PRODUCTION TECHNOLOGY AND PRODUCTION SYSTEMS

1 Introduction

Countries have expressed their commitment to realizing carbon neutrality and are tightening their regulations. It is not a stretch to say that the automotive industry is undergoing a once-in-a-hundred years transformation spearheaded by the connected, autonomous, shared, and electric (CASE) concepts. In addition, as high safety awareness and demand and the need for cybersecurity measures require vehicles to include more functions, automakers continue their efforts to provide unique, attractive, and competitive products in ever shorter time frames and at ever more reasonable prices. Diversifying customer preference has increased the need for product services that satisfy customers. Working practices have been also reformed to instill worker satisfaction. Accordingly, building people-oriented car manufacturing and production systems has become important. Achieving such systems calls for performing all types of work effectively and establishing a framework enabling people to pour their efforts into developing technologies and creating new added value is a major challenge. Advancing model-based development (MBD), as well as the digital transformation (DX) that builds upon AI, IoT and others digital technologies, has become crucial.

2 Vehicle Production Engineering (PE) Technologies

2. 1. Stamping

Needs related to vehicles have been changing greatly in recent years, leading to intensified electrification-oriented development aimed at decarbonization through the realization of carbon neutrality. Reducing weight is essential to increasing the cruising range of electric vehicles (EVs), which have seen a surge in sales over the last several years. However, improvements in driving comfort and safety have tended to increase vehicle weight. This has placed continuously higher expectations on enhancing fuel efficiency by reducing vehicle weight.

The stamping process is a product manufacturing process that uses dies to stamp and form steel sheets. Forming technologies have refined to realize lightweight, high rigidity vehicle bodies that contribute to vehicle performance and fuel economy, as well as exterior surface quality and design shapes that accentuate the vehicle colors and the play of light.

The field of stamping requires technological advances permitting the adaptation of vehicle structures to electrification, as well as the expanded application of ultra-high tensile strength steel sheets (ultra-high tensile strength materials) and aluminum alloy materials to further reduce weight. In addition, globally equivalent production technologies that make it possible to use local materials and resources and flexibly cope with the fluctuation of part production volume are becoming more important to bring vehicles that meet the need of customers to market early in just the right way.

Ultra-high tensile strength 980 MPa or higher class materials have increasingly been used to reduce weight, with automakers and material manufacturers also developing forming technologies for materials in the 1.5 GPa or higher classes. They are working on improving estimation accuracy by developing a forming simulation technology that accounts for changes in the sheet thickness direction during stamping and the impact of die and stamping machine deflection. They are also working on equivalent quality rapid mass production relying on evaluating and incorporating objective indices through the visualization and quantification of surface quality.

Growing demand for reduced weight to achieve carbon neutrality in creating an increased need for forming technologies that can handle ultra high tensile strength and aluminum materials. In terms of life cycle assessment (LCA), other critical issues the entire automotive industry must promptly tackle throughout the supply chain are the full use of steel as an inexpensive and versatile, the reduction of the weight of dies, and the conservation of energy during stamping.

2. 2. Welding

Increasing EV cruising range requires significant weight reduction over the entire vehicle body. As customer needs for enhanced passive safety and maneuverability grows, improving vehicle body strength and rigidity while simultaneously reducing weight is a critical issue.

The body welding process involves aligning hundreds of stamped steel sheets and welding thousands of spots to gradually assemble a body-in-white (unpainted body shell) from small parts. Resistance spot welding constitutes the primary form of welding, and it is automated using robots.

The LCA provides a key index for assessing energy consumption and CO_2 emissions throughout all stages of the life cycle of a product, making the establishment of basic technologies to reduce CO_2 in manufacturing processes an urgent necessity. Manufacturers are working on optimizing processes through the applied welding current control (controlling the welding current while monitoring nugget formation), optimizing power sources, and making the processing and assembly processes more efficient (consolidating processes and improving processing speed).

Multi-material structures are becoming more common in premium cars. Despite the attention they receive, self piercing rivets (SPRs), friction stir welding (FSW), and laser welding present major technical obstacles that prevent their widespread use in mass production vehicles. Therefore, welding and joining technologies relying on other methods, such as adhesives and friction stir welding, must be developed.

