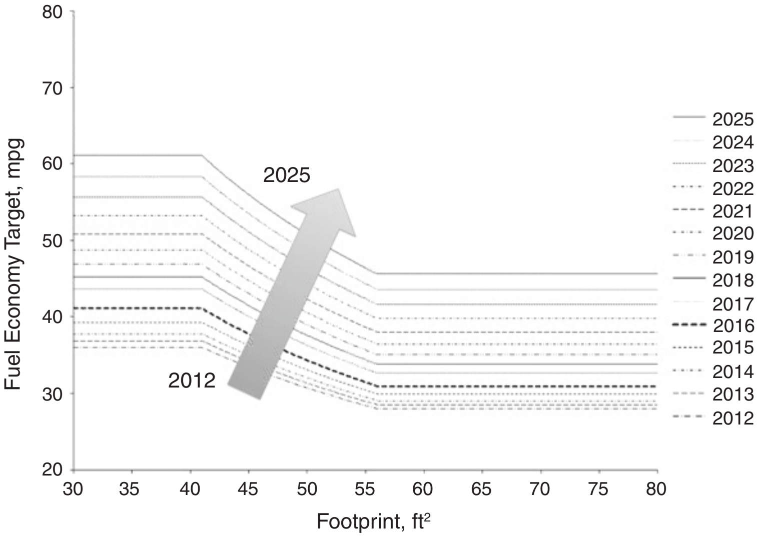

Fig. 1.1 Current and planned minimum fuel economy standards for US passenger vehicles [after US Department of Transportation (2013). Fact Sheet: DOT and EPA Establish CAFE and GHG Emissions Standards for Model Years 2017 and Beyond]

Table 1.1 Potential approaches to reduction of fuel consumption

Electrification/hybridization of powertrains
Development of low-resistance tires
Use of synthetic oil to reduce engine friction
Integration of fuel-tracking devices
Improvements in engine efficiency
Lightweighting of vehicles

above-described regulatory standards for fuel consumption, and associated emissions regulations. To reinforce the importance of this statement, the following are quotes from several automotive OEM's about their commitment toward vehicle weight reduction:

- "The use of advanced materials such as magnesium, aluminum, and ultra-high strength boron steel offers automakers structural strength at a reduced weight to help improve fuel economy and meet safety and durability requirements."—Ford Motor Company [2]
- "Lightweight design can be achieved by engineering lightweight, manufacturing lightweight and material lightweight design."—BMW AG [3]
- "Lightweight design is a key measure for reducing vehicle fuel consumption, along with power train efficiency, aerodynamics and electrical power management."—Volkswagen [4]
- "Excess weight kills any self-propelled vehicle…Weight may be desirable in a steam roller but nowhere else."—Henry Ford [5]

Since the early 1980s, US vehicle weights have increased significantly [6]. A statement from General Motors claims that about 20–40 % of this weight increase is due to the content increase (i.e., navigation, electronics, and accessories) in newer vehicles [7]. Consumer trends toward larger vehicles have also contributed to this upward trend. This increase in weight has led to a decrease in efficiency of these vehicles, even as powertrain efficiencies have improved. Automotive OEMs realize that consumers want more efficient vehicles without compromising desires; this situation has led to a heightened focus on a number of lightweighting techniques.

Vehicle lightweighting is approached through two primary strategies: (1) By using new alloys with high strength-to-weight ratios (e.g., magnesium, high-strength steels, or titanium), or (2) By using creative design strategies (e.g., stainless steels with ribbed designs, integrated material full vehicle designs). Some case studies of creative design approaches are shown in Fig. 1.2. Some of the lightweighting metals may not be as strong as the heavier metals that they are replacing, so a combination of both lightweighting techniques will commonly be used. The following examples show how different lightweight materials and creative design strategies were used to reduce weight in a vehicle without compromising strength.

- For an automobile bumper, a 20 % weight reduction was achieved using stainless steel versus carbon steel, when the C1000 Stainless Steel design included "ribs" for strengthening rather than a large cross section of the carbon steel [9].

