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ORIGINAL ARTICLE

Review: geometric and dimensional tolerance modeling for sheet metal forming and integration with CAPP

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Abstract The focus of this publication is a review of the state of the art in tolerance analysis, synthesis, and transfer for geometric and dimensional tolerances in sheet metal forming and the integration solutions with computer-aided process planning systems. In this context, the general tolerance methods are first described. Then, the mathematical models for sheet metal tolerance analysis and synthesis are examined in detail. To address the CAPP modeling concerns, the paper is then followed up with a brief review of past research works related to feature-based process planning. Finally, those imperative future research areas are identified.

Keywords GDT · Tolerance transfer · Geometric tolerances · Sheet metal · Process planning

1 Introduction

Sheet metal forming (SMF) is one of the most common manufacturing methods for metal parts and is used widely in industries [99]. As in assembly or metal removal processes, design and process tolerances play an important role with respect to functionality and cost. However, mathematical methods for tolerance analysis, synthesis, and transfer used in non-sheet metal forming processes are not readily applicable. Reasons are the differences between sheet metal forming and conventional material removal machining as summarized in Table 1.

Great advances have been made in the field of sheet metal forming. New processes and working methods have been developed. Many tools for design, process simulation, and control are available today [2, 4, 86, 101, 138, 148, 149, 159, 189, 190, 218, 238, 243, 257]. Since the 1990s, due to the rapidly diminishing number of experienced process planners for SMF, the need for shorter product life cycles and the importance of three-dimensional (3D) computer-aided design and manufacturing (CAD/CAM), the research on process planning in this area attracted more attention. The research areas cover topics such as raw material preparation technologies, process selection, tooling design, operation sequencing, fixture definition, and collision detection [69, 170].

Problems related to tolerances emerge in several stages of the life cycle of a sheet metal part. The problems are characterized by the particular viewpoints and objectives of the individual life cycle stages. For example, a process planner has to find the most economical processes and their sequence as well as to fulfill the tolerance specification in product design. For machined parts, tolerance constraints play a significant role in process planning, and computer-aided tolerancing (CAT) has been developed as a key technology for determining machining sequences that can result in the best accuracy on some special features of parts [102, 125, 260]. However, in sheet metal forming, currently, an effective approach of computer-aided tolerance analysis is still not fully developed, and hence, there is no comprehensive method to integrate design and process planning.

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Table 1 Comparison of SMF and conventional machining methods (modified from [95])

Sheet metal forming	Conventional material removal machining process
The initial parts or blanks are cut out to form the required shape from a large sheet metal layout.	The initial raw work-piece is normally sawed, preformed, or prepared by casting or forging process. They are less precise than sheet metal blanks.
The process is irreversible. Once formed incorrectly, parts are scrap.	Work-piece can be machined again if the machined work piece is not undersized (it usually is scrap otherwise).
Surface finish depends on the forming process.	Surface finish largely depends on the final machining operation.
The deformation usually causes significant changes in shape, but not in cross-section (sheet thickness and surface characteristics) of the sheet.	The cross-section in all orientations is potentially changed.

The organization of this review is that, at first, sheet metal forming operations are surveyed, in which bending and punching operations are emphasized; then, the past research efforts on CAT are reviewed; and finally followed by the discussion of its integration with computer-aided process planning (CAPP) aspect.

2 Sheet metal forming processes

Common sheet metal fabrication techniques include a multitude of different operations. These operations can be classified as in Table 2. Bending and punching are the most popular sheet metal forming processes. Some operations, such as folding, flanging, and hemming, may be regarded as bending-like operations because they have similar forming principles.

2.1 Bending operations

Bending is a prevalent type of forming operation, which provides the required shape and further rigidity to sheet metal parts. In this process, usually, a plane sheet or a metal strip is deformed in a circular arc around a straight axis lying perpendicular to the neutral axis as defined in [179]. Metal flow takes place in the plastic range of the metal so that the bent part retains a permanent set after removal of the applied stress. The cross-section of the bend inward from the neutral axis is in compression, and the rest of the bend is in tension [181]. The tensile stress decreases toward the center of the sheet thickness and becomes zero at the neutral axis, whereas the compressive stress increases from the neutral axis toward the inside of the bend.

A typical sheet metal bending operation involves mounting a punch (punches) and mold (die) on a press, which controls relative motions between the punch and die, then, placing sheet metal on a die against a (auto-) stopper block, or a gage, to position the part. Punch(-es) and the mold (die) provide the necessary bending forces or pressures. Sometimes, grippers are used to hold the part during and between operations.

Bending processes fall into several categories: air bending, bottom bending, coining, U-bending, etc. Air bending is a bending process in which the punch forces the work piece into a V-shaped die and the work piece does not touch the bottom of the die. Bottom bending is a bending process where the punch and the work piece bottom on the die. Coining is a bending process in which the punch and the work piece bottom on the die and compressive stress is applied to the bending region to increase the amount of plastic deformation.

2.1.1 Bend allowance

If the bend radius is comparable to the thickness of the sheet, the sheet tends to stretch during bending. This influences the accuracy of dimensions and tolerances of final part and has to be reflected in the working dimensions. This change in length is compensated by the so-called bend allowance (*BA*), which can be estimated as follows:

$$BA = 2\pi \frac{\alpha}{360} (R + \mathrm{K}_{ba} T) \tag{1}$$

Table 2 Common operations on sheet metal parts

Cutting operations	Bending operations
Punching, notching, shearing, blanking, drilling, piercing, nibbling, slitting, trimming, shaving, and stamping	Air bending, coining, bottoming, hemming, folding, and flanging
Joining operations	Other operations
Welding, soldering, bonding, riveting, screwing, and seaming	Drawing, rolling, stretching, spinning, and flattening

where BA=bend allowance, in millimeters; α=bend angle, in degrees; R=bend radius, in millimeters; T=material thickness, in millimeters; and K_{ba} is factor of stretching effect. K_{ba} is defined as t/T, where t is distance from the inside face to the neutral axis. Clearly, K_{ba} is a ratio that gives the location of neutral axis with respect to the thickness of the sheet metal part. The value of K_{ba} is usually estimated by adopting some recommended design values. Many CAD programs calculate the bend allowance by using K_{ba} (or Y-factor in the case of Pro-E, where the Y-factor is $\frac{K_{\mathrm{ba}}\pi}{2}$) [85]. For air bending, bottom bending, and coining, [60] presented a method to determine K_{ba} reversely. Publications on bending allowances are numerous, and two recent ones are given in [116, 217].

