Die Concepts and formability for simultaneous forming of sheet metals and FRPs

X F Fang, T Kloska and A Hajdarevic
Institute of automotive lightweight design, University of Siegen, Germany
E-mail: Xiangfan.fang@uni-siegen.de

Abstract. Fiber-reinforced plastics (FRPs) are increasingly being used to reinforce steel or aluminum (Al) automotive structure components. Currently, these multi-material applications are realized via three-stage manufacturing, which require the corresponding costs. Thus, a new hybrid forming technology has been developed and will be presented here. It is based on the principle of the hydro-mechanical sheet metal-forming technique and uses a heated thermoplastic FRP material (up to 280 °C) in a half melting state as the pressure media to form steel or aluminum sheets. Since the sheet metals are pre-coated with an adhesion promoter, the FRPs are also joined with the sheet metal during this hybrid forming process. In this work, the die and especially the sealing concepts for hybrid forming will be introduced based on different part geometries. The formability of the sheet metals (Nakajima test) at different temperatures up to 280 °C, for each two steel and Al alloys, will be presented. The hybrid formed parts were analyzed using optical method and section analysis. Good forming results were confirmed for both sheet metal and FRPs. A vehicle chassis component was successfully hybrid formed using CP-W800 steel and FRP, and a body component was produced using an Al5182 alloy and an FRP.

1. Introduction
Lightweight design is one of the most important measures to reduce fuel consumption of vehicles using internal combustion engines (ICEs) or extending the driving range of pure battery electric vehicles (BEVs) [1–3]. For ICE vehicles, a fuel consumption reduction of 0.3 L/100 km was determined for a primary weight reduction of 100 kg. For BEVs, a 100kg weight reduction may increase the driving range by 4% in urban traffic [3]. To realize economically acceptable lightweight designs, vehicle body-in-white (BIW) structures are increasingly being built using multi-material designs consisting of steel, aluminum (Al), magnesium, and fiber-reinforced plastic (FRP) [4,5].

The multi-material designs in [4, 5] were both realized using the so-called “post molding assembly” (PMA) and “in-mold assembly” (IMA) approaches. In the PMA process, metal and FRP components are initially manufactured separately and then joined together in a third assembly step. Here, the matching of the two parts is a problem due to different part tolerances, in addition to the increased costs due to the usage of three separate manufacturing steps. In contrast, in the IMA process, a preformed sheet metal part is over-molded by FRPs using, for example, the injection molding process. Alternatively, either a heated thermoplastic or thermoset prepreg can be placed in a preformed and preheated sheet metal part and formed by a well-sealed press die [6]. After the FRPs are press-formed, an adhesive bonding can be created as well when the sheet metal is pre-coated using an adhesion promoter such as VESTAMELT (company Evonik) [7] or adhesion film from company Nolax [8]. Here, the step of making a pure FRP part is eliminated.
To further reduce the processing cost of IMAs, the forming of FRPs and sheet metals or organo-sheets was carried out in the same die but at a separate time step for the injection molding process [9,10]. However, these types of processes were only realized for very simple geometries, such as rotational symmetrical parts made from low-strength mild steels [9]. For high strength steels or even advanced high strength steels and complex geometries, this process has not been realized.

In addition, due to the extruder of the injection molding system and the very small section size of the injection nozzle, the long fibers of the thermoplastics are cut or broken into short fibers with fiber length much lower than 1 mm. Compared to injection molding, compression molding of FRPs results in much longer fiber lengths in the final parts. In addition to plastics with short fibers prepared by the extruder, additional long fibers are placed at the very end of the extruding process (figure 2). These thermoplastics with longer fibers (up to 25 mm) are then press-formed in a well-sealed die to form the desired part. Moreover, since the fibers are only subjected to shear stress when filling the die cavity (no nuzzles), the fiber length degradation is significantly reduced compared to injection molding. Fiber lengths of up to 10 mm could be achieved for a PP glass fiber (GF) material [11], which is thus referred to as long fiber thermoplastic (LFT). According to [12], the material properties significantly depend on fiber length. As shown in figure 1 (a), the stiffness of the materials increases significantly up to ca. 1-2 mm while the strength increases considerably to more than 10 mm. The impact resistance may even increase further with longer fibers of up to ca. 50 mm length. Therefore, in addition to the LFTs with fiber lengths restricted to a maximum of 10 mm in the final part, glass mat thermoplastic (GMT) materials were also investigated in this work. GMT material contains glass mats with very long fibers in the order of 50 mm in addition to the short fibers, and may significantly further enhance impact resistance.

