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Optimization of the Energy Consumption of a CNC Machine Cutting Tool with Hard-to-Formalize Restrictions

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Abstract—The energy consumption of a CNC machine cutting tool is largely determined by the tool's path and depends on the length of idle and working motions, as well as on the number of insertion points. To reduce the consumption level, it is usually necessary to minimize all these parameters. However, the resulting paths are not always technologically acceptable, which can lead to defective products and damage the equipment. This article considers the automatic formation of a technologically acceptable path with the minimal energy consumption. The path formation is divided into the selection of the part-cutting procedure and the selection of the tool-insertion (entry and exit) points. The cutting procedure is selected according to the rules of detecting pockets of material formed by profiles of parts by using geometric centroids and convex cutting profile shells. The insertion points are selected by one of several versions of an intervallic search algorithm and depending on the number of cut-out parts. Cutting restrictions are considered, and cases of pocket formation are described. The restrictions are represented by a list of rules that formalize controversial cutting situations. The optimization criterion is the minimum total cutting time. The technique of penalty functions has made it possible to reject pocket-forming solutions. The general chart and a case of using the algorithm are given and considered.

Keywords: CNC machines, cutting tool, technological constraints, material cutting, routing

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The solution of the cutting-tool (CT) routing problem is one of the key stages in cutting of sheet materials. Optimization of this stage will make it possible to reduce the cost and energy consumption of fabrication of parts. The CT routing across the cutting chart can be presented as the traveling salesman problem with some restrictions: to derive a solution, there are sets of potential tool entry (insertion) points recorded as $C_i = \{p_1, p_2, ..., p_n\}$, only one of which can be selected per contour of cutting (a closed geometric object consisting of a set of arcs and lines) [1–3].

As a general rule, it is impossible to obtain an optimal CT path because of the need to check a large number of variants that grows nonlinearly with the factorial dependence on the number of cutting contours:

$$M(N) = N!\prod_{i=1}^{N} n_i,$$

where M is the total number of possible solutions, N is the total number of cutting contours on the cutting chart, and n_i is the number of potential insertion points in the i contour.

There are a large number of ways to use heuristic algorithms to obtain nearly optimal solutions on the basis of the following criteria [2]:

—minimized idle CT motions across the cutting chart;

—minimized working CT motions, which is attained by means of various cutting technologies;

—minimized total cutting time, i.e., the two previous criteria used together; and

—the best possible quality of the CT path, which is attained by taking account into account hard-to-formalize cases that lead to product failures or emergencies.

The routing problem has been successfully solved before using the first three criteria [4]. Sometimes, however, this approach makes it impossible to draw a CT path without relying on specialist expertise because nearly optimal solutions may appear technologically unacceptable.

In addition, each new generation of machines is more advanced than the previous one, which makes the standard criteria less relevant. Quality criteria form a large group and cannot be formalized in a unique

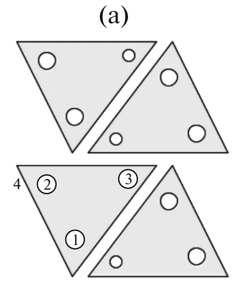

Fig. 1. Technological restrictions on solving (a) the contour nesting level problem, (b) compensated cutting, and (c) cutting in view of an approach to/departure from the contour.

manner. However, they diminish the effect of the human factor on the cutting process.

This article presents a solution for the routing problem by means of hard-to-formalize criteria that make it possible to reduce a machine's energy consumption.

ROUTING-PROBLEM RESTRICTIONS

Whatever the cutting chart may be, the following restrictions on CT path formation must be observed:

—the previous conditions for processing of cutting contours (Fig. 1a)—first of all, the cutting of contours with the highest nesting level—must be established;

—the cutting design must be made with a compensation equal to one-half of the cutting width, i.e., along the contour equidistance (Fig. 1b); and

—at the CT entry and exit, a distance must be taken into account depending on the CT type and processed-workpiece thickness (Fig. 1c).