2.1.2 Springback

When the bending pressure is removed, elastic energy in the bent part causes it to recover partially toward its original shape. This elastic recovery is called *springback*, defined as the increase in included angle of the bent part relative to the included angle of the forming tool after the tool is removed. This is expressed as:

$$\text{Springback} = \frac{\alpha_f - \alpha_i}{\alpha_i} = \frac{R_f - R_i}{R_i}. \tag{2}$$

where α_f is the bending angle after springback in degrees; α_i is the bending angle before springback in degrees; R_f is the final bend radius after springback; R_i is the bend radius before springback.

Springback should be predicted in bending operations and the punch position adjusted accordingly. As it causes changes in shape and dimensions, springback prediction is an important issue. It is difficult for design engineers to predict springback, as many variables influence it: material variations in mechanical properties, tool geometry (including die radius and the gap between the die and the punch), sheet thickness, punch stroke, lubricant condition, etc. Springback is often approximated using

$$\frac{R_i}{R_f} = 4\left(\frac{R_i Y}{ET}\right)^3 - 3\left(\frac{R_i Y}{ET}\right) + 1, \tag{3}$$

where R_f is the final bend radius after springback in millimeters; R_i is the bend radius before springback in millimeters; Y is the yield strength of the sheet metal in megapascal; E is Young's modulus of the sheet metal in gigapascal; and T is the thickness of the sheet material.

For air bending, the springback usually ranges from 5 to 10°. Bottom bending and coining allow for a better control of the bending angle as springback is reduced.

Various investigations show the influence of process parameters on springback, such as bend radius, die gap, and punching speeds, and material properties, such as sheet thickness, flow stress, texture, and grain size [26, 42, 114, 129].

2.2 Punching

Punching is a very efficient, inexpensive, and flexible way of producing cutouts from sheet metal. The term punching describes a shearing process, in which a punching machine separates a sheet of metal by striking it, while supporting it by a die with a hole matching the cross-section of the punch. In punching, the cut out part of sheet is scrap, and the remaining material is a desired part. Opposed to it, in blanking, the cut out section of the part is the required part.

Punching is usually utilized to create holes of various shapes in sheet metal material. Traditional punching operations produce a single geometry with the same tool. numerically controlled (NC) punching operations with multiple standard tools can produce a wide range of geometries characterized by simple geometrical elements like lines and circles [181].

2.3 The “other” forming operations

The forming operations listed under “others” in Table 2 are not addressed in detail in this report. In brief, they either produce

– plain, flat sheet metal, and only thickness tolerance matters, or
– free-form surfaces for which all tolerances are defined by the drawing process (and estimated by finite element methods, for example)

3 Computer-aided tolerancing

Tolerances and tolerance-related problems play a ubiquitous role in both product design and process planning. The existing research can be classified into seven distinct categories as in Fig. 1. Selected tolerancing methods are discussed later. In this figure, the dashed lines indicate that tolerance transfer techniques are derived from tolerance analysis and tolerance synthesis, as explained later in section 3.4.

3.1 Geometrical dimensioning and tolerancing

Two main types of tolerancing schemes are in use: parametric and geometrical. Parametric tolerancing identifies a set of design parameters and assigns limits or distributions to the parameters, such as maximal deviations (conventional ±) or statistical tolerances [175]. A recently

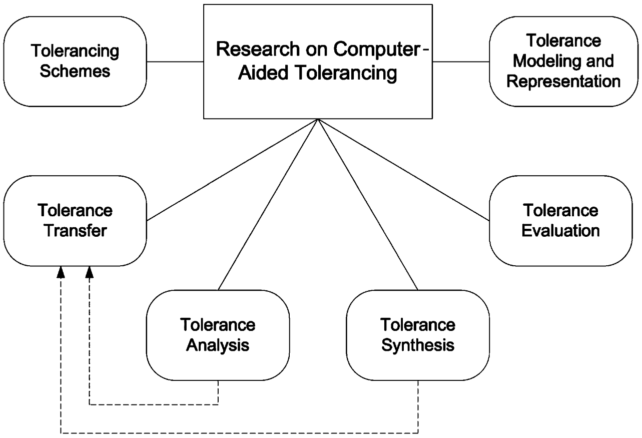

Fig. 1 Research on computer-aided tolerancing [98]

proposed tolerancing scheme called vectorial tolerancing falls into this category [247].

Defined in ISO 1101 and ANSI Y14.15M:1994, Geometrical Dimensioning and Tolerancing is a dimensioning system that benefits both design engineering and manufacturing engineering. It allows designers to set tolerance limits, not just for the size of an object, but also for all of the critical characteristics of a part.

Geometrical tolerances describe the acceptable range of variation in geometry from a nominal or reference geometry. They designate values to certain characteristics of features, such as form, orientation, location, and run-out. Detailed explanation and examples of current standards on geometrical dimensioning and tolerancing can be found in ANSI Y14.15M:1994 or ISO specifications such as ISO 1101:2002, ISO 14660-1:1999, and ISO/TS 17450-1:2005.