![Figure 1. a) Influence of fiber length on mechanical properties of FRPs [11], b) estimated weight of rectangular profiles for energy absorption (for axial crashing) using metal and metal-FRP (glass fiber) composite (100 KJ energy input)](image)

Although FRPs may have high stiffness and strength at a lower weight, they fail suddenly without warning when cyclically loaded. Moreover, if they are overloaded, the car driver may not directly recognize the damage. In contrast, metals show crack formations and stable crack growth during cyclic loading and plastic deformation at overloading; these can be easily recognized due to changes in vehicle driving behaviors. These kinds of properties of metals are called fail-safe.

2. Principle of the hybrid forming method

Due to the lack of fail-safe behavior of FRPs, the idea of hybrid forming was developed to produce a metal-FRP multi-material component with material-based large-area joining between metal sheets and FRPs [11]. The FRP may have different thicknesses and rib structures to effectively reinforce the sheet metal panels. In this way, the lightweight potential of FRPs and the fail-safe behavior of metals can be combined. In addition to the fail-safe properties, the FRP-metal hybrid may absorb higher energy during a crash since FRPs generally possess much higher energy absorption capabilities than metals (figure 1 (b)). Therefore, these kinds of hybrid materials are highly suitable both for vehicle chassis and body applications. Furthermore, the well-known hydro-mechanical sheet metal forming and FRP compression
molding techniques can be combined to make such kind of multi-material parts in a one-step process and, thus, be very cost-efficient.

During the well-known hydro-mechanical forming process, the sheet metals are deformed by the hydrostatic pressure of the pressure media, such as water or oil, in a well-sealed die cavity. Since the thermoplastic composite materials for FRP compression molding, such as PP or PA (with fibers like GF), are in a half-liquid state before compression molding, they can also be used as pressure media. This combined method is called the hybrid forming of sheet metal and FRPs [11].

In figure 2, the entire process chain of hybrid forming is illustrated. In the first step, the long fibers with ca. 50 mm length are mixed with the extruded short fiber materials at the end of the extrusion process. This material, which was in a half-liquid state, is then placed onto the sheet metal blanks (e.g., steel or Al) that have already been positioned in a forming die. The sheet metal blanks are pre-coated with a bonding agent, for example, VESTAMELT (Evonik), in this work [7]. The sheet metal blanks are preheated in an oven between 180 and 220 °C to activate the bonding agent, while a PA GF 40 should have a temperature of approx. 280 °C, and a PP of 220 °C. Instead of direct feeding from an extruder, also pre-extruded LFT or GMT materials can also be reheated in an IR-heater and subsequently placed onto the sheet metal blanks. Therefore, the process can also be applied by all metal forming companies having a hydraulic press and an oven or IR heater.

In the third step, a special sealed hybrid forming die forms the LFTs or GMTs with the sheet metals simultaneously. At first, the punch presses and forms the LFT/GMT material, and the LFT/GMT on the other side forms the sheet metal. Since the LFT/GMT materials are enclosed by die sealing, high pressures are created, which finally form the LFT/GMT over the entire surface of the sheet metal with a pre-defined thickness, and the sheet metal is formed to the final shape as well. In the same time, ribs for reinforcement and functional integration are formed. In the final step, after ca. 20 s die closing time (when the LFT/GMT is cooled to ca. 80 °C), the adhesive bonding of the materials is completed, and the part can be removed from the press.

Figure 2. Process chain of hybrid forming of sheet metals and FRPs.