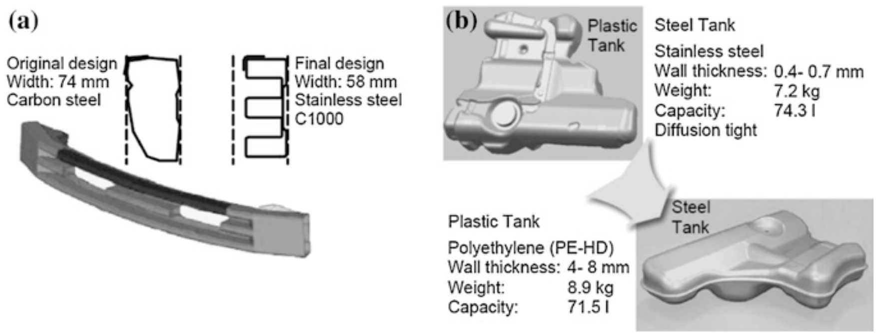

Fig. 1.2 Lightweight design strategies [8]. Using lightweight materials or creative design strategies are two main methods for lightweighting. **a** A stainless steel ribbed bumper beam [9] design saves weight compared with a carbon steel design, **b** The reduced thickness of a stainless steel gas tank [10] decreased the weight and allowed for greater capacity compared with a plastic tank. **a** Stainless steel bumper beam [9], **b** Plastic versus steel gas tank [10]

- For an automotive fuel tank, a 4 % capacity increase and a 20 % weight reduction were accomplished by using stainless steel as the tank material compared with conventional plastic used in fuel tanks, because the tank wall thickness could be decreased [10].

Aside from the two examples shown above, the overall material content used in vehicle production as a whole has changed dramatically over the last century [11]. Specifically, larger amounts of high/medium strength steels, aluminum, polymers, and even some magnesium are being integrated into all components of the vehicle (e.g., body panels, trim, engine) to reduce weight [11]. An example of this integration is the BMW X6 Sport-Activity Vehicle, which received the “Great Designs in Steel, Automotive Excellence Award” from the Automotive Applications Council of AISI’s Steel Market Development Institute (SMDI) for utilizing ultra-high strength steels (UHSS) to enforce strength without increasing weight [12].

Overall, there is a greater amount of aluminum and magnesium being implemented into the vehicles. With the limited formability of these metals compared to current automotive metals, there is the need for an efficient metal-forming technique capable of making components from these and other comparable metals in place of the current metals.

1.2 Present Forming Technologies

There are numerous techniques used in manufacturing plants today that help to improve metal formability. Within this subsection, several of the most common techniques are described and their advantages/disadvantages are discussed.

1.2.1 Hot Working

Hot working is defined as the deformation of a material at an elevated temperature. As part of this process, the metal is heated above its recrystallization temperature, thus increasing the formability of the material. Advantages to hot working include decreased flow stress and increased ductility. This is one of the simplest manufacturing methods because all that is required is a heat source, such as a heater or furnace. In many cases, however, these benefits come at the expense of part quality. One key disadvantage includes lower dimensional accuracy, due to uneven thermal expansion resulting from temperature gradients within the material. Moreover, a rougher surface finish (resulting from an oxide layer developing on the outside of the part) is another consequence of using this process. Also, as the size of the workpiece increases, larger furnaces will be needed, proving to be more costly and taking up a larger footprint on the shop floor. Further, energy use is much higher for this technique. Regardless of the minor fluctuations in part quality and cost, this relatively simple and effective process makes it a desirable choice when holding rough tolerances where secondary finishing operations will likely follow.

Using the stress versus strain graph in Fig. 1.3, the effects of hot working can be compared to a room-temperature (i.e., cold forming) compression test when forging Ti-6Al-4V. Due to hot working, the compressive flow stress was decreased and the amount of achievable compressive displacement prior to fracture was increased when compared to cold-working conditions.