Orientation and position tolerances are often used in sheet metal parts. Orientation tolerances include perpendicularity, parallelism, and angularity tolerances, as shown in Fig. 2. Discussions of geometrical error evaluation and related research work can be found in [155, 179, 180, 193–196, 232, 233]. The methods are mainly based on CMM, computational geometrical techniques, and artificial intelligence (AI).

3.2 Tolerance analysis

Tolerance analysis is used to estimate the accumulation of process variations on assembly dimensions and features and to verify the proper functionality of a design. This topic has drawn considerable attention, and many papers have been published on 1D, two-dimensional (2D), and 3D tolerancing.

The analysis methods can be classified based on the types of analyzed variations:

- Dimensional (lengths and angles)
- Geometrical (flatness, roundness, angularity, etc.)
- Kinematic variations (small adjustments between mating parts in mechanical assemblies) [31]

Dimensional and geometrical variations are the result of variations in component parts due to manufacturing processes or raw materials used in production. Kinematic variations occur at assembly time, whenever small adjustments between mating parts are required to accommodate dimensional or form variations.

3.2.1 Tolerance analysis models

Figure 3 gives an overview on mathematical models used in tolerance analysis. Tolerance chain models, or dimensional tolerance chain models, fall into two categories:

1. Linear/linearized tolerance accumulation models. One of the most common models for the accumulation of component tolerances T_i into the predicted assembly tolerance T are, according to [73], worst-case models with

$$T = \sum_{i=1}^{n} T_i$$

Another commonly linearized model type, root sum square models (RSS, the original theoretical model of this method belongs to statistical category as discussed in the next section), has been used for tolerance estimation purpose as follows:

$$T = \sqrt{\sum_{i=1}^{n} T_i^2}$$

This approach is applied in [83, 84] to worst-case tolerance and root sum square tolerance analysis. A similar analysis method for more complex mechanical assemblies

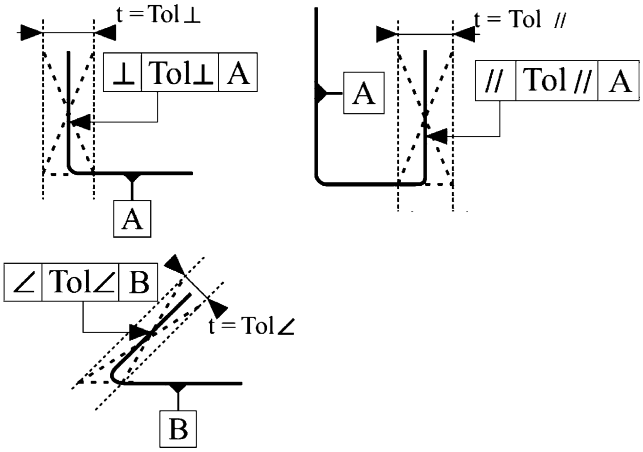

Fig. 2 Orientation tolerances (from ISO 1101:2002 and [53])

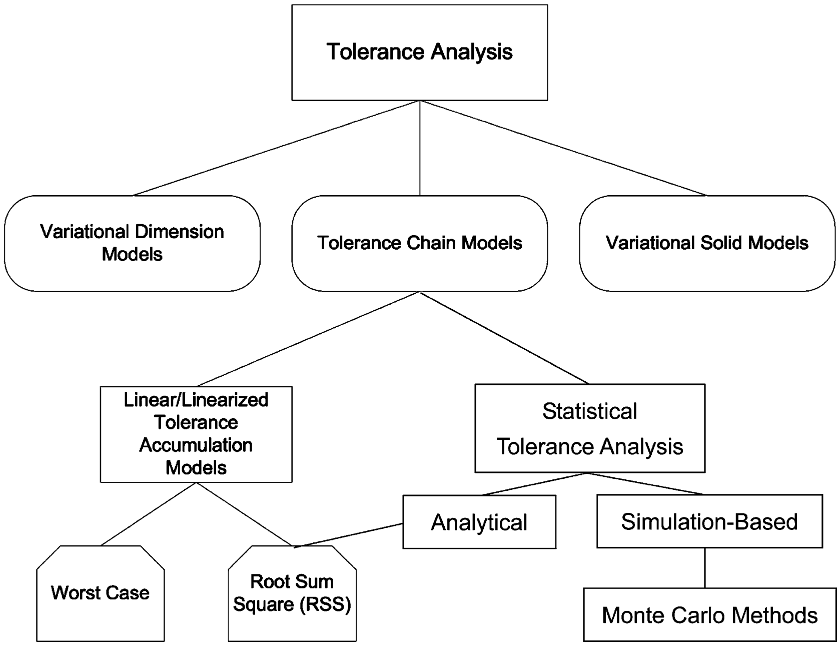

Fig. 3 Main tolerance analysis models

and kinematic linkages is based on the direct linearization method (DLM) [27, 28, 31, 77, 82, 248]. The role of tolerance and assembly analysis in robust assembly design is discussed in [66] and applied to nesting forces for exactly constrained mechanical assemblies in [162]. A comprehensive system based on dimensional tolerance chain model has been developed [29, 77] which includes dimensional, geometric, form, and kinematics sources; vector loops are defined by homogeneous transformation matrices, similar to robotics models.

2. Statistical analysis methods. In this category, two major approaches exist. The analytical analysis approach was developed from the tolerance chain technique, which aims to determine the probability distribution of system response functions [182]. RSS method belongs to this group. The DLM is applied to make the analysis model more convenient to use with small variations about the nominal dimensions [75, 82–84].

The second approach is simulation-based analysis. The most developed and commonly used method is Monte Carlo simulation which circumvents the difficulty in statistical tolerance analysis, which is to determine statistical moments of accumulated tolerances in a closed form. Therefore, Monte Carlo simulation methods are frequently used [32]. This method can be readily used for tolerance analysis, but is rarely for tolerance synthesis due to the difficulty to obtain derivatives of design functions [200]. The results of the direct linearization method with those obtained from the Monte Carlo simulation are compared in [75]. New metrics for assessing the accuracy of the Monte Carlo analysis method for assemblies are presented in [48]. Geometrical feature variations defined in ANSI Y14.5M-1994 are addressed statistically and propagated kinematically in a manner similar to the dimensional variations in assemblies [29].