3. Forming and sealing concept of the hybrid forming die
Real vehicle parts in BIW have very complex 3D geometries. In order to develop generic forming and sealing concepts, which are the most challenging aspects of a hybrid forming die, a tube geometry and a U-profile with two open ends were studied. The second one serves as the basis for complex 3D curved open ended profiles with different widths and draw depths, which is currently being developed. Furthermore, for the open end geometry with a uniform draw depth and width, a simplified sealing concept has been already developed. The general requirements for die sealing is that it should prevent LFT/GMT press-outs, while the formability of sheet metals should not be impaired.
3.1. Tube geometry
In figure 3 (a), a tube geometry with different draw depths, radii, and closed ends is illustrated. The target is to evaluate the formability of sheet metals during hybrid forming, especially with regard to whether the geometry transitions can be formed by LFT pressure and if the LFTs may be pressed out when wrinkles appear in the four corners of the part. Similar to a deep drawing die, draw beads were introduced, which may control both sheet metal forming and wrinkle formation. They should also prevent LTF or GMT press-out in addition to the blank holder. The designed die can be seen in figure 3 (b). The blank holder was supported by a die cushion with adjustable forces. Detailed descriptions can be found in [11].

![Figure 3. a) Part characteristic of tube geometry and b) the corresponding hybrid forming die](image)

The first hybrid forming experiments with this die showed leakage of LFT in the corner areas due to wrinkles, which are typical when sheet metals deform in a strong deep draw mode. This LFT leakage prevented a complete hybrid forming process for two reasons: 1) there was not enough LFT left in the cavity to complete the metal forming; 2) the leaked LFT prevented the complete closing of the upper and lower die. By analyzing the force curves for the pressing and the blank holder for the first trials (figure 4 (a)), as well as the forming results, it can be determined that an LFT leakage happened when the pressing force slightly decreased (marked by a blue circle). Or in other words, due to the LFT leakage, the hydrostatic pressure could not be further maintained until the gape was closed after 3-4 mm further stroke.

The solution to avoid this leakage was using a travel-dependent hydraulic die cushion force. The principles (i.e., the pre-settings of the press parameters and results after optimization) are depicted in figure 4 (b). At the process beginning, the blank holder force was set low enough to enable a smooth material flow of the sheet metal. Towards the end of the process, especially between -20 and -10 mm distance to the bottom dead end, the blank holder force was increased stepwise to 100 KN so that no distinct decrease of press forces appears in the blue circle. In this way, a constant sealing between the blank holder and metal sheet was ensured, and LFT leakage was prevented. The reduction of the blank holder force from 300 kN to 200 kN (figure 4 (a) compared to (b)) at the process end (-3 mm) is due to the minimization of the necessary blank holder force and has no further influence on the tightness.

Since the punch velocity of the press can only be driven but not be controlled during the pressing process, which is standard for many hydraulic presses, the actual velocity of the upper die is different from the preset values. The pressing force is a reaction force of the whole system, which depends on the preset velocity and the die cushion force. It increases continuously until the whole cavity is filled up with LFT and the sheet metal is almost completely formed – without any leakage. At the end of the process, the LFT is used as a forming medium, and the forming force increases rapidly to the set value of 1800 kN, which is not shown in figure 4 for reasons of clarity. All curves end up at around 2-3 mm above the bottom dead end, which is the thickness of the constant LFT layer in the tub geometry. The thickness of this LFT layer depends on the amount of inserted LFT.
5.2. Open end U-profile – concept 1
Since many of the real car body parts show open ended geometry with various section sizes (width, depth, etc.) with transitions from different sections, the first die concept has been developed using a homogeneous U-profile shape. A generic die sealing concept principle should be developed in this way. Currently, this simplified generic sealing concept is being further developed for arbitrary shapes with open end profiles. For the homogeneous U-profile, it is obvious that the sheet metal forming is very easy (figure 5 (a)). However, the LFT/GMT materials can be very easily pressed out due to the open ends. In order to guarantee the sealing, two measures were introduced. One is the introduction of a small geometry characteristic in the profile, and the other is the separation of the die into several segments.

The first measure is to introduce a small (<5 mm) step at the open end of the U-profile (figure 5 (a)), with which the LFT/GMT flow can be stopped or delayed. The punch was then divided into three segments: the mean punch in the middle and two sealing elements at each end (figure 5 (b)). The sealing elements are supported by gas pressure springs and can deflect by an offset to the major punch, which is responsible for the hybrid forming of sheet metal and LFT/GMT. During the forming process, the sealing elements move ahead. In combination with the counter holders of the lower die (figure 5 (a)), these sealing elements clamp and deform the sheet metal on both lateral ends before the main forming by the major punch and LFT/GMT pressure increases. It was assumed that if both ends of the profile were preformed, these undercuts could work as a mechanical sealing.

