JOURNAL OF AIRCRAFT
Vol. 44, No. 4, July–August 2007

Automated Aircraft Sheet Metal Component Production Technologies

K. S. R. K. Prasad*
Indian Institute of Technology, Bombay, Mumbai 400 076, India
and
P. Selvaraj,† P. V. Ayachit,‡ B. V. Nagamani,‡ and R. K. Ramanathan§
Aeronautical Development Agency, Bangalore 560 017, India

DOI: 10.2514/1.11873

This article comprehensively presents an overview of the technological advances in automated aircraft sheet metal component production technology developments due to the initiative by the Aeronautical Development Agency, Ministry of Defense, Government of India, since 1989 in collaboration with the Indian Institute of Technology, Bombay. Commencing with a modest computer-aided flat pattern development software system suitable for a class of sheet metal components, this activity after several stages of development has now resulted in the development of full-fledged, personal-computer-based graphical interactive, three-dimensional application flat pattern development and automated production loft generation system. This research, encompassing the practical methods (exclusively developed for flat pattern software), literature survey, development of key algorithms suitable for designing a system for automated loft generation for a variety of surfaces with complex geometric features characteristic of aircraft sheet metal components with the aid of a wide choice of surface model creations, and testing and validation (carried out through an associated aircraft factory, Hindustan Aeronautics Limited), is now being published through four full-length papers concluding with the present paper. In fact, comprehensive illustrations of production lofts sampled from over thousands of parts used in the factory pertinent to the Indian Light Combat Aircraft (termed as Tejas) and other projects like Advanced Light Helicopter (termed as Dhruv) sheet metal components are included here to provide insight into these developments, and also to provide a glimpse of the success of the mission of indigenous automated aircraft sheet metal component manufacture.

Introduction

AVAILABILITY of CAD/CAM technology for component modeling, and computer numerical code (CNC) programming and machining is quite substantial when we compare the same to the sheet metal (SM) manufacturing automation. A brief chronological account of the initiative, planning, options exercised, and strategies of development adopted by the Aeronautical Development Agency (ADA) for evolving the automated aircraft production loft generation system is presented here together with appropriate illustrations. These encompass sheet metal component (SMC) classification together with suitably developed methods, surface model creations, and transportation/processing options, and the system potential with the aid of appropriate loft generation examples selected from among thousands of SMCs pertinent to new aircraft and helicopter design, and production developments undertaken by ADA with active participation of Hindustan Aeronautics Limited (HAL) with a task force of over 20,000 well-qualified technical personnel.

Unsuccessful trials in 1988, with the then commercially available flat pattern (FP) system [1,2], have led ADA to conclude that computer-aided complex SMC production is impossible without research and exclusive development. Hence, computer-aided loft generation activity was initiated in 1989 by sponsoring research and development projects to the aerospace engineering department and extending full-fledged ADA's CAD capabilities, manual lofting inputs, and manufacturing know-how in defining the system requirements. Thus, ADA acted as a prime mover in the successful completion of computer-aided and computer-integrated flat pattern systems from 1989–1993. These were released to factories simultaneously planning extensive supervised validation tests to facilitate automation for the flat pattern development activities to follow.

Thereafter, several in-house research and development programs have evolved by ADA using the services of the author (where needed) as a consultant to design forming tools, improvise flat pattern development (FPD) with progressively increased complexity, and to effect refinements made based on feedback from industry. All these efforts have finally resulted in the automated aircraft sheet metal component Production Loft Generation System both on commercial CAD systems as well as on PCs using the ADA's PC-based Graphical Interactive Three-Dimensional Application (GITA) CAD system [3] and subsequent releases.

Review of Available Technologies

A preliminary account of CAM and (CIM) technologies relevant to light combat aircraft (LCA) prototype development at ADA was first published in [4]. The scope of the present paper is to provide an overview of the technological advances concluding the current series of publications giving a complete know-how, commencing with the publication of basic research on practical methods, and survey of literature pertinent to contemporary research and development of SMC manufacture presented in [5]. This is followed by the presentation of considerations on the design of the Production Loft Generation System (PLGS) in [6] and some exclusive aspects and key algorithms of PC-based FP activity related to complex SMCs (without any flat surface, with double curvatures, and with several

Received 29 June 2004; revision received 29 June 2004; accepted for publication 14 April 2005.

*Professor, Department of Aerospace Engineering and Consultant for Manufacturing Systems Group Aeronautical Development Agency.

†Group Director, Computer-Aided Design/Computer-Aided Manufacturing, and Computer Engineering.

‡Scientist.

§Project Director, Technology Development.

design and production features) are brought out in [7]. Thus, this concluding paper first presents a review of the available technologies followed by the chronology of contributions to the developments related to loft generation systems, key algorithms, geometric feature based options, model creations issues, and various facets of the system design including extensive illustrations of the system potentials.

Summary of Concurrent Developments

CATIA version 4 [8] comes with sheet metal software composed of customizable methods for bend allowance computation. It generates bend reliefs when a bend is defined. It is possible to check folding and unfolding results for manufacturing feasibility. It includes the necessary information for downstream applications. However, it needs exclusive modeling technique and hence involves additional effort, as readily available surface models from design office are not suitable for this system.

UniGraphics [9] generates flat pattern data for parts with curved faces. FP is associative to the part geometry. Automatic analysis of the model is possible to determine proper flattening procedure. Annotation tools are available to augment flat pattern geometry for shop floor interpretation.

Pro-Engineer [10] can create flat patterns of curved SM parts using bend allowance calculations. Bend order tables are created in detailed drawings to communicate information to manufacturing such as order of bends, inside or outside bend radii, and bend angle and direction. It can display outside mold lines to help dimension flanges for older press brake controllers.

As can be seen, the preceding sheet metal software packages available in other CAD/CAM systems have still not met the fully automated loft generation requirements of aircraft industry using the model development work associated with design.

Here, we present an overview of these challenges, algorithms, techniques, and our documented experiences relevant to aerospace technology in general and in-house projects like LCA, in particular, complementing our publications [5–7]. Insofar as technologies of aircraft SMC manufacturing automation is concerned, we had to go all alone. A summary of capabilities and strategies adapted for the activities are given in following section.

Sequence and Strategies of Developing a Production Loft Generation System

At the initiative and sponsorship of ADA, Indian Institute of Technology, Bombay (IITB) undertook onsite development of FPD packages termed as computer-aided flat pattern development (CAFPAD) and computer integrated flattening package (CIFPAC) systems on a turnkey basis. The former is basically an FPD system with postprocessing features such as stand-alone subsystems, whereas the latter has integrated the same with additional functionalities such as shop floor display, improvisation of process economy by using symmetry, etc. ADA has extensively tested these packages and deployed them in the LCA prototype development. These software systems reside in commercial systems (CADDS4X/CADDS5). They address all SMCs with a principal flat surface (PFS) comprising 70% of the SMCs. The remaining 30% called non-PFS SMCs are defined only by three-dimensional surfaces. The loft generation pertinent to these surfaces needed further research and development.