1.2.2 Incremental Forming

Incremental forming (IF) is a type of manufacturing process in which a metallic part is deformed in small steps with a minor heat treatment (i.e., a process anneal)

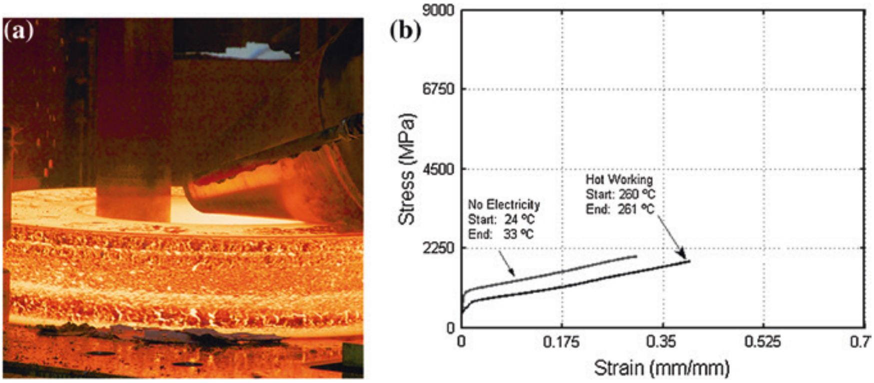

Fig. 1.3 Hot working. Parts are bulk heated to induce thermal softening, then formed at high temperature with lower forces. **a** Ring being hot rolled to increase diameter. **b** Stress–strain curve for Grade 5 Titanium showing cold working (*upper curve*) versus hot working (*lower curve*) stress profiles. **a** Hot ring rolling [13], **b** Ti-G5 hot working [14] (Figure courtesy of McInnes Rolled Rings, Erie, PA, USA)

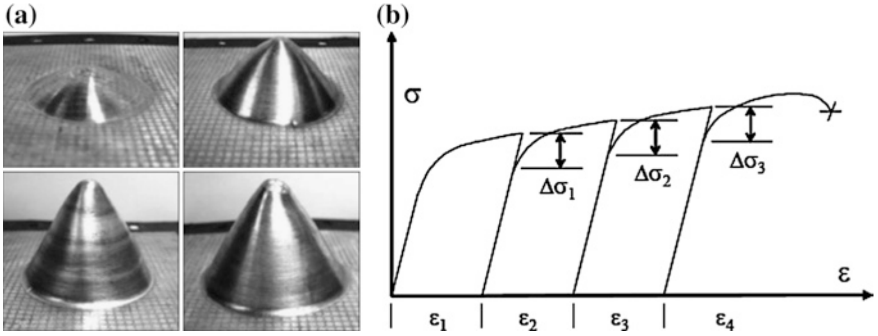

Fig. 1.4 Incremental Forming (IF): Parts are deformed in small increments, with a minor heat treatment usually performed off-line in between steps. **a** A cone is formed from a flat sheet of metal in four forming steps (increments). **b** A stress–strain schematic of an IF process

performed in between steps [16]. Figure 1.4 shows a schematic diagram of the incremental-forming process, along with a graphic of a blank at different stages of the IF process. This type of manufacturing is especially beneficial when forming brittle sheet metals and is used in the automotive and aircraft industries. The major advantages to this process are the large amounts of deformation and the decrease in the required deformation forces that can be obtained. These advantages are possible because of the minor heat treatments performed in between the increments of deformation. The treatments eliminate the effects of cold work or strain hardening by causing recrystallization to occur during each process anneal, thus resulting in a new, overall weaker material. Aside from the benefits, this process does have its disadvantages. A big downfall is the potential for low-dimensional accuracy, since the part must be continuously removed and re-fixtured before and after the heat treatments. The decreased accuracy arises from the fact that the part may not be fixtured in the exact fashion each time it is removed and re-installed. Also, this process can be very time-consuming, depending on the variables such as the number of heat treatments and their respective durations, as well as the depth of the desired deformations. Using this technique, production times are greatly increased, hence, IF may not be an optimum process for high-production or high-precision manufacturing, however, materials can be formed to great distances and complex shapes can be achieved.