Figure 4. Process forces and velocity of the die with leakage (a) and without leakage (b) for hybrid-forming of a DC04 (2.0 mm) steel together with 300 g LFT PA GF 40

Figure 5. a) Hybrid formed part with homogeneous open ended U-profile, b) and the sealing concept.

However, the LFTs could still be pressed out at the upper end of the profile since the gap in the triangle sealing element - die - BH can only be fully closed at the dead end. To avoid this situation, the
blank holder was extended inwards of the die (figure 5 (c)). In this way, the press out of the LFT could be fully avoided, as shown by the pressed part in figure 5 (a).

3.3. Open end U-profile – concept 2

However, the concept in figure 5 is quite complex. Therefore, for an easy homogeneous U-profile, a simplified sealing concept was developed, as shown in figure 6. In contrast to figures 5 (b) and (c), no counter holder for the sealing element is needed, and the sealing elements also do not move separately from the punch. It is mounted together with the punch, and is thus a part of the punch. Through the small step between the sealing element and the main punch, the FLT/GMT press out could be prevented. The height of the step was equal to or slightly larger than the required thickness of LFT/GMT (2-3 mm usually), and its width was between 5-10 mm. If different sheet metal thicknesses are to be tested, the width of the sealing element must be changed accordingly.

Figure 6. A simplified die sealing concept for homogeneous open ended U-profile.

4. Results and analysis

4.1. Materials and sheet metal formability

In this work, the following materials (table 1) were used for the hybrid forming investigations. The properties of steels were taken from EN10346. Both Al and steels with different strengths were investigated. A PA6 GF 40 with a fiber length of up to 25 mm when placed on the sheet metal was chosen for LFT. In addition, a PP GMT (40% GF) was also included. For bonding, the adhesion promoter VESTAMELT (Evonik) was applied using a powder coating method [7].

| Material            | Rp0.2 [MPa] | Rm, min [MPa] | A80, min [%] |
|---------------------|-------------|---------------|--------------|
| Al 5182 H111/O      | 135         | 280           | 24           |
| Al 6451 T4          | 130         | 280           | 24           |
| DC04                | 140-210     | 270-350       | 38           |
| HC340 LAD           | 340-420     | 410-510       | 21           |
| DP 600              | 330-430     | 590-700       | 20           |
| DP 800              | 440-550     | 780           | 14           |
| CP-W800             | 660-820     | 760-960       | 10           |

Since the sheet metals have to be preheated to temperatures between 180 and 220 °C to activate the adhesion promoter VESTAMELT [7] and afterward hybrid formed together with 220 °C PP GMT or 280 °C PA LFT, the formability of the metals were, firstly, determined using the Nakajima tests according to the DIN EN ISO 12004 [13]. Five samples with different widths and, thus, stress states...
were utilized. For each stress state, three samples were tested, and an average value was built. The press velocity was 2mm/s. For Al sheets, the cut-outs in the samples were parallel to the rolling direction, and for steel, perpendicular, as defined by [13].

Prior to the Nakajima tests, the sheet metal blanks were spray-painted with a stochastic black and white speckle pattern that may resist the forming at temperature up to 300 °C so that after the tests, the forming could be measured using the GOM Aramis system, and the failure strain could be determined according to the method defined in [13].

**Figure 7.** FLCs at four different temperatures for a) 2 mm steel DC04, b) 2mm steel DP 600, c) 1.5 mm Al A5182, and d) 1.5 mm Al A6451

Figures 7 (a-d) show the FLCs determined at RT, 100, 200 and 280°C. The temperature dependencies of the four materials are very different. For the mild steel DC04, the FLC shifts to higher values when tests at 100 °C compared to RT. Further increases of the temperature to 200 °C and 280 °C reduce the level of FLCs. For the AHSS DP 600, the FLC shifts up-wards at 100 °C in both deep drawing and stretch forming area, whereas, in the small minor strain range, the forming limit remains unchanged. At 200 and 280 °C, the forming limit in the deep drawing and stretch forming area is very similar to RT, and in the small minor strain area much lower than RT. The reduction of formability of steels in the temperature range from 200 to 400 °C was often determined and should be a result of blue brittleness or the aging effect of steels [14]. Therefore, the temperature of steel blanks should be kept below 200°C for hybrid forming.