Following a series of research and development projects such as tool design, nesting, and router interface suitable for CNC, a sheet metal manufacturing application software system termed GITA Flat Pattern Development (GFPD) is developed on a PC (with modular structure), envisaging a GITA surface model of relevant SM components as input. This incorporated the entire range of loft generation algorithms so far developed and also provided augmentation of the technology with additional functionalities where relevant, expanding the scope of complexities of the SMCs addressed.

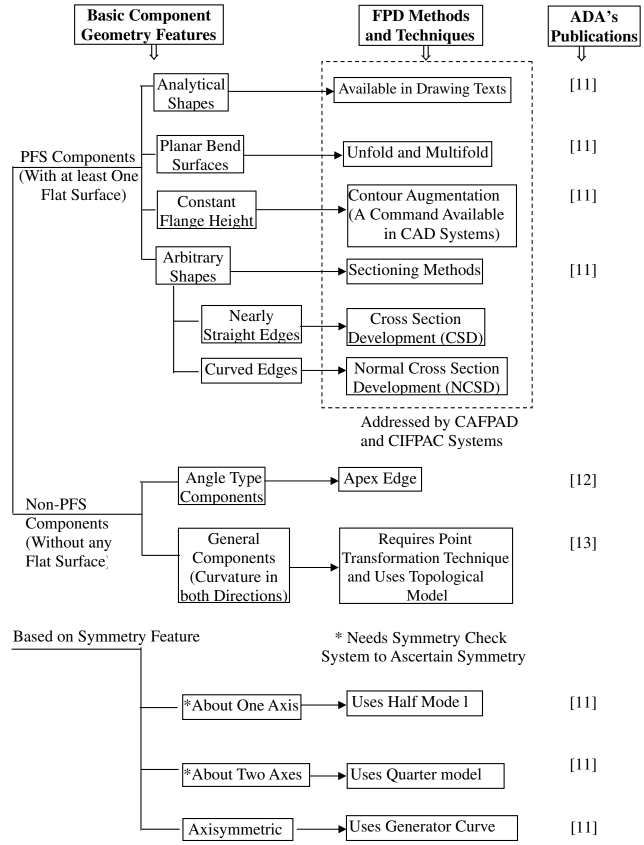


Fig. 1 Documentation scheme for FPD methods and techniques based on component features.

Yet, for expeditious development, parallel generations of models from other CAD environments (via initial graphics exchange specification route) were also successfully implemented and were progressively replaced by GITA models. GFPD addresses the FPD for PFS as well as non-PFS SMCs.

An overview of the entire range of aircraft sheet metal component features, together with relevant FPD methods developed, implemented, and published by ADA are detailed in Fig. 1. These are followed by Table 1 depicting the chronology of development of CAFPAD, CIFPAC, and GFPD systems for loft generation of LCA, their functionalities, and summary of illustrative figures. A summary of key algorithms together with their functions and documentation details are presented in Table 2.

The entire parametric definitions and nomenclature relevant to FPD and loft generation technologies are illustrated in earlier publications [5–7]. Also, the entire numerical data needed for the systems has been drawn from the lofting manuals of HAL and through continuous update during the production of new aircraft. Different FP methods are developed to address various geometric features of PFS as well as non-PFS aircraft SM parts (Fig. 2). The suitability of methods for each of the noticeable geometric features of SMC is as follows:

1) The cross section development method can be used for SM parts with mild curvature by defining three modes of sectioning.

2) Normal cross section development is used for the majority of aircraft parts with doubly curved flange surfaces.

3) The unfold method can be applied to generate FP for parts with planar flange surfaces.

4) Parts with uniform flange height, bend radius, and bend angle can be efficiently flattened using the contour augmentation technique.

5) The contour offset method is used for parts with constant or linearly varying flange height.

Various process options available in CIFPAC and GFPD are fast, medium, and slow in the order of increased accuracy depending on the surface curvature of a sheet metal part; with the

Table 1 Overview of system development sequence and functionalities addressed

FPD systems	Data integration	SMC classes			Symmetry	Post-processing	CAD platform(s)	Documentation and chronology of development	Publi-cations	Present figure nos.
		PFS	Non-PFS							
			Apex edge	General						
CAFPAD	✓	✓	——	——	✓	✓ (S)[a]	CADDS4X	IITB (1989–91) IITB/ AE/CASD/ 091-CAM-01 & 02	[5,6]	13 and 14
CIFPAC	✓	✓	✓	——	✓	✓ (I)[b]	CADDS5	IITB (1991–93) AE/CASD/ 093-CIM-01 & 02	——	13–18
GFPD-f	——	✓	——	——	——	——	GITA–3.0	ADA (1999–2000) ADA/C&C/SMCMA/ GFPD/- FEAS/001	——	14
GFPD-1	✓	✓	✓	——	✓	✓ (S)[a]	GITA–3.2	ADA (2000–01) GFPD-1 system and user manuals	[6]	13–18
GFPD-2	✓	✓	✓	✓	✓	✓ (I)[b]	GITA–3.3	ADA (2001–2003) GFPD-2 system and user manuals	[7]	19–22
PLGS and GFPD-O[c]	✓	✓	✓	✓	✓	✓ (I)[b]	platform independent	ADA (1993–2003) GFPD optimizer manual	[6]	13–27

[a]S: stand alone
[b]I: integrated (with stand alone option)
[c]GFPD-O: GFPD optimizer

Table 2 Summary of key algorithms developed and deployed

Algorithm	Functional details	Publications	Present figure nos.
Bend correction	correction formula incorporating surface model selection as well as direction of bend: $BC = (kt\phi) - \frac{1}{2}t\phi - \frac{1}{2}(t\phi)s1 \cdot s2$ as per parametric definitions in [5] (created by the author during feasibility study in May 1989)	[5]	13–27
Apex edge	designed to develop flat patterns for a class of non-PFS components; consists of sectioning normal to the apex edge to arrive at FPD	[6]	19
Bend relief	cutout provided in the loft to avoid interferences/crack initiation at the junction between adjacent flanges of an SMC	[6]	16
Point transformation	used in the FPD of non-PFS aircraft SMCs to find a suitable method of dividing each of the CCVs of the topological model boundary curves	[7]	22
Recursive division algorithm	number of divisions and spacing between them defined using recursive logic for efficiency and effectiveness in controlling accuracy	[5]	13–27
Radial, parallel, and orthonormal sectioning	basically transitional adaptations of sectioning techniques used for FPD of PFS class of SMCs in CAFPAD, CIFPAC, and GFPD-1	[7]	22
Symmetry check and processing	processing time for FPD is reduced for symmetric components completing FP through appropriate mirroring of the FP generated based on the fractional model (a preprocessor designed to perform symmetry check is termed SYMCHECK)	[5]	15 and 16
Joggle smoothening	designed to facilitate FPD removing interferences of FP segments corresponding to sharply bent PFS edges, as well as providing extra material to compensate for local plastic flow	[6]	13 and 16–18
Postprocessing	algorithms that use practical databases designed to incorporate FP production requirements in lofts and eliminate the need to model some of these features explicitly (e.g., don hole, tooling hole, pilot hole, tooling lug, etc.)	[6]	14

doubly curved surface requiring medium or slow process execution only.