1.2.3 Superplastic Forming

Superplastic forming (SPF) involves heating a material to extremely high temperatures (roughly two-thirds of its melting temperature) when deforming, as seen in Fig. 1.5. This process can produce tremendous elongations of up to 2,000 %, coupled with greatly reduced flow stress [17]. Other advantages include being able to form precise complex shapes in which minimal or no residual stresses are present. Also, lower strength tooling and fixtures can be used since the required forces

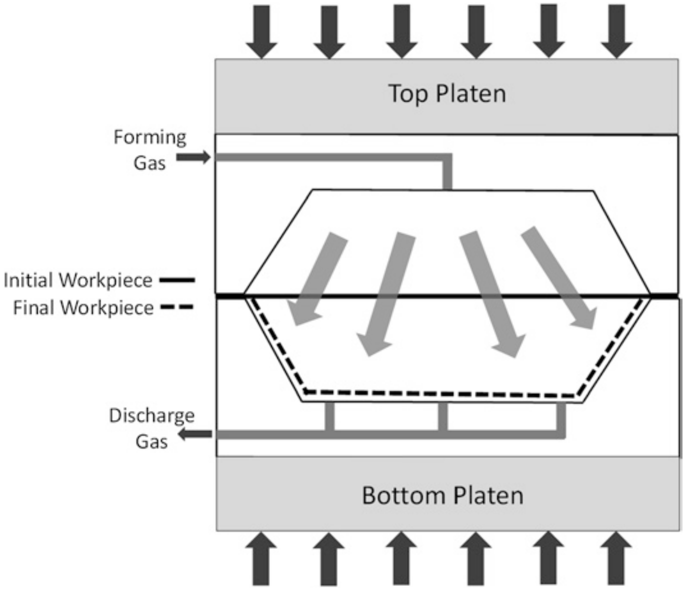

Fig. 1.5 Superplastic forming. A part is heated to roughly two-thirds of its melting temperature and formed to allow for great elongations and a formed part with very few residual stresses

for deformation are minimized. This process can be used to form complex shapes because of the very low-forming forces; however, it also has its disadvantages. First, the superplastic-forming process is only applicable for very fine-grained alloys (less than 10–15 μm), such as some aluminum (5083-FG and 7475), titanium (Ti-6AL-4V), and magnesium alloys (Mg-AZ31B). These small grains allow for GBS (grain boundary sliding) to occur at elevated temperatures, which is the primary SPF deformation mechanism responsible for the huge elongation increases. Another consequence of this process is that extremely slow strain rates must be used ($10^{-4} - 10^{-2}$ s^{-1}). Similar to the incremental-forming technique, the superplastic technique may not be practical for many high-production manufacturing applications and can be classified as a batch-forming process. Neglecting the limited number of applicable materials and the slow strain rate that is required, this process is capable of producing precise complex geometrical parts with little or no finishing operations needed. Vehicle manufacturers, such as Porsche and Aston Martin, have used SPF to form components for their low-production exotic cars.

1.2.4 Tailor-Welded Blanking

When using tailor-welded blanks (TWB's), different sheets of material (i.e., differences in material grade, thickness, or coating) are mechanically or automatically welded together before the forming process [18]. This allows the manufacturers to produce custom blanks, where strong, lightweight materials are placed where they are needed, while utilizing more formable steels in other areas, thus allowing for a relatively strong and easily formable part. However, this process can be time-consuming, costly and can result in reduced part accuracy because of all the extra manufacturing steps and associates required to prepare the blanks.

1.3 Limitations of Current Technologies

The goal of any manufacturing engineer is to produce quality parts as efficiently and cost-effectively as possible. For many common engineering metals, this can be accomplished rather easily, however, it has proven challenging with some of the stronger, more lightweight metals which are being incorporated into today's designs. These materials, such as high-strength aluminum-, steel-, magnesium-, copper-, and titanium-based alloys, all possess high strength-to-weight ratios, but their limited formability makes them impractical for use in many real-world applications that require complex part geometries. The main downfall in using these materials to make complicated shapes is the fact that, with current technology, the forming capability is insufficient, such that the forming process is extremely time-consuming and some very complex shapes may not even be able to be formed at all. In this case, numerous simpler parts must first be formed and then attached using screws, rivets, or welds, which can significantly increase the overall cost and useable lifecycle of the products.