Variational dimension models are a kind of special variational geometry in which only the dimension (size) can vary [184]. Recent research work focuses on tolerance sensitivity analysis in this area [63]. Variational solid models were developed to overcome the problems of variational dimensional models with non-polygonal/polyhedral models and certain types of geometrical tolerances [18]. They were shown to be appropriate for tolerance analysis of assemblies of toleranced parts [3, 127].

3.2.2 Three-dimensional tolerance analysis

With the advancement of 3D CAD and other engineering analysis technologies, the traditional dimensional tolerance chain models need to be enhanced to meet the requirements of explicit 3D geometrical tolerance specifications. A 3D tolerance propagation scheme has to address two related issues:

- Representation of tolerance zones and
- Spatial tolerance propagation mechanism

Categories of three-dimensional tolerance analysis methods are shown in Fig. 4.

Preliminary work motivating the development of the 3D tolerance propagation techniques is regarded as the spatial dimensional chain technique [163–165]. Other methods are mostly a variation of the spatial dimensional chain technique. For example in [163], the propagation of

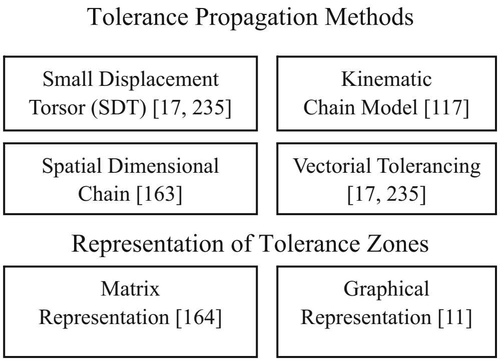

Fig. 4 Main three-dimensional tolerance analysis methods

position errors is taken into account in terms of a kinematic chain, where the individual error is represented as matrices with three-dimensional and three angular position errors. For pairs of functional elements in a kinematic chain model is associated with a set of six virtual joints, three for small translations, and three for small rotations [117].

Three-dimensional tolerance propagation models based on the concept of a small displacement torsor (SDT) are used to simulate three-dimensional fixturing and machining errors and their impacts on the geometry of the finished part. An SDT is a mathematical object that represents the displacement of a rigid body using three rotations and three translations. This approach models the influence of a process plan on functional tolerances as a chain of torsors. Assuming that the displacements are small enough, linearization is used to derive a torsor T as:

$$T = \begin{pmatrix} \alpha & u \\ \beta & v \\ \gamma & w \end{pmatrix} \tag{4}$$

where α, β, and γ are the small rotations of the element; u, v, and w are the small translations [17, 57].

The traditional tolerance chain models can be used for tolerance synthesis as shown in [30], but the related methods are relatively difficult to be uniformly generalized from case to case. The SDT-based and three-dimensional tolerance propagation overcomes such limitations. Based on the SDT method, a detailed model of mechanical parts, part-holders, and machining operations was developed [235] and extended to tolerance synthesis [236].

Vectorial tolerancing can be applied to geometrical tolerance analysis, see [231] for example. Form variations (ANSI Y14.5:1994) [29] and coordinate transformations can be used to represent tolerance zones [57]. Alternatively, a graphical representation of part features, process plans, and functional requirements defined with an ISO standard can be employed to analyze three-dimensional tolerance specifications and to generate manufacturing specifications compatible with ISO standards [11].

3.3 Tolerance synthesis

Tolerance synthesis, or tolerance allocation, is the reverse process of tolerance analysis. It provides a rational basis for assigning tolerances to working dimensions. Tolerance synthesis has enormous impact on cost and quality. It affects the fit and function of the product, which can cause poor performance and dissatisfied customers. With respect to manufacturing, tolerance requirements determine the selection of machines, tools, and fixtures; the operator skill level and set-up costs; inspection and gage precision; etc. In conclusion, tolerance synthesis affects almost every aspect of the product life cycle. Most tolerance synthesis approaches are based on the optimization of a cost-tolerance function. These approaches try to get optimal tolerance values when the tolerance stacks are assumed to be fixed. Nevertheless, the utilization of these models in industry is still limited. One major reason is that these models try to take advantage of the superficial knowledge of processes, which is usually obtained from machinist handbooks or company manuals. Process knowledge at this level cannot provide the designer with sufficiently precise tolerance values.

Commonly used tolerance synthesis methods include [27]:

- Allocation by proportional scaling: component tolerances are linearly scaled by a common proportionality factor.
- Allocation by constant precision factor: component tolerances are allocated by means of weight factors. In this way, weight factors are assigned to each component tolerance in the accumulation model and the system distributes a corresponding fraction of the tolerance pool to each component. Larger weight factors and corresponding bigger tolerances can be given to those dimensions that are the more costly or difficult to manufacture, which improves the cost and manufacturability of the design.
- Allocation by optimization techniques: the most popular optimization technique of component tolerance allocation is to minimize the cost of production of an assembly. It is accomplished by defining a cost-tolerance mathematical model for each component part in the assembly. An optimization algorithm assigns the tolerance for each component and searches systematically for the combination of tolerances that minimize the cost.

3.3.1 Tolerance synthesis models

Tolerance synthesis or tolerance allocation can be interpreted as minimizing a cost function C(T) with respect to a set of tolerances T. According to the nature of the target function *C*(·) (the cost is modeled to change linearly, reciprocally, or exponentially with the tolerance), existing tolerance synthesis models can be classified as shown in Fig. 5.