For more complex components with and without PFS, the following can be used:

1) Apex Edge (AE) systems for components with AE (AE is defined as loci of consecutive vertices of angle type sections).

2) Combinatorial application of basic methods [6] can be used for parts that do not fit into any of the preceding categories if the component requires such a procedure for efficient implementation.

3) For the components with bidirectional curvature and other complexities, point transformation techniques or its hybrids with the any of the preceding can be deployed.

In addition to the flat pattern profile for a given SMC, the sheet metal shop requires design and production features such as cutouts and their locations, and inner and outer mold lines as illustrated in Fig. 3. These features are used for tool fabrication and part forming. Most of the features are also used for inspection of a formed part.

Joggles are provided at places where two or more SM components overlap. Rivets or bolts fasten them by providing a depression in one component. The projection of overlapping components is thus accommodated. Such a type of joint is generally required when one side is to be covered with "skin." Joggled parts may be assembled normal (90 deg) to the flange mold line termed straight joggle assembly or inclined to the mold line at an angle termed inclined joggle assembly (Fig. 4). Joggles can be of two types: 1) single flange joggle, or 2) shear joggle (Fig. 5).

Improvisations in CAD Operational Efficacies

The following methodologies are implemented to achieve operational efficacies.

1) Symmetry processing (illustrated in the section titled Illustrations of Production Lofts): To speed up the FP development process; if a model is symmetric about an axis or both, then only a

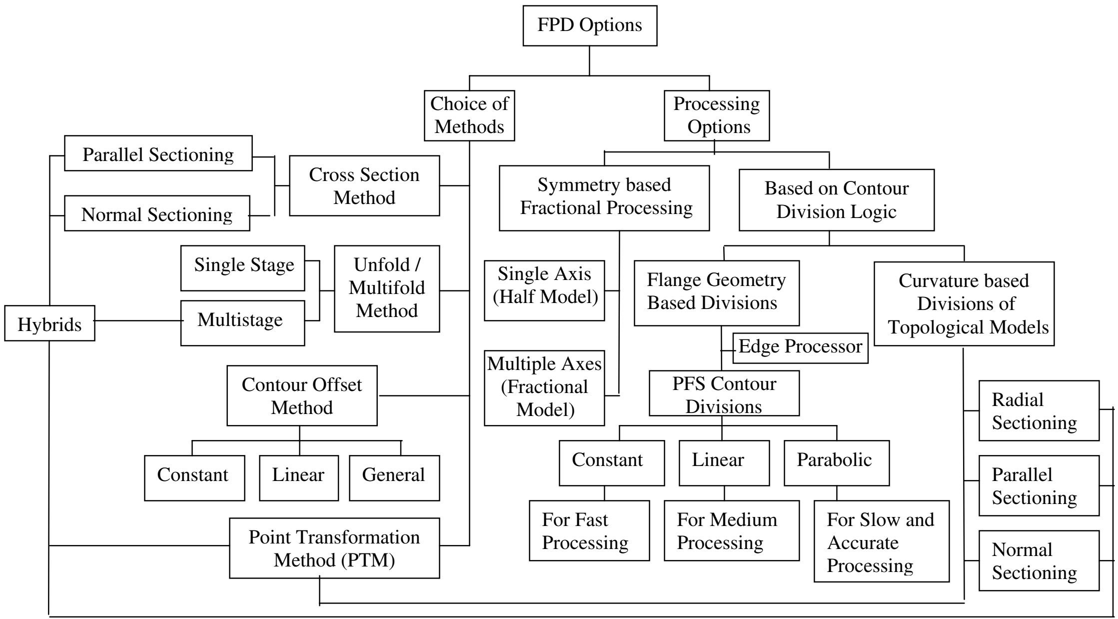


Fig. 2 Geometric feature-based options exercised in FPD generation of SMCs.

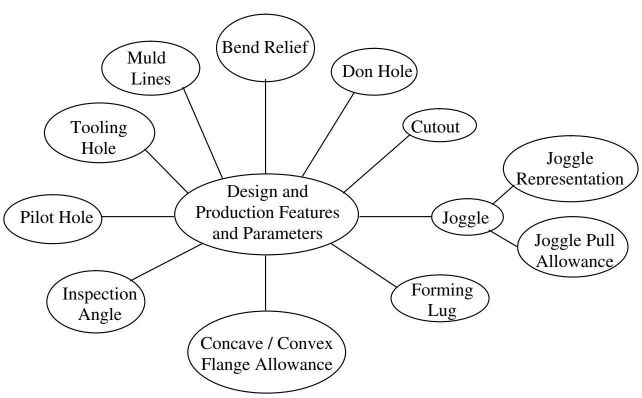
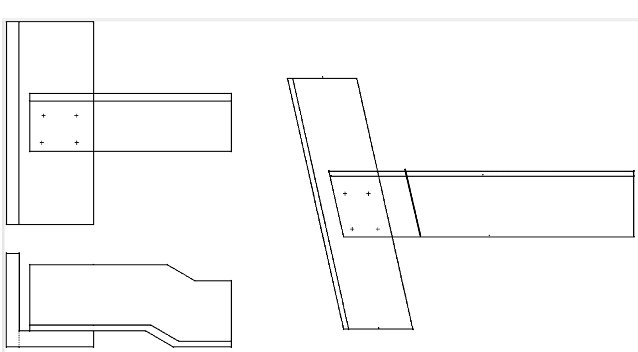
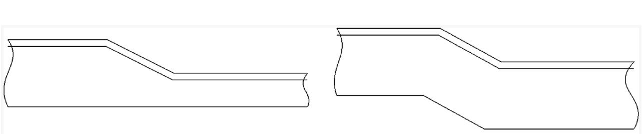


Fig. 3 Design and production features of aircraft SMCs.



a) Straight joggle assembly **b) Inclined joggle assembly**

Fig. 4 Joggle assembly types.



a) Single flange joggle **b) Shear joggle**

Fig. 5 Joggle types observed in aircraft SMCs.

half or quarter model is required for processing, respectively. The software, however, generates FP for the entire part automatically through a mirroring technique.

2) In case of a lightening hole or a don hole, it need not be modeled in a part. Only its center needs to be defined with an appropriately tagged point. Software generates FP development for the don hole complete with all production features, such as outer and inner mold lines.

3) Similar to a don hole center point, tooling holes and pilot holes also need definitions. The holes need not be modeled in part. Software generates these holes at bend-corrected locations complete with production details on the flat pattern.

4) Several functions are defined to execute multiple activities thus saving time, for example, batch processing of sections and other geometrical operations

Also, for minimization of processing times, efforts have gone into contour division methods and numerically efficient marching algorithms. A contour division technique called trisection logic is also evolved to minimize processing time for FP generation taking cognizance of the end complexities of flange geometry.

Overview of Surface Modeling Techniques

Figure 6 illustrates surface model creation techniques. The current release of GITA provides extensive options to create and manipulate surface models, as illustrated in Fig. 7.