High-production costs and poor part quality issues can result from attaching smaller, simpler parts together, making the disadvantages of using these materials outweigh their great strength-to-weight characteristics. To this end, formability-enhancing techniques are used to increase the overall efficiency of the manufacturing process, thus increasing the applicability of these materials and allowing more complex part geometries to be formed from single blanks rather than attaching many smaller components together. Formability-enhancing techniques must be devised and employed on current manufacturing methods to make them more applicable for forming lightweight metals. Experts say that extensive research, which couples materials and manufacturing engineering, is the key toward further developing lightweight engineering [19, 20]. Not only do novel manufacturing techniques need to be created and proven, but computer-aided engineering (CAE), analytical modeling, and simulations of these novel processes must be further developed in order to gain industry acceptance for a specific formability-enhancing technique.

1.4 Plastic Deformation of Metals

Plastic deformation can be classified as permanent reshaping of a metal. In plastic deformation by slip, dislocations move through the crystal structure of the metal, breaking, and reforming metallic bonds. Dislocation motion (i.e., deformation) can be hindered by defects in the crystal structure of the metal. In this section on plastic deformation, the following will be explained:

- Bonding
- Dislocations
- Crystal structure
- Lattice defects

1.4.1 Bonding

Any group of bonded atoms has an associated energy. The bonding force for metallic bonds consists of the attraction forces, due to opposing charges of the atoms, and the repulsion forces, that are due to the overlapping of the outer shells of the electrons. The equilibrium spacing is achieved by balancing the attractive forces and the repulsive forces. As these forces increase, the energy state of the bonded atoms increases, and thus, it is more willing to find another atom to bond with that will decrease the energy state. In metals, the ion nuclei (consisting of protons and neutrons) exert a net positive charge. The valence (or free) electrons (with a negative charge) surround these ion cores, creating an attraction. Note that the mass of an electron (9.11×10^{-31} kg) is much smaller than the mass of a proton or neutron (1.67×10^{-27} kg) [21]. Each ion core carries a net positive charge because its valence electrons were given up to create the “electron cloud” or “sea of electrons” that is shared between all the ion cores. The positive charge of a particular ion core and the same positive charge of neighboring ion cores lead to the ion cores having repulsive forces between them. The negatively charged valence electrons are attracted to the much larger positively charged ion cores. In doing this, the valence electrons negate these repulsive forces from the neighboring ion cores. The valence electrons create the spacing between the ion cores and absorb the repulsive forces from the same charges. Depending on the magnitude of the charge of the ion cores, a corresponding amount of valence electrons will be attracted to it.

Of the three main types of bonds (ionic, covalent, and metallic), metallic bonds are the weakest. A bond generally consists of atoms or a core, and electrons. Surrounding each atom are shells of electrons. Each shell has the maximum number of electrons that it can hold in it. The electrons in the outer-most shell are called valence electrons or free electrons because they have the ability move from one outer shell to another. If a particular atom has open spaces for extra electrons in its outer shell, then that particular atom is at a higher energy level as compared with an atom with all of the open spaces in its outer shell occupied. If the atoms have their outer shells completely full of electrons, then they will be at the lowest energy state and will not be reactive to the other atoms (i.e., the noble gases at the far right column of the periodic table). If there are openings available in the outer shell, the atom is still at a higher energy state than what it could be. In addition to missing valence electrons, the energy of the atoms could also be increased by an applied external stress. As this external stress on the atom increases, it will create an energy state higher than what the atom can withstand and will force the atom to break its bonds and reform new bonds and share valence electrons.