Cost-tolerance models are typical analytical cost estimation techniques [244]. The objective of these models is to estimate product cost considering design tolerances of a product as a function of the product cost. As an example, in the minimum cost optimization method, a set of tolerances is initially selected. Then, an optimization algorithm is used to find the minimal cost. However, due to the number of variables, the optimization can be rather involved, and a global minimum is often not attained [27, 30].

Some recent optimization methods are based on AI techniques, such as genetic algorithms, artificial neural networks, simulated annealing, neuro-fuzzy learning, and ant colony algorithm [166, 167].

Taguchi et al. presented quality engineering as an approach to handling tolerancing issues [211]. Quality engineering aims at an integrated production system with an overall quality control, in which every activity is controlled in order to produce the products with minimal deviations from target values. Details of various application methods of quality engineering to tolerance analysis and synthesis can be found in [46]; the application of parametric design and quality loss functions is discussed in [39, 70, 71].

Statistical tolerancing synthesis (and process capability index applications) drew attention in recent years. It assumes that the final tolerance specifications and the distributions of the process dimensions are known [230]. This idea was further developed:

- The distribution function zone approach was extended to an optimized cost-tolerance model, which solves the statistical tolerance synthesis problems. The model is illustrated with an assembly example in [259].
- Process capability index applications in tolerance synthesis are another important research area [187].
- An optimization model, named reliability index model, with consideration of the required functional reliability, the minimum machining cost, and quality loss was established [104].

In summary, tolerance synthesis is mainly used for assembly tolerances. However, tolerance synthesis for parts, especially sheet metal parts, has its own, only partly addressed, characteristics.

3.4 Tolerance transfer

Tolerance transfer, as tolerance analysis and synthesis in process planning, is a method to convert design tolerances into a manufacturing plan.

3.4.1 Conventional tolerance transfer method

Tolerance charting is the most popular conventional tolerance transfer technique. A tolerance chart is a graphical tool for process planners to determine the manufacturing dimensions and tolerances of each machining operation, based on the design dimensions and tolerances.

The fundamental idea of tolerance charting is discussed in [21, 22]. The two main fundamental tolerance charting techniques, Wade's and Bourde's model, are compared in detail in [126]. The author concludes that Bourde's model appears more appropriate for the treatment of resultant dimensions obtained under a single setup.

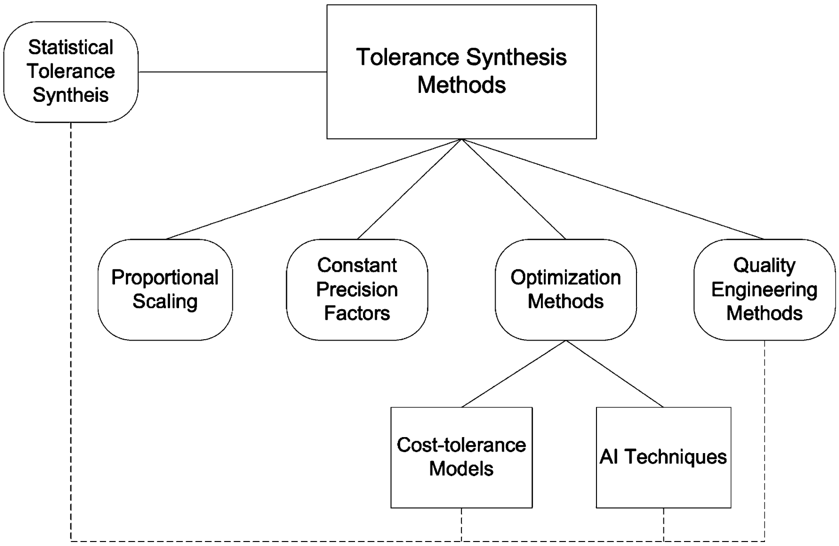

Fig. 5 Main tolerance synthesis methods

An overview of important tolerance charting-based approaches is given in [98]. Since then, the three referenced approaches were further developed:

- Angular tolerance charting [106, 107, 255, 256]
- Digraphic tolerance charts [1, 157]
- Rooted tree model and datum-hierarchy tree method [20, 221, 222]

Although tolerance charting is applied widely in tolerance transfer, it has a major shortcoming: it cannot deal with complex spatial tolerance transfer issues or geometrical tolerances.

3.4.2 Three-dimensional tolerance transfer

Most tolerance charting techniques can handle only the size-dimensional tolerances or a limited set of geometric tolerances. Thus, it is necessary to develop new tolerance propagation techniques in process planning for 3D tolerance transfer, especially for geometric tolerances. Existing approaches to three-dimensional tolerance analysis that are suitable for tolerance transfer are listed in Table 3.

3.5 Monte Carlo simulation

The Monte-Carlo, or random sampling, method numerically determines approximate solutions in mathematical physics and engineering [177]. This stochastic technique was utilized for centuries, but only from 1940s has it gained the status of a method capable to address complex applications.

The Monte Carlo method has been used extensively for statistical tolerancing. Derivation of the statistical moments of a function of random variables is usually impossible in closed form, especially when the functional form is complicated or piecewise-defined. The Monte Carlo method has the advantage of simplicity and flexibility. However, this method can be computationally expensive. With the improvement of computational capacity of computers, the Monte Carlo method is adopted by many software packages, for example, variation simulation analysis, and then applied in some commercial software including CATIA, Pro/Engineer, and UG [98, 178].

The Monte Carlo method can be easily used for tolerance analysis [76, 98, 186, 200], but it was rarely used in tolerance synthesis, as it is difficult to obtain derivatives or gradients with it. This changed, though, in recent years [59, 102, 118, 121, 122, 134, 203].

4 Applying feature-based tolerance analysis in CAPP

4.1 Current tendency

The Society of Manufacturing Engineers defines process planning as the systematic determination of methods by which a product is to be manufactured, economically and competitively.