Complex SMC surface models created in other CAD systems are also ported to GITA using the initial graphics exchange specification (IGES) translator (Fig. 8a). Models such as that shown in Fig. 8b are created in GITA.

The following steps are used to create an SM model in GITA as shown in Fig. 8b

1) Construct the boundary of principal flat surface as shown in the drawing.

2) Create a wire frame using the lines and arcs.

3) Create fillet and flange surfaces using Extrude options.

Observations on Model Transportation

GFPD software built in the GITA CAD [3] environment contains an IGES translator facilitating transfer of the model from any CAD system. To address the issue of CAD packages not having one-to-one correspondence with CATIA CAD features and to avoid data loss during transfer, a topological CAD model is derived to transfer from one system to the other.

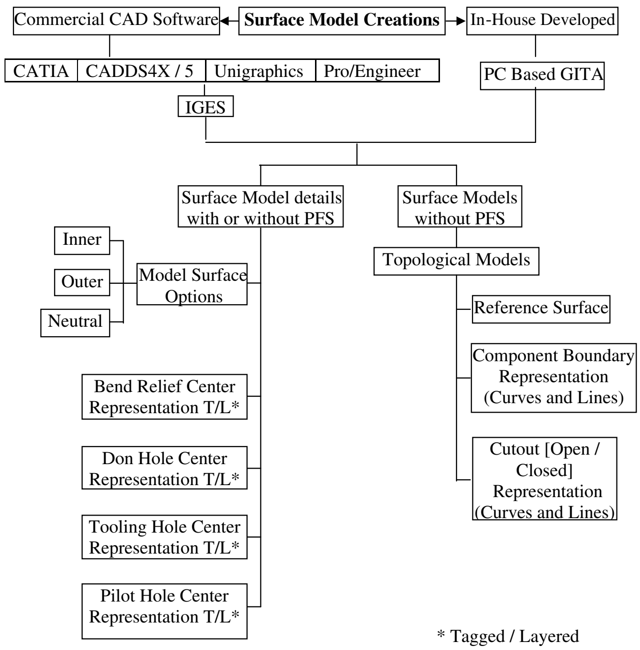


Fig. 6 Overview of surface modeling techniques.

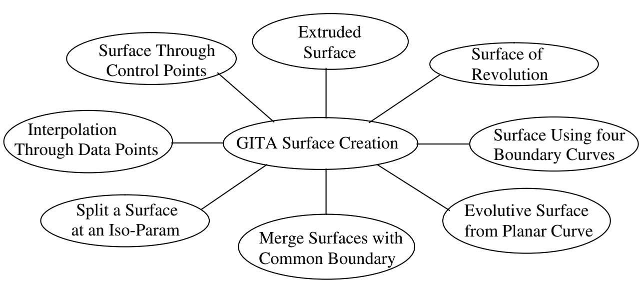


Fig. 7 GITA surface model creation options.

Almost all of the complex sheet metal components involving numerical master geometry (NMG) are modeled in CATIA. These models are transferred to GITA for using GFPD. To recreate non-PFS surface geometries generated in CATIA, only a topological model (defined by the bounding three-dimensional space curves including cutouts residing on one or more NMG surfaces as shown in Fig. 9) is considered for transferring to GITA CAD. Because FPD technology is now developed using these models and employing the point transformation technique [7], this not only simplifies the process but also makes it a highly reliable and accurate sure-shot method suitable for *any type of SMC*.

A topological model consists of an NMG base surface and bounding curves of the component, which lie on the base surface.

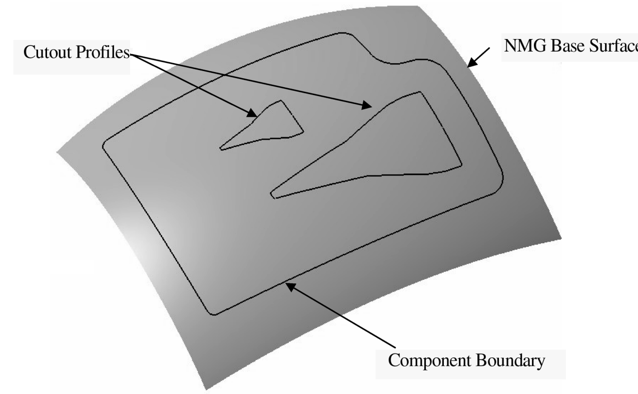


Fig. 9 Topological model of a non-PFS aircraft SMC.

The model also contains details of reference planes, which are required for the mapping FP output onto a two-dimensional layout. If the reference planes do not exist, it can be created in GITA locally by analyzing the models or referring to the drawing of the component.

The images in Fig. 10 show a typical aircraft structural sheet metal part having curvatures in more than one direction and the corresponding flat pattern complete with all production details generated using the CIFPAC [5,6].

Different features like joggle and doubly curved flange bent down with respect to the PFS of the part can be seen in this SMC. It also has a nibbled cutout provided for weight reduction (lightening), stiffening, and to route system cables.

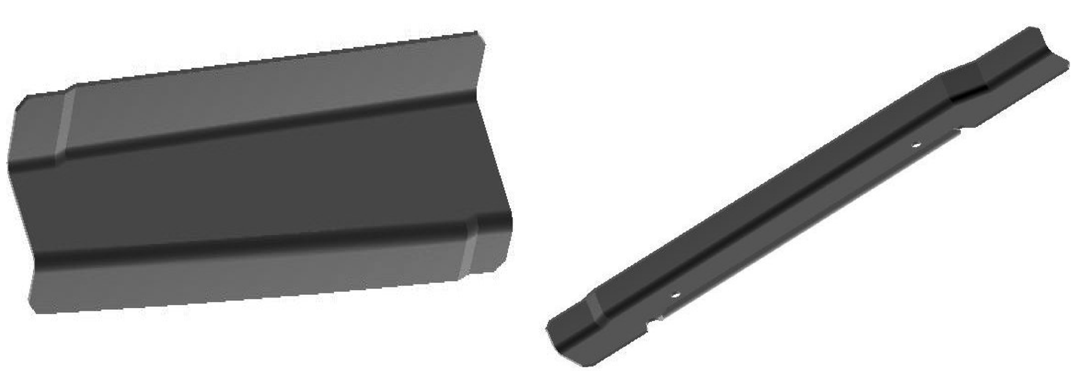
These features are represented with their bend-corrected lengths in the flat pattern. Upon careful study, it can be noticed that the FP also contains details such as bend angles, joggle representation, and inner and outer mold lines required for tool and part fabrication.

Production Loft Generation System: Additional Features and Manufacturing Applications

Some of the input parameters required for FPD are contour offset, thickness of SMC, and edge gap. Edge gap [6] in millimeters is the allowance given for the gap that may be present between adjacent flange surfaces of a SMC surface model. This ensures appropriate sections for FPD.

1) A cross section file can be generated at any given location for SMC inspection purposes. Fillets or chamfers are provided for all flange developments as per design requirements. An option is provided to generate FP either normal to the mold line or normal to PFS. FPD normal to the mold line is generally used.