Steel sheets are the primary material in mass-produced vehicles, and the use of ultra-high tensile strength steel sheets (1.5 GPa hot stamped material and 1.2 to 1.3 GPa cold ultra-high tensile strength material) is increasing.

In production processes, the introduction of collaborative robots, automated logistics, and automated inspection and measurement are part of efforts at further automation intended to address the upcoming labor shortage. Furthermore, the processes as a whole are digitized (modeled), with expanded theoretical examination and automation using a digital twin and model-based development serving to significantly reduce, the mass production preparation period. Information obtained from plants is increasingly applied to tasks such as preventive maintenance and quality control (automatic inspection technology). Making use of the big data obtained from those tasks and of AI is yielding more sophisticated approaches to raising work efficiency, reforming working practices, and improving quality.

A major challenge for the field of welding production will involve finding ways to cope with large changes made in vehicle structures and production processes to respond to market needs and achieving carbon neutrality.

2. 3. Plastic Molding

Resin, which is lightweight and flexible in shape, is widely used primarily in vehicle interior and exterior parts and structural parts. Resin is expected to fill an increasing variety of roles, including further weight reduction to accommodate the accelerating pace of electrification, as well as the refinement of the styling and sense of quality of the interior and exterior.

Weight reduction efforts involve the use of carbon fiber reinforced plastics (CFRPs) mainly for the outer panel parts and body frames of high-end sports cars and EVs. It has also recently been used for hydrogen tanks, which require ultra-high pressure resistance. Expanding the use of CFRPs requires addressing the crucial issue of reducing energy consumption in the carbon fiber manufacturing acrylic resin sintering process, as well as in the pre-heating and other part manufacturing processes.

Design trends include combining plated parts and plastic in bumpers—the face of the vehicle—to create a powerful form, as well as reducing the step size from the body panels to give a strong impression of continuity at the joints. In interior parts occupants can touch, urethane foam is also used in the instrument panel and rear seat door trims of low-cost vehicles to provide a soft texture, while combinations of plastic and different materials such as wood and aluminum are used to offer a high sense of quality and greater diversity in high-end vehicles.

Plastic molding ranges from the most common injection molding to hot pressed, sheet molding compound (SMC), and other various forming methods. Improving dimensional accuracy is one of the most important challenges in achieving weight reduction and sophisticated designs. The nature of the materials and methods involved in heating or melting resin, or inducing chemical reactions in it, make it impossible to avoid contraction deformation in the curing process. Therefore, techniques to estimate and control that deformation are required. Production design and process design based on CAE have been carried out for a long time. Joint model-based research (MBR) efforts have also been initiated by industry, academia, and the government.

Technologies that foster innovative approaches to realizing carbon neutrality will bear watching. One such technology involves multi-material structures that takes advantage of the characteristics of resin and metal. Adhesive materials and surface treatment are being developed to join dissimilar materials, but have to overcome issues of strength and mass productivity. Another technology consists of a method to replace painting. A new method that sets a film after plastic molding is under actively developed, and will require advances in technologies to consolidate processes such as in-mold coating/film insert molding that are used for some small parts.

2. 4. Paint

The vehicle painting process includes coating the vehicle surface with layers of base, intermediate, and final paints, imparting a good appearance, through beautiful colors and finished surfaces, as well as durability in terms of protecting the vehicle body from rust and stone chipping.

The COVID-19 pandemic and other factors have led to changes in how people spend their leisure time and diversified their tastes and preferences over the past few years. This has also led for a demand for individuality of vehicle appearance that reflects user preferences. Color-related needs are also broadening, with the colored clear coating providing vivid and deep colors for sophisticated designs complemented by the multi-tone colors mainly used on compact vehicles and, more recently, earth tones reflecting the SUV boom. Achieving electrification and carbon neutrality requires an extensive reform of production methods extensively as well as flexibly meeting diversifying market needs.