In other words, process planning is the transposition of engineering design information into process steps and instructions to efficiently and effectively manufacture products. Process planning activities include the following [241]:

- Interpretation of product design data
- Determination of production tolerances
- Determination of setup requirements
- Selection of tool sets
- Selection of machine tools
- Sequencing of operations
- Tool path planning
- Determination of machining conditions
- Generation of process route sheets
- Selection of machining methods and processes
- Design of jigs and fixtures
- Calculation of process times
- NC program generation
- Capacity planning

Although CAPP uses almost the same steps taken in manual process planning, it requires less time compared with manual process planning. Due to the rapid diminishing number of experienced process planners in industry, compressed product life cycles, and the broad use of CAD/CAM, the research on CAPP has gained more attention than ever before. Approaches used in CAPP can be categorized as two types [152]:

- *Variant process planning* follows the principle that similar parts require similar plans. This technology is often used with group technology for coding and classification.
- *Generative process planning* utilizes decision logic, formulae, manufacturing rules, and geometry-based

Table 3 Three-dimensional tolerance transfer methods

Small displacement torsor (SDT) and proportioned assembly clearance volume (PACV)	[125, 215, 216, 235]
Technologically and topologically related surfaces model (TTRS)	[56, 58]
Product data translator (PDT) approach	[263]

data to develop a new plan for each part based on input about the part's features and attributes.

Beside the above classification, research can be categorized on the basis of their geometrical modeling (Fig. 6). Most research in this area is focused on optimization of process plans, although some other issues, such as knowledge and data management in CAPP, are important topics [55]. Optimization techniques used in CAPP can be categorized as:

- Knowledge-based reasoning [43, 250].
- Graph theoretic approaches [19, 44, 105, 136, 223].
- Heuristic algorithms [131, 132, 169].
- Artificial intelligence, such as evolutionary or genetic algorithms, artificial neural network, fuzzy logic, expert systems, and so on [6, 15, 44, 81, 119, 120, 130, 172].

4.1.1 The concept of features

The use of features originates in the reasoning processes to associate domain knowledge with object representations by natural means. Numerous feature definitions are used in CAD, computer-aided engineering (CAE), CAPP, and CAM. At first, machining features were used to integrate CAPP and CAM packages on a geometrical level. More recently, the feature concept was expanded to relations between geometrical and non-geometrical entities. Historical definitions of features are reviewed in Table 4.

Regardless of how features are defined, features can be considered as the smallest elements which possess explicit engineering meaning. Therefore, features are suitable as a link between life cycle stages. According to their applications in different stages, features can be classified for the following engineering stages (modified from [33]): conceptual design, embodiment design, detailed design, assembly design, CAE, manufacturing, process planning, and inspection.

It can be envisaged that a new stream of feature technology is to be developed for geometric and dimensional tolerance (GDT) applications. Such features are to be identified and related to computer-aided tolerancing functions. With them, systematic design tolerance specifications can be modeled and captured in the detailed design stage. These features may involve a hierarchical relation tree to associate the ideal functionality of a product to each individual assembly feature tolerance. Such an assembly tolerance feature can be further broken down into a set of associated part GDT tolerance features that are required when specifying individual part tolerances. At both stages of tolerance specification, tolerance propagation and synthesis are to be involved and always part of the design task for manufacturing aspect. The application of geometric and dimensional tolerance when a process plan is developed and the final inspection carried out requires the implementation and check of tolerance features with manufacturing tooling, processes, and measures.

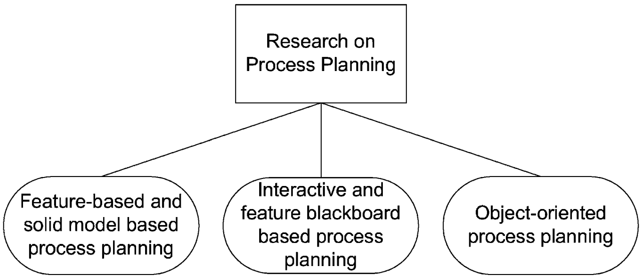

Fig. 6 Research on process planning

Sheet metal feature definitions are as diverse as the general feature definitions discussed above. In order to support design and process planning for sheet metal forming, sheet metal features highlight formability. Thus, the following attributes define the sheet metal forming features of the part in design and process planning stage [modified from 214]: feature identifier, feature form, material, dimensions associated with the feature, geometrical tolerance associated, primary working direction or die closure direction, positioning datum, and sheet metal forming method.

4.1.2 Associative features

Associative features are a recently defined group of user-defined, object-oriented, self-contained, and flexible semantic features [16]. They are proposed as classes to represent relations between different forms of non-geometrical and geometrical entities depending on specific applications [143–147]. Based on object-oriented technology, those features that are difficult to be defined in a traditional feature concept can be modeled parametrically and generically. Associative features are consistent to model the evolvement of features in different stages of product life cycle.

Figure 7 shows a sheet metal part that can be fully defined with some typical associative forming features. First, basic geometric features are defined as those primary features or elemental plates which represent the overall shape of a sheet metal part as the base for more detailed shape definitions. In Fig. 7, the primary feature is the S-plate. The primary features include plates, walls, L-brackets, U-channels, curves, and boxes. Then, based on the above primary features, subsidiary features can be defined to represent those manufacturing-related feature elements which represent localized characters of a sheet metal part. Subsidiary features are modifications of the basic features. Typical subsidiary features are bends, pierced holes, extruded holes, embosses, lancing forms,

Table 4 Definition of features

Definition of a feature	Source
A region of interest in a part model	[246]
Any geometric form or entity that is used in reasoning in one or more design or manufacturing activities	[47]
Generic shapes associated to certain properties or attributes and knowledge useful in reasoning about the product	[183, 185]
A partial form or a product characteristic that is considered as a unit and that has a semantic meaning in design, process planning, manufacture, cost estimation, or other engineering discipline	[245]
Regions of an object that are meaningful for a specific activity or application	[229]
A representation of geometrical shape with a set of engineering attributes	[25]
The representation of shape aspects of a physical product that are mappable to a generic shape and that have functional significance	[184]
A set of form elements with a functional meaning in a given application context that allows an association between shapes and functionality	[153]
A representation of shape aspects of a product that are mappable to a generic shape and functionally significant for some product life cycle phase	[16]

hems, beads, slots, bosses, ribs, and set-outs. In Fig. 7, the four bends and the hole are subsidiary features.