2) Edge angle modification is a technique used to provide extra material on the flange edge to account for flow of material during forming due to presence of features such as a joggle. Joggle end normal correction is another technique used for the purpose.



a) Model ported from other CAD systems **b) Model created in GITA**

Fig. 8 Sheet metal component models.

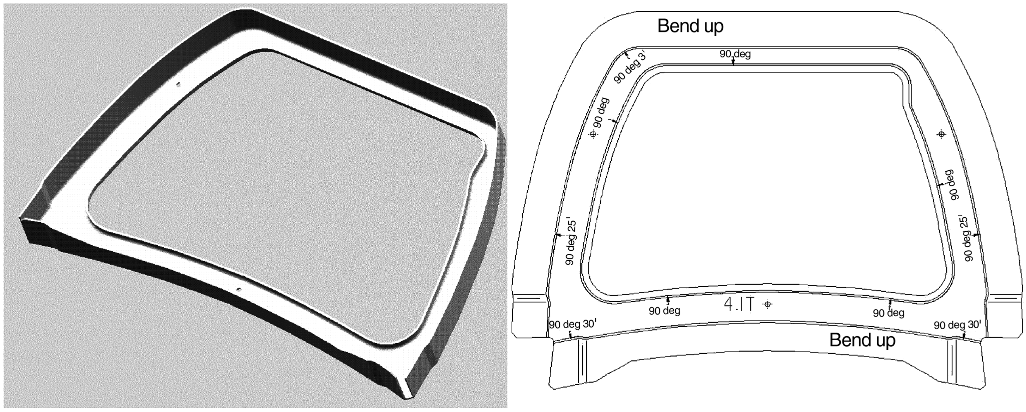


Fig. 10 Typical aircraft SMC with different features and its FPD generated using PLGS.

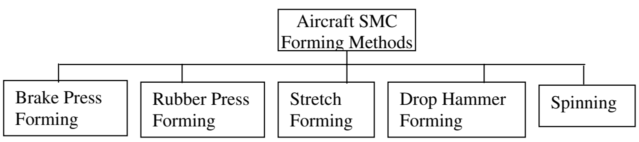


Fig. 11 Forming methods generally used for aircraft SMCs.

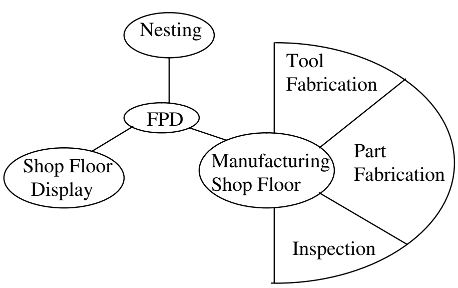


Fig. 12 Applications of FPD in SM manufacturing.

3) FP for SM parts along with complete production features can be saved as a different file that can then be supplied to the SM shop for manufacturing.

Different forming methods used to fabricate the majority of the aircraft SMCs are described in Fig. 11. Brake forming is used for angle-type SMCs. Rubber press forming is used for parts with a PFS. Stretch forming and drop-hammer forming are used for large non-PFS parts such as a skin. Spinning is used for parts with an axis of rotation. The production loft for a SMC with relevant details is also based on the forming method used.

Manufacturing applications of FPD are shown in Fig. 12. FPs for a number of parts can be fit on a sheet metal blank using an optimization algorithm to maximize material utilization. FPs are then cut using a numerical control router. Flat pattern is used for tool fabrication, part fabrication, and to facilitate inspection. FP is used for display on the shop floor to facilitate proper understanding of a part by an operator. The CIFTRANS module of CIFPAC is used to transfer an FP generated on a Unix machine onto a shop floor PC.

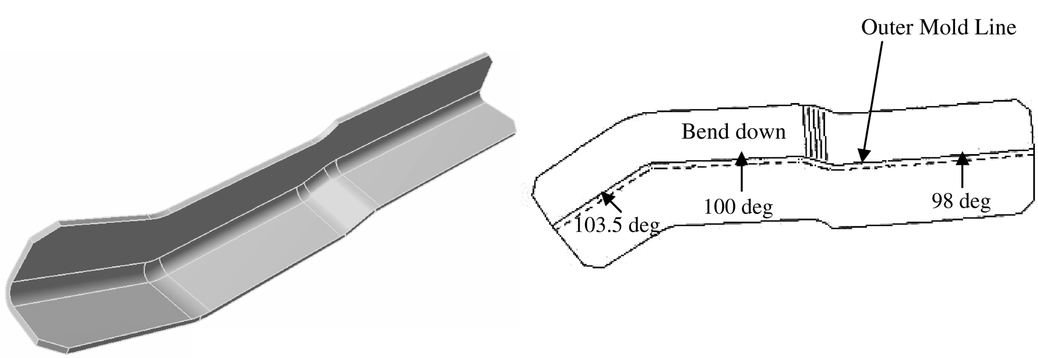


Fig. 13 SMC with three-dimensional flange surface with inclined joggle.

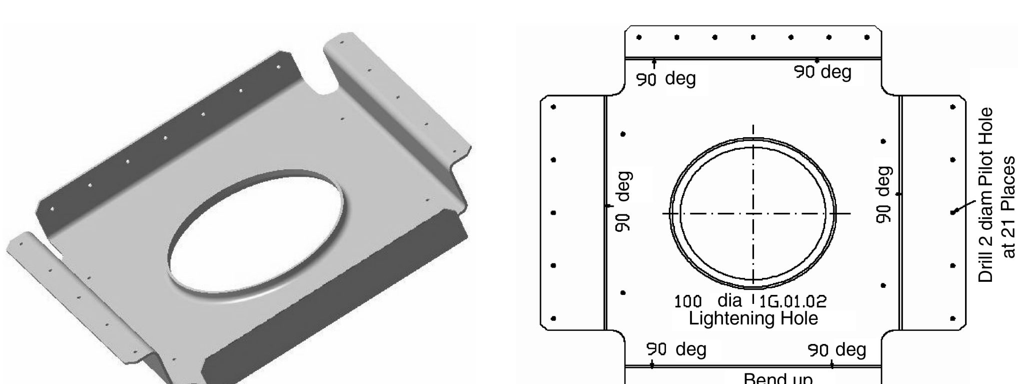


Fig. 14 SMC features: multifold flanges, don hole, and pilot holes.