In essence, the classification of the bond type is dependent on how the valence electrons are utilized by the material. In ionic bonds of NaCl, the valence electrons are permanently transferred from a metallic element to the nonmetallic element. In doing so, the two elements now will have equal and opposing charges. This is a strong type of bonding because the valence electrons are not shared, but actually transferred, and each atom exclusively owns their electrons.

Materials with ionic bonding are ceramics. These materials can also withstand high temperatures, since their bonding strength is high and it would take a lot of heat to increase the energy of the atoms to cause the bonds to break.

In covalent bonds, the valence electrons are shared between multiple atoms. Methane (CH_4) is an example of a covalently bonded material, since electrons are shared between the carbon element and the four hydrogen elements. In this case, each element needs the shared valence electrons to stay bonded. This type of bond is typically not as strong as the ionic bond because the valence electrons are being shared, rather than actually being transferred from one atom to another, so several atoms own the electrons and each can have an effect on what happens to the total electron count in the bond. In the case of CH_4, if one out-of-the four total hydrogen elements (per CH_4 molecule) breaks and reforms with another set of elements, then the CH_4 molecule is now left at a higher energy state and desires another hydrogen element to share electrons.

1.4.2 Dislocations

Dislocation motion is required for plastic deformation by slip. A dislocation is simply a misalignment of the atomic structure in the lattice of a metal. There are three types of dislocations (edge, screw, and mixed dislocations). In the edge dislocation shown in Fig. 1.6, there is an extra set of atoms within the top half of the lattice. The location of where the string of atoms is un-bonded at its end is the dislocation in the lattice structure, and it is at a higher energy state as compared with the bonded atoms. As a force is applied to the metal, the string of atoms that were previously un-bonded at its end will now bond with the neighboring string of atoms in the lower half plane. This will then leave the neighboring string of atoms in the top plane, which are one atomic unit in the direction of the force, and un-bonded. Thus, the dislocation or the bonding defect in the lattice moved one atomic unit. As the bonds continue to break and reform, which is caused by the external force exerted on the metal leading to the stress exerted on the dislocation, the bonding defect (dislocation) will migrate through the metal's lattice. This overall shifting of the dislocations is termed plastic deformation. To clarify the difference between elastic and plastic deformation, in elastic deformation, the bonds are only stressed, and the lattice goes back to its original spacing once the metal is unloaded. Conversely, bonds must be broken for plastic deformation to take place. Once bonds are broken, the metal cannot go back to its original shape without re-breaking and reforming of the bonds.

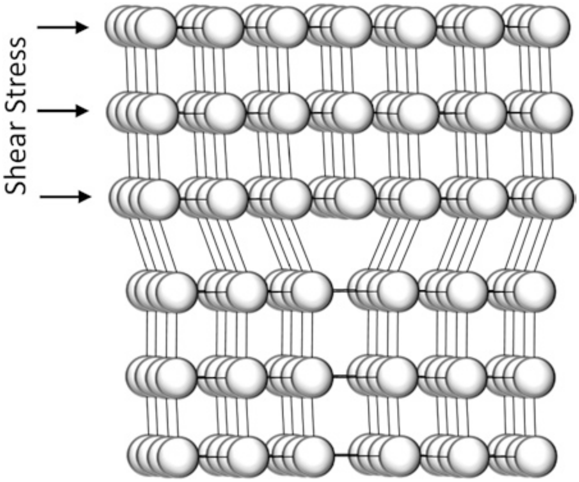

Fig. 1.6 Edge dislocation. The bonding defect in the center of the lattice, where there is a string of un-bonded atoms, is an edge dislocation