In addition, sheet metal forming resources, such as machining tools and fixtures, can be explicitly defined in feature class as attributes or constraints. The associations can be created by reasoning processes such as sequencing, tool selection, gage selection, and fixture selection. A potential feature-based sheet metal forming planning system can be developed based on the relevant associative feature theory and applications [33–36] because in the above-listed references, associative concept design features, detailed design features, and process planning features have been defined using a unified feature model. A prototype system was developed to demonstrate the capability and feasibility of the proposed product modeling scheme.

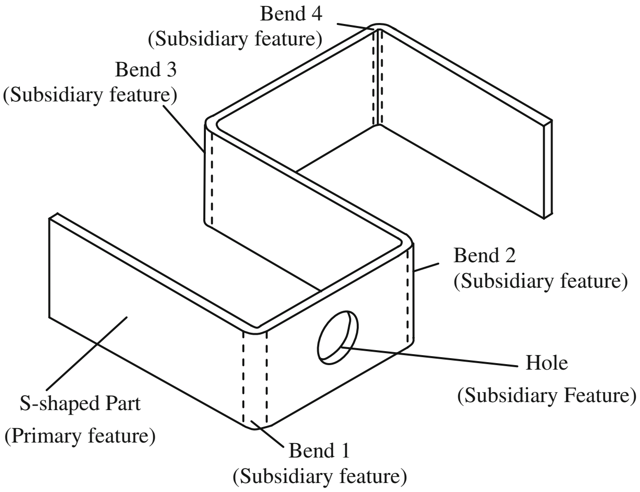

Fig. 7 Examples of sheet metal part features

4.1.3 Feature-based process planning

Feature-based process planning plays a crucial role in an integration effort of product life cycle. In feature-based process planning, machining features are recognized CAD model, and machining processes and their sequences are determined based on the features and other machining information.

With a feature-based hierarchical description of the part design, process planning decisions are made based on individual features or groups of features. A feature-based approach allows one to automate or semi-automate the processes from design to manufacturing. A simple feature-based flexible process planning system is laid out in Fig. 8. A summary of recent research in this field is given in Table 5.

Feature-based process planning was a hot research field in recent years. Although many researchers focus on developing CAPP systems [8, 9, 25, 37] or finding optimal process planning procedures, more and more attention is paid to the details of applying feature techniques on process planning. For example, besides feature modeling and recognition [5, 10], *design by features* approach is utilized in feature conversion, composition, and de-composition [7, 12, 24, 47]. Association and integration of CAD/CAE/CAM and CAPP [23, 25] are equally important topics, and more attention is focused on optimization methods by AI [13, 61, 108].

4.2 Process planning in sheet metal forming

4.2.1 Overview

In the 1990s, process planning for small batch part manufacturing of sheet metal parts became a major research area. Some researchers focus on computer-aided process

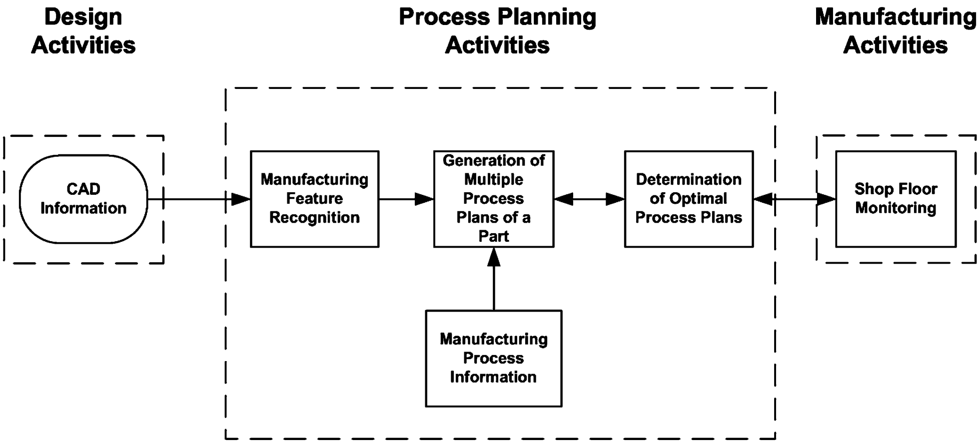

Fig. 8 Example of a simple feature-based process planning system

planning for sheet metal forming [136, 170, 227]. The sheet metal manufacturing process comprises many complex operations, which make it difficult to construct a comprehensive CAPP system for all sheet metal parts. Being the most common operation of sheet metal forming, bending is one of the most researched topics in this field [72, 219]. Other operations such as drawing or combined operations begin to gain more attention. Table 6 shows a survey of papers on CAPP of sheet metal forming. Only certain typical operations were selected for review, as too many sheet metal forming methods exist to be listed comprehensively.

4.2.2 Feature-based process planning in sheet metal forming

An early topic in this field is feature representation and classification. In [49–54], a CAPP system is presented which relies on a feature type referred to as *connections*. A connection is a design feature, typically a bend or a welded seam. A further division, the bend features in simple bends and those with hemmed or curled edges, is discussed in [225]. Basic sheet metal features are classified in [14] into walls, bends, form features, cuts, punches, notches, and so on.

An integrated system presented in [239] for the design and production of sheet metal parts identifies several bend features: bend graph, internal tab, essential and optional collinear bend, outside/inside bend, taller flange, shorter/longer bend, channel, corner, hemming bend, large-radius bend, part overhang, louver, and dimple.