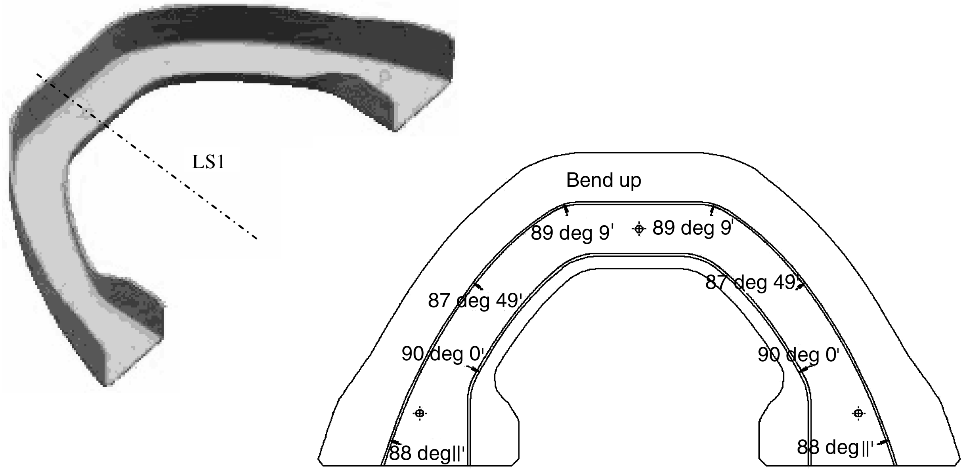


Fig. 15 Symmetric SMC with PFS, tooling holes, and bend up flanges derived from NMG.

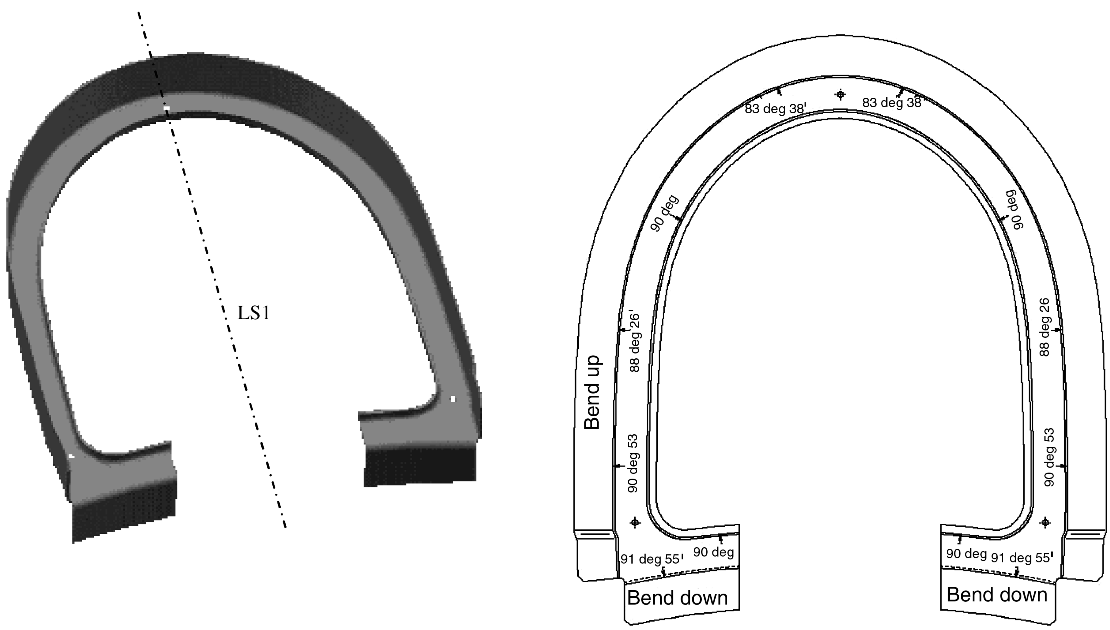


Fig. 16 Symmetric SMC with joggles and nibbled cutout (LS1: line of symmetry about axis one).

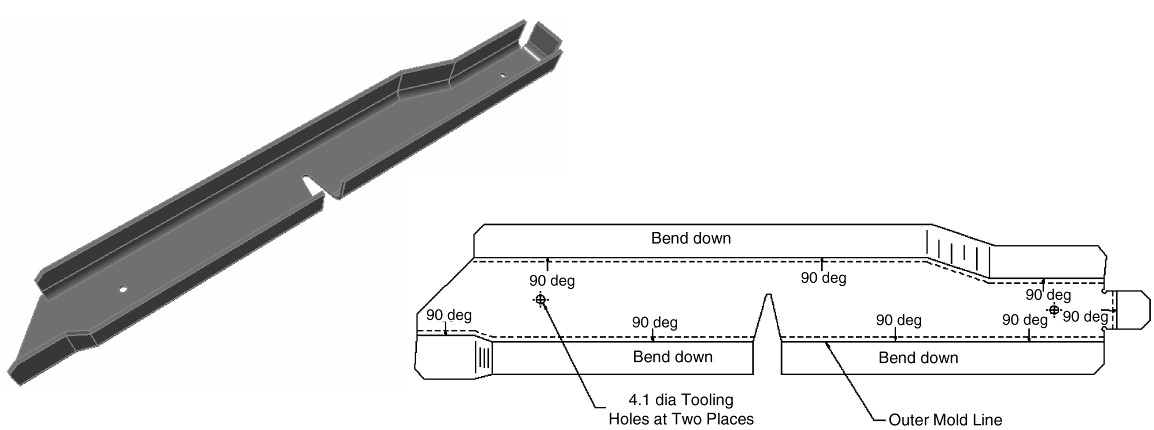


Fig. 17 SMC features: PFS, tooling holes, bend up flanges, and cutout.

Illustrations of Production Lofts

Figures 13–27 show a variety of typical aircraft SMCs and the lofts (complete with different design and production features) generated from their surface models.

Summary and Conclusions

The Indian LCA program development, entrusted to ADA by the Government of India, prompted indigenous development of CAFPAD (1989–1991) and CIFPAC (1991–1993) initially through

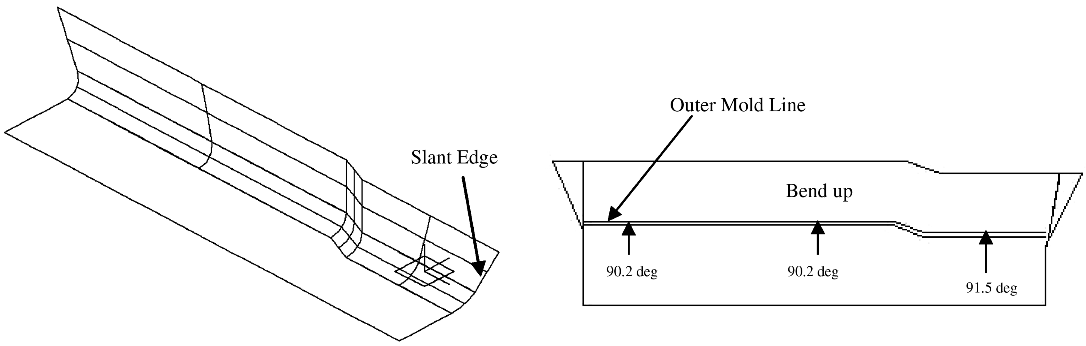


Fig. 18 Case of slant edge feature of SMC addressed by edge processing method.