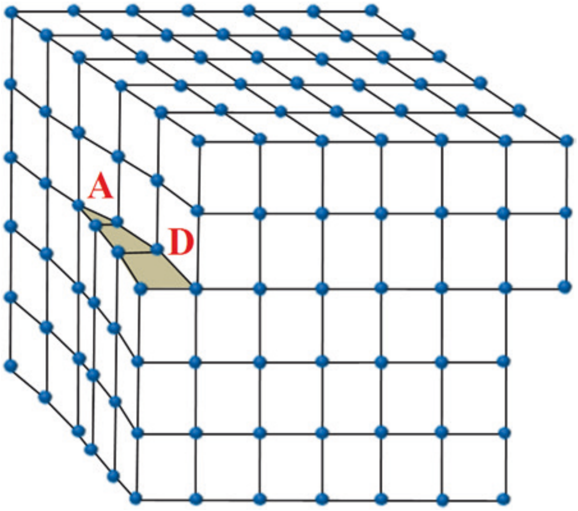

Fig. 1.7 Screw dislocation. The screw dislocation is created by a shear stress that causes the lattice above or below the shear line to advance one atomic spacing unit

The second type of dislocation is the screw dislocation, as seen in Fig. 1.7. In this type of dislocation, there is a step or ramp shape that is created due to the external forces. As seen in the figure, the external forces create a shear stress that moves the front upper region of the lattice one atomic spacing unit past the front bottom region. As you examine the depth of the lattice, a screw-like "ledge" is formed since the front region shifted a complete atomic spacing unit and the rear region did not yet. As a greater amount of shear force is exerted, the neighboring bonds near the front region will become more stressed and will likely break and reform to enable this shift to move its way along the depth of the crystal structure in the figure.

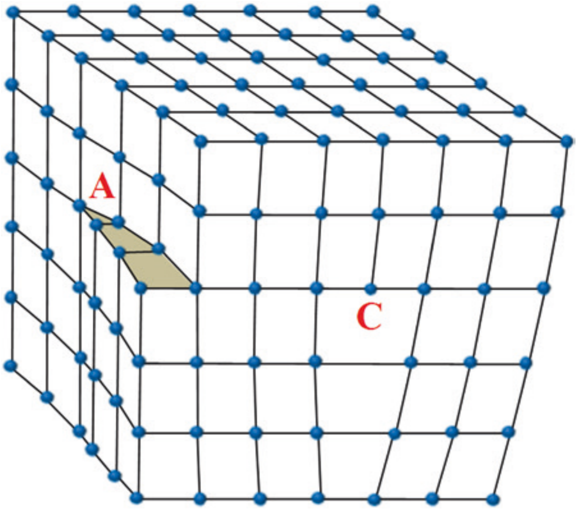

Fig. 1.8 Mixed dislocations. Mixed dislocations are a combination of edge and screw dislocations

The third type of dislocation is the mixed dislocation, as shown in Fig. 1.8. Most of the dislocations in metals are mixed dislocations, since they may consist of multiple lattice defects that are representative of both edge and screw dislocations. In the figure, as the force is exerted at point A, the bonded atoms at the location of where the force was applied break bonds with the aligned atoms and reform bonds with the atoms one atomic spacing in the direction of the force to cause a screw dislocation. This causes one set of bonded atoms in the top half of the unit cell to now be un-bonded, which is shown by the edge dislocation at point C.

Regardless of the dislocation type, the number of dislocations within a metal increases as the level of plastic deformation increases. This is because the dislocations do not only move through the lattice, but new dislocations are created at lattice defects. A dislocation line can be classified as an un-bonded string of atoms. A defect in the lattice disrupts the equilibrium bonding of the lattice. If forces are exerted on the lattice and bonds must consistently break and reform, this disruption by the lattice defect can create bonding inconsistencies in the form of dislocations, because of the extra energy needed to break and reform bonds around this defect.

There are certain “pathways” that dislocations can move throughout a metal’s lattice. These pathways are called slip systems. The dislocations travel on slip systems, which are comprised of slip planes and directions, and are specific to the particular crystalline structure of the material. While traveling on these slip systems, the dislocation motion can be hindered by different interfacial defects within the lattice. Such defects include impurities, voids, grain boundaries, faults, and other dislocations. As these obstacles hinder the dislocation movement, the dislocations begin to pileup, thus increasing the forces needed to continue plastic deformation. This phenomenon is known as strain hardening. In order for the dislocations to be able to surpass the obstacles, additional energy is required to force the dislocation past the defect. In order for the dislocations to continue moving, there must be enough energy to: (1)