The painting process has booth equipment that provides a clean and air-conditioned environment at a temperature and humidity appropriate for spraying, and drying furnaces that create a strong coating film through the cross-linking reaction caused by heating the paint applied to the vehicle body. Each of those large long facilities emits a considerable amount of CO_2. Moreover, the painting process is the largest source of volatile organic compound (VOC) emissions among vehicle manufacturing processes. Therefore, vehicle manufacturers have prioritized decreasing VOC emissions in the context of the industry-wide issue of reducing substances of concern. Decreasing the amount of VOCs is being achieved through the development of hybrid waterborne intermediate and base coat paints, high solid clear paints, and other materials containing fewer VOCs, as well as through the introduction of devices to treat emissions and more efficient waste collection as part of measures to reduce the amount of VOCs produced by painting facilities.

Waterborne paints, which represent the main measure against VOCs emissions, require a lot of energy to control booth air conditioning and treat emissions, creating a conflict with efforts to reduce CO_2 emissions. Consequently, three-layer wet painting, two-layer coating with no intermediate coating, and other means of shortening the process by consolidating the functions of paint or equipment have recently become mainstream to reduce both VOC and CO_2 emissions. Increasing efficiency using through compact facilities and space-saving layouts is another effective solution. Such efforts to significantly reduce air conditioning energy consumption by decreasing the amount of absolute air consumption include airless spraying devices that improve coating efficiency, better paint mist collection, and the use of dry booths to shrink booth volume.

Reaching carbon neutrality will require technical development to support highly efficient facilities and reinvented processes that take CO_2 reduction to another level. Efforts already undertaken include recycling heat energy, lowering sintering temperature for final and base coats by developing technology for a low temperature curing process, eliminating the drying furnaces used to dry sealers and undercoats, and developing films and adhesion methods to replace painting.

2. 5. Vehicle Assembly

Vehicle assembly is the final process, and involves building completed vehicles by assembling various types of parts onto painted bodies. Typical vehicle assembly lines handle the mixed production of various vehicle models and variants. The variety of parts assembled using different processing methods (e.g., fitting, fastening, bonding, press fitting, or injection) calls for a flexible assembly process. Accordingly, vehicle assembly is characterized by its high degree of dependence on human intervention and its emphasis on creating processes and facilities that enable the production of various vehicle models.

The ongoing diversification of market needs (the growing demand for SUVs and gradual transition to HEVs and BEVs) has been magnifying the difference in vehicle structures on mixed production lines. The growing number of part types and expanding differences between variants are making it difficult to achieved leveled workloads. Electrification, typified by HEVs and BEVs, presents a notable production strategy planning challenge due to the many factors that need to be considered to make development and production plans, including the speed of technological progress, the diversity of structures, the balance of supply and demand, and issues surrounding the social infrastructure. In addition, the increase in tasks involving the assembly of new parts such as high-voltage components or sensors is imposing a burden on activities to ensure worker and work process safety and quality. This backdrop has created a growing need to revamp the vehicle assembly process based on fresh and unconventional thinking, and automakers have implemented various initiatives.

A new form of automation relying on robots that coexist and cooperate with people to take over heavy workloads, as well as powered suits and devices that assist with the assembly of heavy components, are being introduced to reduce the burden on workers. People-friendly parts supply methods are also being created. One example is a system that supplies prearranged assembly parts to the line (eliminating the need for workers to walk to, look for, and select parts), thereby reducing assembly errors and the task burden. Such methods are applied in creating processes that ensure safety and quality even in the face of unstable labor conditions outside Japan or of labor shortages due to the global decline in birthrate and aging of the population.

The entry of new competition from other industries is accelerating the transition to EVs, and intensifying the importance of creating competitive products. This situation is pushing automakers to put extra effort into further improving their longstanding technologies by, for example, leveraging data and applying high-precision assembly to introduce techniques that improve appearance quality and suspension performance.

2. 6. Vehicle Inspections

The vehicle inspection process involves ensuring compliance with regulations of destination countries as well as quality to meet customer need, and ensuring uniformity of products to type approved vehicles. Inspections items are increased as automatic braking and other advanced safety technologies are widely used.