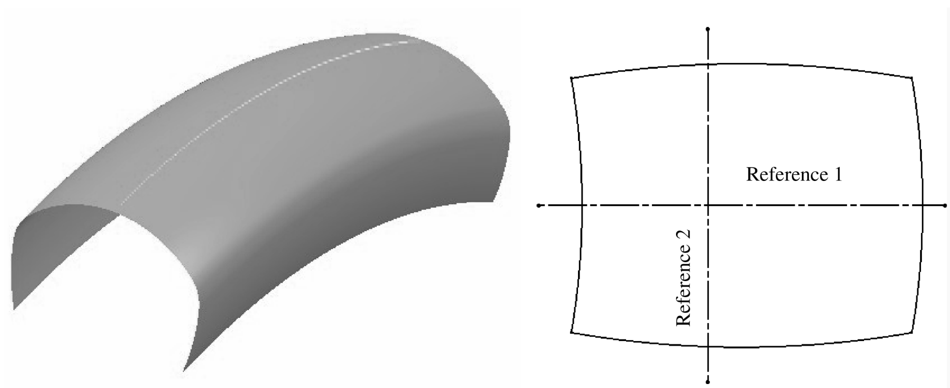


Fig. 19 Non-PFS SMC addressed by apex edge method of FPD.

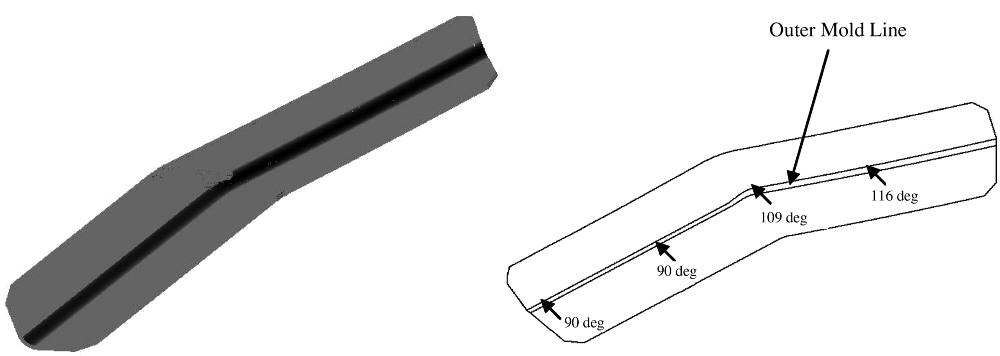


Fig. 20 SMC with PFS and bend up flange.

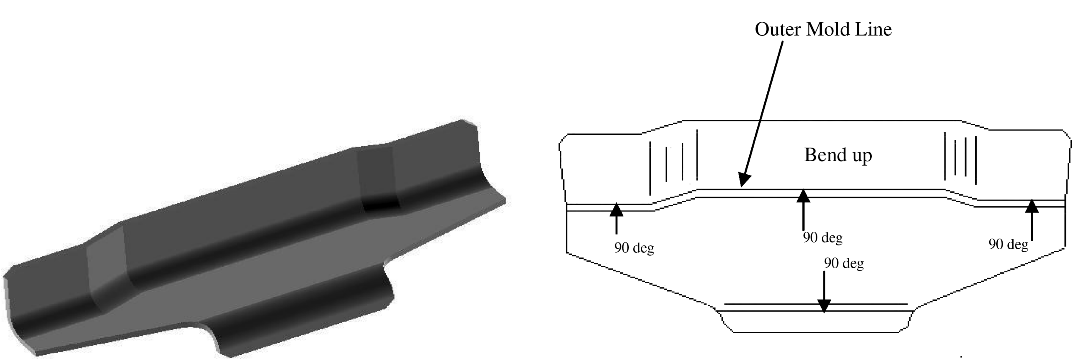


Fig. 21 SMC features: PFS, bend up and bend down flange.

sponsorship to IIT–Bombay after ascertaining the nonavailability of suitable public domain software systems. Subsequent in-house research and development, with continued association of IITB over the past decade, paved the way for evolution through several stages resulting in a PC-based GFPD and a complete PLGS. Supply of SMC lofts by ADA for LCA prototypes and limited series production has provided real-life extensive testing and validation opportunities for the evolution of the PLGS. PLGS has resulted in drastic reduction in production time to the tune of 70% compared with the manual lofting procedures employed for initial stages. The sample illustration of the

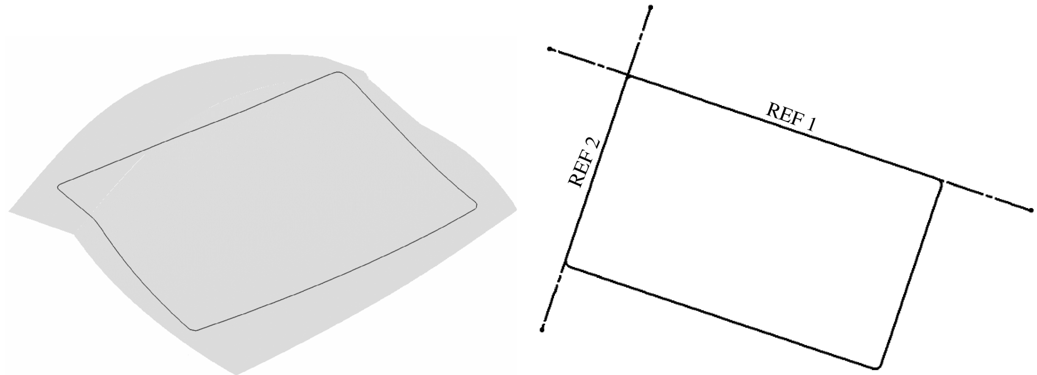


Fig. 22 SMC topological model with three-dimensional surfaces.

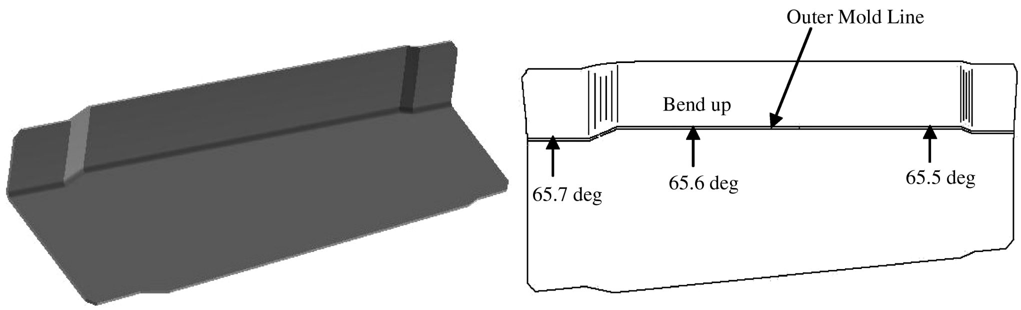


Fig. 23 SMC features: PFS, joggle, and flanges.

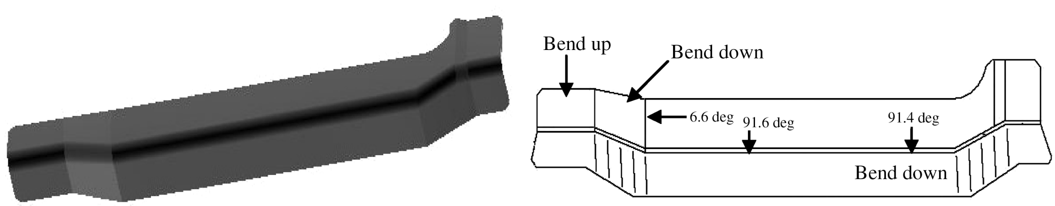


Fig. 24 SMC features: PFS and web joggles.