For Al, the FLC movement strongly depends on the type of Al alloy. For Al 5182 alloy, when no aging effect may occur, the formability is significantly improved (figure 7 (c)). For the Al6451 T4 alloy, because of the nucleation and growth of the precipitations in the alloy matrix (aging effect), the FLCs change irregularly (figure 7 (d)). For a first approximation, the RT FLCs may be used for hybrid forming analysis.
4.2. Analysis of hybrid forming results on tube geometry

All sheet metals in table 1 have been investigated, and here, some examples are presented. In order to determine the hybrid forming results, the sheet metal blanks were etched prior to forming with grids so that after the forming the deformation of the sheet metal can be determined using the GOM ARGUS system. In figure 8 (a), the equivalent strain on the tube geometry is shown directly on the part itself with different colors. The corresponding minor and major strains are plotted against the FLC with 10% and 20% margins of the steel used (DP600) at RT, since the steel blanks were preheated to ca. 200°C and the die temperature was 80°C. For more precise selection of FLC, the temperature of sheet metal blanks must be measured in the future. The color of the measurement points in the FLC was chosen to be the same as those indicated in the part. Since the pre-etched grids on the steel sheets were destroyed on the radii of the parts, the strains could not be determined there, as can be seen by the white areas of the tube geometry in figure 8 (a).

![Figure 8. a) Forming analysis on DP 600 steel, b) thickness of DP 600 steel and LFT in tube geometry](image)

In order to determine the forming of the geometrical details and the distribution of LFTs as well as the sheet steel thickness, the parts were cut into different sections. Moreover, the quality of bonding between LFT and steel could be visually inspected. These results are shown in figure 8 (b). The same was done for DC04 steel but not shown here. Due to the higher strength of DP 600, LFT thicknesses at the radii were significantly reduced and often less than 1 mm, whereas it was much thicker in the flat bottom area. For steels with lower strength, i.e. DC04, the thickness distribution was much more homogeneous [11]. In addition, due to the differences of strength of DC04 and DP600 the radii of the part made from DC04 formed more sharply in comparison to DP600 when using the same die and same press force. For forming DP600, higher forces must be applied. This fact must be considered at the CAD design stage of the part and/or when designing the die.

5. Application in vehicle chassis and body parts

Due to the different material properties of steel (higher strength) and Al (higher energy absorption rate), the steel hybrid forming was applied first on chassis (Steel) and BIW parts (Al). For chassis parts, two wheel-guiding components of a compact class vehicle (VW MQB Golf 7) [15] were investigated. The originally manufactured control arms using advanced high strength steels CP-W800 (table 1) were redesigned using steel-LFT hybrid, which should be formed by hybrid forming developed by the authors. The development results are shown on the example of the longitudinal control arm of the rear axle (figure 9 (a)). At first, all the load cases of VW for this control arm were calculated using FEM [15]. The resulting stress values and their distribution then served as target values for the new hybrid design. In the second step, the original sheet metal thickness of 3.5 mm was reduced to only 2 mm by applying LFT materials which is bonded to the entire surface of the steel base part, with various additional
reinforcement ribs. The steel thickness must have a minimum of 2mm due to corrosion issues of chassis parts. This hybrid formed part weighed 20% less than the pure steel reference.

![Figure 9. a) A longitudinal control arm of VW Golf rear axle made by hybrid forming of a CP-W800 steel and PA6 GF 40, b) A crash box made from Al 5182 and PP GMT (40% GF) after the axial crash test.]

Due to the very good energy absorption rate of Al and Al-FRP hybrid (figure 1 (b)) and its perspective to be used in car body’s front rails or crash box, a generic crash box was designed using Al 5182 alloy and a PP GMT (40% GF) (very long fiber and thus higher energy absorption according to figure 1 (a)). It consists of two U-profiles with flanges for joining. Using the die in figure 6, the hybrid forming was performed. The two U-profiles were then assembled using the self-piercing riveting technique. The crash box was finally impact-loaded using a drop tower test \(V=6.2 \text{ m/s}, m=375 \text{ Kg}\) with 7 KJ kinetic energy. As can be seen in figure 9 (b), through the folding process of Al sheet metal shell and the breakage as well as the delamination of GMTs, high amount of energy could be absorbed.