In this vehicle inspection process, certified inspectors perform a complete inspection on the basis of the present vehicle type approval system. However, labor-saving measures and enhanced efficiency in complete inspections have become urgent issues due to the labor shortage resulting from declining working population in Japan.

One promising means of solving the problem is the use of systems incorporating AI or other advanced technologies capable of taking over the complete inspections that relied on the checks and judgment of inspectors, assist their work, and check conditions. The use of such systems is also anticipated to improve quality thanks to a higher inspection accuracy resulting from uniform and stable task performance.

These circumstances have prompted the Ministry of Land, Infrastructure, Transport and Tourism to draw up a guideline for automated complete vehicle inspections. The "Refining Regulations Based on Social Implementations of Digital Technologies" section of the *Action Plan of the Growth Strategy* (approved by the Cabinet in July, 2020) proposes in that "with regards to all processes of the inspection for checking the conformity to each approved type (hereinafter referred to as complete inspection), regulations premised on complete inspection personnel will be reviewed if it can be confirmed that the level of inspections using AI, etc. are equal to or higher than inspections performed by conventional complete inspection personnel."

In response, Japanese automakers initiated demonstration projects based on applications received in 2020 by the New Energy and Industrial Technology Development Organization. Requirements for the automated complete inspection were then studied, and a notice on reforming the system was made public on November 30, 2021.

The need for labor-saving measures and enhanced efficiency in complete inspections will continues to rise, spurring more active efforts to develop automated systems and introduce them into actual production processes.

3 Powertrain (PT) Production Technologies

3. 1. Casting

The casting process involves melting metallic materials and forming them in to required shapes. It consumes more energy and emits more CO_2 than other manufacturing processes. Achieving carbon neutrality in our society requires reducing energy consumption in the casting process and switching to decarbonized energy. Therefore, the entire industry is tackling this issue.

Reducing energy consumption must be prioritized. Steadily developing new materials in parallel with the electrification of plants and establishing the smallest and shortest possible casting processes is extremely important. Specific measures such as replacing cupolas with electric furnaces, establishing plant waste heat recovery technologies, decreasing the frequency of melting through improved manufacturing processes, increasing yield by reducing product weight, eliminating heating processes and using of low melting point materials (aluminum and magnesium instead of iron), and using inorganic binders for casting molds are steadily being implemented. The pace of the development of energy-saving measures will need to be accelerated.

The situation around the automotive industry has been changing dramatically with respect to protecting the environment, and expectations placed on cast parts have also changed significantly. In practice, cast parts are not expected to be complex, large, and thin-walled, as well as formed without processing and designed to accommodate the electrification of vehicles and lighter vehicle parts. With such requirements raising the difficulty of casting, there is a need for further greater dimensional accuracy, temperature control during casting, and highly accurate advance verification technologies. Achieving high quality and low cost in the shortest possible lead time and fewest possible work hours to bring such high difficulty cast parts to market effectively has become a critical issue. In particular, it is important to expand the application of MBD to various types of work including production requirement study, mold design and fabrication, casting tryouts, quality confirmation, and modification tryouts to achieve both functionality and productivity without creating physical products for the casting process in preparation for mass production. This requires theoretical modeling. Phenomenons must first be correctly observed, and this requires sensing technologies and measurement technologies related to control factors and parameters. Moreover, process stabilizing technologies that use AI and collected big data need to be developed.

In the future, it will be important to extend MBD-based manufacturing beyond the field of casting to the development and production (casting, processing, and assembly) stages, as well as to part manufacturers, and make it the basis for manufacturing the best products at every step.

3. 2. Forging

The requirements for lighter forged parts are also intensifying in response to the spread of vehicle electrification. At the same time, reducing energy consumption is taking on greater importance at forging plants, and the use of waste heat produced by forging is being studied. Efforts to solve such problems rely on digital technologies.

Forging has the benefit of imparting high strength and high toughness, and is therefore often used for parts designed to transmit power transmitting or bear loads. Lightweight engine crankshafts and connecting rods have been developed to reduce inertial force. One example is the development of a material that promotes more precipitation strengthening than conventional materials, used in conjunction with improved yield strength achieved by controlling the cooling speed after forging, to create a lightweight connecting rod.