There are no exceptions to the enumerated restrictions, and the consequences of violating these restrictions are clear and well-grounded [3]. In certain conditions, however, some situations may yield invalid results. For example, let us take the *locking* of parts in pockets of material that are formed by processing nonconvex contours (Fig. 2a, parts 4 and *5* after the machining of part *3*) or by simple sequential cutting of several simple contours (Fig. 2b, part 9).

Taking into account such particular conditions as material thickness, contour shape, pocket area, CT type, etc., the processing of this pocket will cause failure of the workpiece or the CT itself.

It is a nontrivial task to formalize such cases. In practice, they are controlled by the machine operator, which requires an extended period of time to check large cutting charts with several hundred parts.

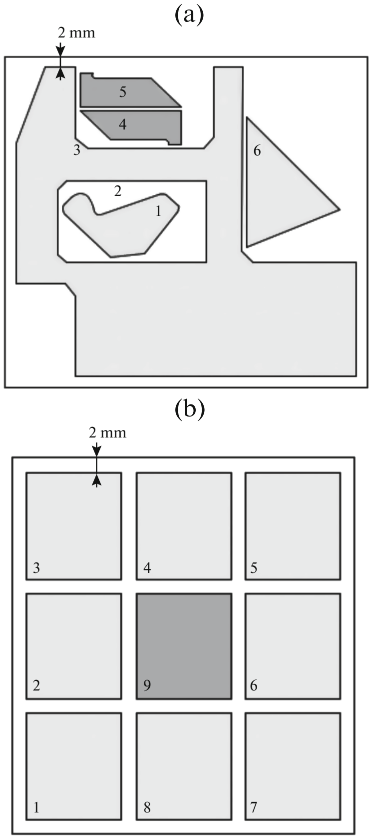

Fig. 2. Cases of material pocket formation: (a) parts 4 and 5 in the pocket of part 9; (b part 9 in the pocket after the other parts are processed.

CT ROUTING ALGORITHM

The routing problem is solved in two stages. In the first stage, a sequence is formed for the machine to bypass the cutting contours. Insertion points are then selected on the contours in accordance with the sequence that has been created.

The division into stages makes it possible to reduce the amount of calculation by avoiding many worse options. This approach also allows using various solution-search algorithms in each of the stages.

The restrictions consist in a list of rules making up a set of potentially dangerous cutting situations. The problem's criterion is the minimization of the total cutting time within the limits of the set of acceptable solutions set by the list.

The list of rules can be formed dynamically, this depending on the CT type and specific priorities in cutting. We shall now see how to construct a list using the example of the following rules and restrictions.

1. If uncut contour $c_j \in C$, $i \neq j$ discovered when processing contour $c_i \in C$ is such that contour c_j is

found inside contour c_i, then c_i cannot be the next point on the path (the precedence term, Fig. 1a).

2. If uncut contour $c_j \in C$ discovered when processing contour $c_i \in C$ is such that the geometric centroid of c_j is found inside the convex shell of c_i, then c_i cannot be the next point on the CT path (Fig. 3a).

We shall now introduce $Hd_i = Y_{\max i} - Y_{\min i}$, where i is the cutting-contour index and $Y_{\max i}$ and $Y_{\min i}$ are the maximum and minimum ordinate of the i contour, respectively. We shall then draw a straight line through the centroid of the i contour parallel to the Y axis. We shall then mark off the $Hd_i/4$ section (up and down) from the centroid along the straight line that has been drawn and obtain section h_i with its center coincident with the centroid. Thus, if the projections of h_i and h_j overlap one another, $i \neq j$ on the Y axis, and the abscissa of the j centroid is less than the abscissa of the i centroid, then contour c_i cannot be the next point on the path (Fig. 3b).