A fully automated experimental feature recognition system for sheet metal forming process planning extracts the sheet metal feature information from 2D orthographic drawings to generate process plan without any user interaction [197].

Other research is focused on the development of feature-based process planning systems:

- In the integrated modeling and process planning system developed by [40, 41, 45, 128] for planning bending operations of progressive dies, the geometrical bend mapping function for feature elements within individual bends and the transformation matrix for connected sub-bends are formulated.
- A prototype STEP-compliant process planning system for sheet metal product development integrates software modules for nesting optimization, path optimiza-

Table 5 Summary: features in process planning

Topic	Source
Feature modeling and classification	[8, 173, 226]
Roles of manufacturing features in process planning	[228]
Feature recognition/extraction technique	[5, 10, 24, 65, 94, 96, 109, 113, 115, 139, 154, 161, 174, 209, 252]
Feature-based CAPP system	[9, 37, 38, 62, 64, 92, 111, 137, 140, 161, 242, 253, 258]
Integration of CAD/CAE/CAM and CAPP	[33, 100, 224, 251]
Feature-based analysis of the manufacturability of machined parts	[90]
Feature composition and decomposition	[123, 124, 133, 210]
Feature-based process planning for environmentally conscious machining	[205, 206]
Feature-based inspection process planning	[13, 249, 261]
Optimization by AI and KBE techniques	[61, 108, 141, 198, 199]

Table 6 Review on CAPP for sheet metal forming

	All operations	Bending	Punching	Drawing	Blanking	CAPP system	Operation and tool selection	Sequencing
[202]	√					√		√
[97]		√						√
[50]		√				√		√
[207]	√					√		
[54]		√				△	√	
[168]		√						√
[89]		√				√	√	√
[40]		√			√	√		
[87]		√					√	
[191]		√						√
[51]		√				√		△
[142, 208]	√					√		
[219]		√					√	√
[91]	√						√	
[112]		√	√			√	△	
[160]				√		√		
[103]			√				√	√
[67]		√					√	
[201]	√					√		
[240]			√			△	√	√
[45]	√			△			√	√
[234]		√	√				△	△
[44]			√			√	√	√
[49]	√					√		
[204]	√					√	△	△
[192]		√						√
[74]		√					√	
[158]		√					△	√
[52]		√					√	
[135]		√					√	√
[68]		√						√
[88]		√					√	√
[41]				√	√	√		
[78]	√					√		
[7]	√						√	
[12]	√						√	√
[110]				√		√		△
[151]		√					△	△
[220]		√						√
[176]		√						√
[156]		√					√	
[237]	√					√	√	△
[23]		√					△	√
[171]			√		√	√		
[81]			√			√	√	√

Tick symbol discussed in detail, *triangle* touched on tion and planning, simulation, and machining parameters set-up and CNC machining [254].

- Another CAPP system based on feature technique addresses stamping processes for automobile panels [262].

Feature-based sheet metal part stampability evaluation and stamping process planning approaches have been studied in a two-part paper. The first part identifies the aims and criteria of a stampability evaluation and formalizes the stampability evaluation knowledge [212]. The second part presents a feature mapping system which connects the stamping design feature space and the stamping process feature space [213].

Opposed to traditional machining process planning, feature-based process planning for sheet metal forming is little represented in literature. Feature representation, classification, recognition, and development of feature-based process planning systems are current research topics; other characteristics of sheet metal forming processes are unaddressed.

5 Tolerance transfer in sheet metal part forming

Tolerance transfer in process planning of sheet metal part forming attracted only little attention in the past as shown in Table 7 according to available literature. Furthermore, all the references listed focus on bending operations and raise or leave the following issues unaddressed:

- Computer-aided tolerancing does not address processes including several operations of distinct nature, such as bending, punching, blanking, and deep-drawing.
- Machining errors and their causes and inter-dependencies are not characterized comprehensively as the sources of final error accumulation, although some of the errors are discussed in papers above.
- Only size-dimensional tolerances (using conventional worst-case models) are discussed in detail.
- Statistical tolerancing approaches reflect actual part tolerances better than worst-case tolerancing. However, they are utilized only for sheet metal assembly issues [200] or size dimensions [79, 80, 93].
- Tolerance synthesis/allocation for sheet metal part forming are seldom studied. Currently, research works are focused on sheet metal assembly [150, 188].

6 Summary

Even though process tolerances of individual sheet metal forming operations are well understood and the industry has adopted geometric tolerances and dimensions via some standards, the combinational theory and applications of tolerance stacks and the allocation of tolerances to individual operations are not mature. This discrepancy is mostly due to insufficiencies of tolerance transfer methods—certain differences with assemblies and material removal methods make the problem a unique challenge. Only a small number of publications address geometric tolerances and, as compared with metal removal processes or assemblies, they cover a limited scope and depth. We observed the following points:

- Insufficient coverage of operations. Although there have been numerous publications addressing CAPP for sheet metal, including systems, operation, tool selection, and sequencing, more than half of the 46 publications examined by the authors focus on bending operations only.
- Limited integration to other computer solutions. Feature-based process planning considering sheet metal forming tolerancing, i.e., geometric tolerance feature associations in the integrations of CAD, CAE, CAM, and CAPP are only partially addressed.
- More research work is required for tolerance transfer of geometric dimensions. Only nine publications were discovered by the authors.
- Geometric tolerance synthesis should be studied; no publication has been found.

Table 7 Tolerance transfer in sheet metal part forming

Resource	Size dimensional tolerance	GD&T	Tolerance analysis	Tolerance synthesis	Worse case	Statistical tolerancing	Analytic	Graphical
[52–54]	√	△	√		√		√	△
[191]	√		√		√		√	△
[79, 80, 93]	√		√			√	√	
[95]	√		√		√			√
[12]	√		√		√		√	

Tick symbol discussed in detail, *triangle* touched on

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