Other reported weight reduction efforts include highly complex shapes with thin walls and an acute draft angle, and hollowed-out motor shafts. These examples require more advanced forming techniques than ever before. There are also initiatives to reducing weight by forging light alloys. In chassis parts, aluminum forging is becoming widely used to improve vehicle maneuverability in addition to reducing weight. Aluminum sheet forging, and plastic fastening with an iron sheet in combination with the forging have also been attempted.

Shapes with higher degrees of complexity result in increased forging loads and reduced yields. Reducing energy consumption must therefore address the issues of molds and process design that minimize the amount of material used. Moreover, in forged aluminum chassis parts, which are critical safety parts, weight is reduced while also aiming to increase strength. Obtaining the intended strength requires identifying forming conditions not just for alloy components, but also for forging temperature, plastic deformation, and other factors. Advancements in CAE and measuring technologies has improved estimation accuracy, while MBD provides an effective means of overcoming the challenges of obtaining complicated shapes and the required strength in aluminum forging.

At the same time, some production sites are applying data to expand sensing functions and conduct real time analysis based on data collection and the use of AI. Such initiatives produce higher quality and rates of operation that lead to highly efficient production and consequently helps reduce energy consumption. Furthermore, the use of waste heat from forging as heat energy for thermoelectric elements or binary power generation is also being investigated.

3. 3. Machining

Amid increasingly fierce competition, products that meet diverse customer preferences need to be provided to market in a timely manner. In parallel with electrification, fuel efficiency and reduced weight are pursued as aspects of product functionality. At the same time, efforts to reduce energy consumption have also become essential on production lines.

The equipment that makes up a machining line has been transitioning from dedicated devices for individual processes to general-purpose devices enabling flexible line configurations. This change has made it possible to mass-produce various types of products in a short period of time compared to the previous configuration. Standardizing equipment, tools, and machining conditions, and creating a system that clearly defines the fixed and fluctuating factors of various products, is important to build flexible machining facilities with low investment.

In newer products, resin materials and metallic materials with high strength, high rigidity, and high toughness are actively used to enhance functionality and reduce weight. Control that senses the states of various equipment during machining and gives feedback on the results to the machining operation has been introduced to achieve high-precision machining of such highly difficult to grind materials. Diversified needs also make it necessary to produce various types of power units on the same production line, and combined processing machines and gear cutting processes formerly implemented with dedicated processing machines are being introduced.

Automakers are working on reducing energy consumption not only by optimizing output through even more accurate inverter control of the motors and pumps and decreasing electricity consumption by expanding the stop range, but also through regenerative drive energy, making adjustments to cutting conditions and cutting tool shapes, and shortening machining time. Efforts to shorten the time to market are also underway as part of the mass production preparation process. Assessment efficiency is being raised by using the same 3D model, and sharing it with suppliers, throughout the entire process, and simulations are increasingly used to cut down evaluation performed with actual vehicles.

3. 4. Heat Treatment

Heat treatment is an important vehicle part manufacturing process that contributes to forging and machining productivity, as well as to reducing the size and weight of products, by changing the mechanical properties of steel. Product electrification needs are increasing to realize a decarbonized society, and it has become necessary to produce a greater variety of speed reducers than before while keeping the environment burden low.

Speed reducer gears are mostly produced by carburizing and quenching. This is process is widely applicable to obtain the various types of durability performance required in automotive parts. Strength against bending and torsion increases with the depth of the hard layer obtained through carburizing and quenching. Such high strength is obtained by continuously heating parts for a long time. The use of carburizing and quenching requires processing a large number of parts at the same time. This makes having an intermediate stock of parts between machining processes essential, increasing the amount of space necessary on plant premises due to the higher quantity of applicable parts.

The automotive industry as a whole is replacing the previously mainstream gas carburizing furnaces with vacuum carburizing furnaces, and this has led to reports of achieving a 50% reduction in CO_2 compared existing processes, as well as of significantly reducing the time required for heat treatment by integrating it into the machining process. In terms of product quality, gear face grinding is typically used to address heat deformation and achieve high levels of strength and quietness, but poses the problem of requiring a prolonged heat treatment to obtain a hard layer extending to the margin. The upcoming challenge will be to find a fundamental solution to that problem and shorten the heat treatment time.