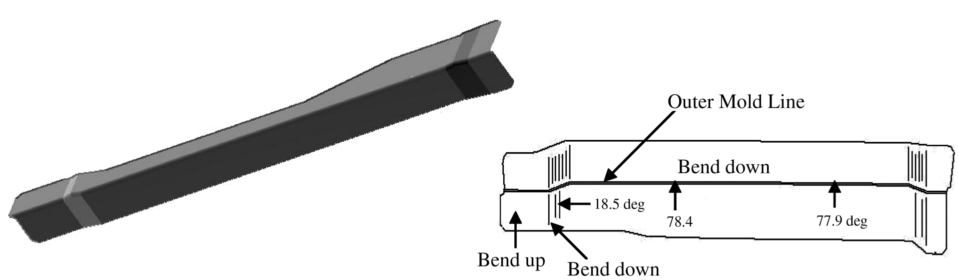


Fig. 25 SMC with web joggles and flanges.

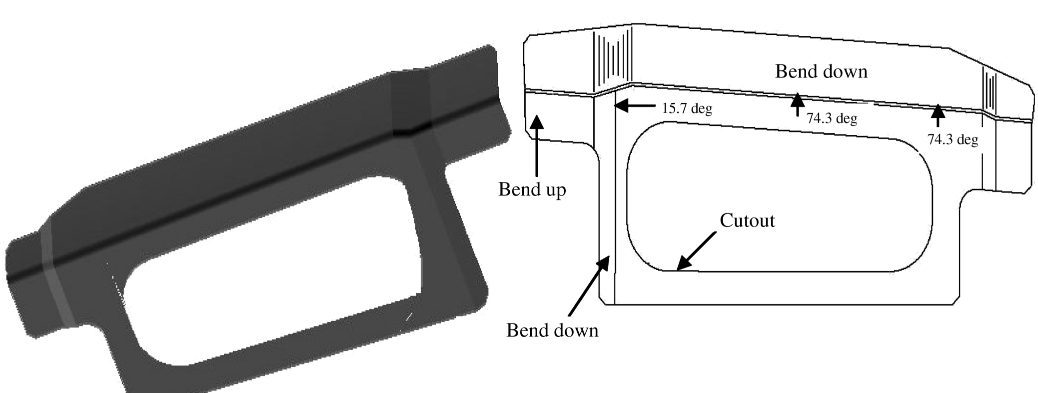


Fig. 26 SMC with joggles and bend up flanges.

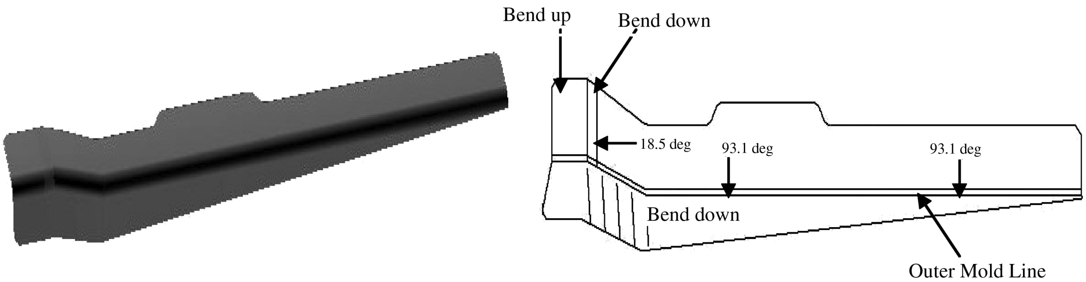


Fig. 27 SMC features: PFS, web joggles, and flanges.

utility of the system included here has proved its uniqueness, not only in terms of its scope, potential, and versatility, but also in being the only comprehensive powerful system whose design technologies are being made available in open literature through four full-length papers ([5–7] and the current paper), eliminating the need to reinvent the wheel by scientists and engineers engaged in development of SMC manufacturing automation.

Acknowledgments

The authors wish to acknowledge the initiative of the Aeronautical Development Agency, Bangalore for sponsoring this research since 1989 and for authorizing these publications in open literature, and Indian Institute of Technology–Bombay for continued collaboration. Many individuals from both organizations, particularly the members of the computer-integrated manufacturing group (now called manufacturing systems) and members of the graphical interactive three-dimensional application computer-aided design team led by V. Vani, have contributed to this research, coding, documentation, and its validation. Grateful acknowledgments are due to invaluable thought-provoking comments, wholehearted cooperation, and commitment from C. Gajendran, former Group Director of the computer-integrated manufacturing group, Aeronautical Development Agency (currently Director, Central Manufacturing Technology Institute, Bangalore), T. G. Pai, Distinguished Scientist (formerly Project Director, Technology Development, and Navy, Aeronautical Development Agency), and Kota Harinarayana, former Program Director, light combat aircraft, Aeronautical Development Agency.

References

[1] Anon., Sheet Metal Design User Guide, DOC36784-001, Computer Vision Corp., 1983.

[2] Anon., CADDS Station Software Mechanical, CADDS4X Reference Manuals, Computer Vision Corp., 1987.

[3] Yoosuf, S. M., Ravi, K. K., Ramanathan, R. K., and Swaminathan, S., "GITA: a Framework for Incorporating New CAD Technologies," *Proceedings of the National Seminar on CAD/CAM Applications in Aerospace*, Aeronautical Development Agency, Bangalore, India, 1995, pp. 117–134.

[4] Selvaraj, P., and Gajendran, C., "Evolution of CAM/CIM Technology in LCA Prototype Development," *Journal of the Aeronautical Society of India*, Vol. 54, No. 2, 2002, pp. 177–183.

[5] Prasad, K. S. R. K., and Selvaraj, P., "Practical Methods of Computer Aided Flat Pattern Development for Sheet Metal Components," *International Journal of Production Research*, Vol. 42, No. 15, 2004, pp. 3011–3039.

[6] Prasad, K. S. R. K., and Selvaraj, P., "Considerations for the Design of Automated Aircraft Sheet Metal Component Production Loft Generation System, PLGS," *International Journal of Production Research*, Vol. 43, No. 14, 2005, pp. 3045–3067.

[7] Prasad, K. S. R. K., Selvaraj, P., Ayachit, P. V., and Nagamani, B. V., "Development of Lofts for Doubly Curved Sheet Metal Components," *International Journal of CAD/CAM* (to be published), 2006.

[8] Anon., CATIA Generative Aerospace Sheet Metal Design User's Guide, Ver. 4, No. SH52-7379-24, 1997.

[9] Anon., Sheet Metal Design, Unigraphics Solutions, User Manual, Ver. 15.0, Oct. 1998.

[10] Anon., Pro-Engineer Sheet Metal Design User Manual, Parametric Technology Corp., 2001.