6. Summary and conclusions
Multi-material design has increasingly been used in lightweight design for vehicle body and chassis structures. Up to now, a multi-stage production process has been applied, in which metal and FRP parts are produced separately and joined together in a subsequent process step. In this work, the idea of hybrid forming, a simultaneous sheet metal forming and LFT/GMT compression molding process, has been successfully realized. Three die sealing concepts have been proposed and developed, covering tube geometry and open ended profiles. For open profiles, a generic sealing concept has been proposed using a segmented die and punch with individually adjustable kinematics. This concept has already worked for U-profiles with homogeneous geometry. It could also be simplified without segmentation of the die and punch and using simple kinematics. Currently, the generic sealing concept is being further developed for complex-shaped open ended profiles. For all concepts, the corresponding process parameters were identified, which are all applicable for industrial companies without difficulty. The hybrid forming results were analyzed using forming, thickness, and part geometry measurements and rated positively.

Using the developed process and die concepts, a real wheel guiding chassis component, the trailing arm of a multi-link suspension axle, was developed and produced in an industrial press line (Company Weber Fibertech, Germany) using high strength steel CP-W 800 and PA6 GF 40 LFT material. A weight reduction of more than 20 % was realized. In addition, a crash box for crash energy absorption was developed using Al 5182 alloy and PP-GMT hybrid. This hybrid part could be successfully crash deformed with high energy absorption.
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References
[1] Rohde-Brandenburger K, 2013 Was bringen 100 kg Gewichtsreduzierung im Verbrauch? Eine physikalische Berechnung, ATZ, 07, 584
[2] Trautwein T, Henn S and Rother K, 2011, Gewichtsspirale – Stellhebel in der Fahrzeugauslegung, ATZ 05, 390
[3] Hoffmann M, Hillebrecht M and Schäfer M, 2018, Leichtbaupotential in urbanen Elektrofahrzeugen, Lightweight Design, 06, 48
[4] Ahlers M, 2016, Carbon Core – die neue BMW 7er Karosserie, Karosseriebauung Hamburg 2016 Proceedings, Springer Vieweg, Wiesbaden
[5] Audi AG, Der neue Audi A8, https://www.audi-mediacentre.com/de/pressemappen/audi-a8-9072
[6] Lauter C, Frantz M, Tröster T, 2011, Großserientaugliche Herstellung von Hybridwerkstoffen durch Prepreg-pressen, Lightweight Design, 04, 48
[7] Risthaus M, 2017, VESTAMELT® Hylink Adhesion Promoter (Technical Information). http://adhesivessealants.evonik.com/sites/lists/RE/DocumentsAC/FlyerVESTAMELTHylink.pdf, accessed 30 June 2017
[8] Frey T, 2021, Klebefilme für belastbare Metall-Kunststoff, Leichtbauteil, Adhäsion, 11
[9] Hussain M, Rauscher B, Tekkaya A, 2008, Wirkmedienbasierte Herstellung hybrider Metall-Kunststoff-Verbundbauteile mit Kunststoffschmelzen als Druckmedium, Materialwissenschaft und Werkstofftechnik, 39/9, 585
[10] Landgrebe D, Kraeusel V, Rautenstrauch A, Albert A, Wertheim R, 2016, Energy-efficiency in a hybrid process of sheet metal forming and polymer injection moulding, Procedia CIRP, 40 109, https://doi.org/10.1016/j.procir.2016.01.068
[11] Fang X F and Kloska T, 2020, Hybrid forming of sheet metals with long Fiber-reinforced thermoplastics (LFT) by a combined deep drawing and compression moulding process, International Journal of Material Forming, 13(4), 561
[12] Buerkle E, Sieverding M and Mitzler J, 2003, Spritzgiessverarbeitung von langfaser-verstärktem PP. Kunststoffe 3, 47
[13] DIN EN ISO 12004, Metallic materials Sheet and strip - Determination of forming-limit curves – Part 2: Determination of forming-limit curves in the laboratory
[14] Saxena K K, Drotleff K and Mukhopadhyay J, 2016, Elevated temperature forming limit strain diagrams of automotive alloy Al6014-T4 and DP600: A case study, Journal Strain analysis, DOI:10.1177/0309324716651028
[15] Kloska T and Fang X F, 2021, Lightweight Chassis Components – The Development of a Hybrid Automotive Control Arm from Design to Manufacture, International Journal of Automotive Technology, 22/5, 1245, DOI 10.1007/s12239-021-0109-0