Although the deformation during the carburizing and quenching applied to obtain high strength is inevitable, it is possible to produce high-precision parts by eliminating variation in that deformation, and by predicting and factoring it before applying the heat treatment. Consequently, the approach proceeding entirely in small lots and quenching one part at a time to reduce variation in deformation is gaining attention.

Heat treatments affect all manufacturing processes and impact product reliability. Automakers need to take the initiative in activities that integrate product development and manufacturing processes, and implement that significant reform.

3. 5. Powertrain Assembly

The latest stricter environmental regulations are leading to the electrification of units, resulting in a higher number of parts and types for powertrain units. That increase is also concurrently significantly enlarging the difference in assembly task time between unit types. The difficulty of predicting production types and volume fluctuations also causes productivity to decrease. Minimizing the impact of such fluctuating models and volume on the cost of mixed model production requires constructing a mixed model production system that quickly responds to model changes and additional models of power train units, as well as fluctuations in production volume.

Unit assembly was originally a manual process to ensure flexibility in mixed model production. Automated assembly was generally limited to high-precision assembly and fastening, functional assurance, and tasks calling for ergonomic considerations because of heavy burden they put on assembly workers. Automakers are implementing combinations of measures such as creating products that incorporate production and functional requirements, gate management using equipment that ensures assembly line quality and functionality, and measures against human error to prevent any deterioration in quality assurance levels. In the future, it will be necessary to cope with the labor shortage resulting from the declining birthrate and aging of the population and ensure the quality of complicated products. Accordingly, technologies to automate the assembly and inspection work that has depended on skilled workers in-house is becoming a critical issue. Addressing that issue requires automakers to improve their production systems by both increasing the flexibility of automated processes and reducing capital investment through a combination of general-purpose robots, including AGVs and collaborative robots, and modularized/standardized software. They must also expand the scope of mixed model production technologies by combining sensing, image processing, and AI technologies.

Introducing these new technologies into mass production in response to changes in products requires a high degree of flexibility and efficiency not only in production systems but also in production preparation systems. Therefore, the use of digital technologies is not limited to the centralized management of design and process information. It also extends to fostering product quality and enhancing facilities through the visualization of manufacturing KPIs using production real time information (quality and operation information) and feedback provided to the product and process design departments.

Electrification will continue to expand rapidly, making it important to combine the accumulated expertise in mass production technologies for powertrain units and the latest technologies in the electric unit field, and to build unit assembly lines that are versatile and also enable the low-cost production of powertrain units as a whole.

4 Digital Technologies

MBD has started to play an important role in the efficient development of hundreds of thousands of vehicle component parts. It is applied to not only the product design and production processes, but also to the production lines and production facilities. Moreover, MBD is expanding to various fields, as exemplified by the digitalization of the information for the entire plant to assess productivity. The Japan Automobile Model-Based Engineering Center was established in September 2021 by administering members consisting of five vehicle manufacturers and five parts manufacturers, all from Japan, to promote MBD in the Japanese automotive industry. This organization aims to build a state-of-the-art development community that serves the mobility society by implementing totally optimized and sophisticated manufacturing in a highly efficient manner and without rework. Model-based development will connect the engineering chain between completed vehicle manufacturers and part manufacturers to achieve further development efficiency.

Various digital technologies have replaced the traditional gathering of parties involved in meetings and actual visits to work sites that were prevented by the COV-

ID-19 pandemic, and these effective approaches that eliminate the need for business trips will remain in use. Advances in AI and robotic process automation (RPA) are enabling the building of systems that robotize routine work and free people to focus on things they need to do. This is expected to foster further support for engineers and dramatic improvements in efficiency in non-technical departments. In the field of plants, digital transformation (DX) is enhancing the connected plants and cyber physical systems (CPSs) activities started with Industry 4.0. Ultimately, expanding DX to the entire industry will constitute an important step toward carbon neutrality.