The list of rules makes it possible to determine whether a contour is acceptable for cutting at a particular stage. If the contour-processing results in the formation of a pocket of material, this contour will be delayed until the next check. The most acceptable contour is then selected through minimization of the total cutting time. The minimal overall length of the CT idle run to the point of possible insertion and penalty, proportionate to the abscissa of the possible insertion point, makes it possible to reject some potential pocket-forming solutions.

1. Problem-solution stage two consists in an intervallic search for contour-insertion points in the fixed processing sequence by one of several methods.

2. An exhaustive search is suited for cutting charts of up to eight cutting contours in size (Fig. 4a).

3. An intervallic step-by-step search is suited for cutting charts of 30–40 contours in size and an interval size of no more than 5 (Fig. 4b).

4. A successive intervallic search is suited for cutting charts of 70–100 contours in size and an interval size of not more than 6 (Fig. 4c).

5. A random intervallic search is suited for cutting charts of more than 100 contours in size and an interval size of 5 (Fig. 4d).

The general chart of the elaborated algorithm is given in Fig. 5.

To derive the solution using the suggested algorithm, it is necessary to check the finite number of CT paths as

$$M(N) = M^3 + m\prod_{i=1}^{N} n_i,$$

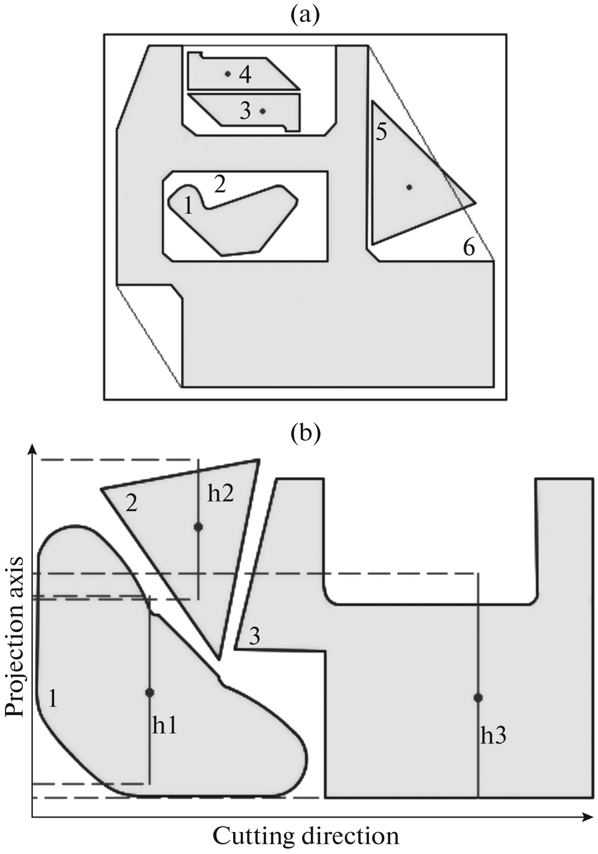

Fig. 3. Illustration of the contour-cutting bypass rules: (a) detection of pockets by convex shells; (b) detection of pockets along the tool travel path.

where M is the total number of possible solutions, N is the total number of cutting contours on the cutting chart, p_i is the number of potential insertion points on the i contour, and m is the number of exhaustive-search intervals.

EXPERIMENTAL CHECK

The original data used in testing the routing algorithm were cutting charts constructed in the ITAS Nesting system [5].

A simple cutting chart of 12 parts (48 contours) (Fig. 6a) contains no odd idle CT transitions and no parts *locked* in the pocket at the moment of cutting. According to the suggested list of rules, the path on the complex cutting chart (Fig. 6b) with 11 parts (13 contours of different sizes, shapes, and nesting levels) is also technologically valid, i.e., contains no parts in the pockets of material at the moment of cutting.

Thus, the proposed algorithm makes it possible to reduce the energy consumption of a CNC machine cutting tool and form a technologically valid path when cutting a sheet material. The algorithm takes

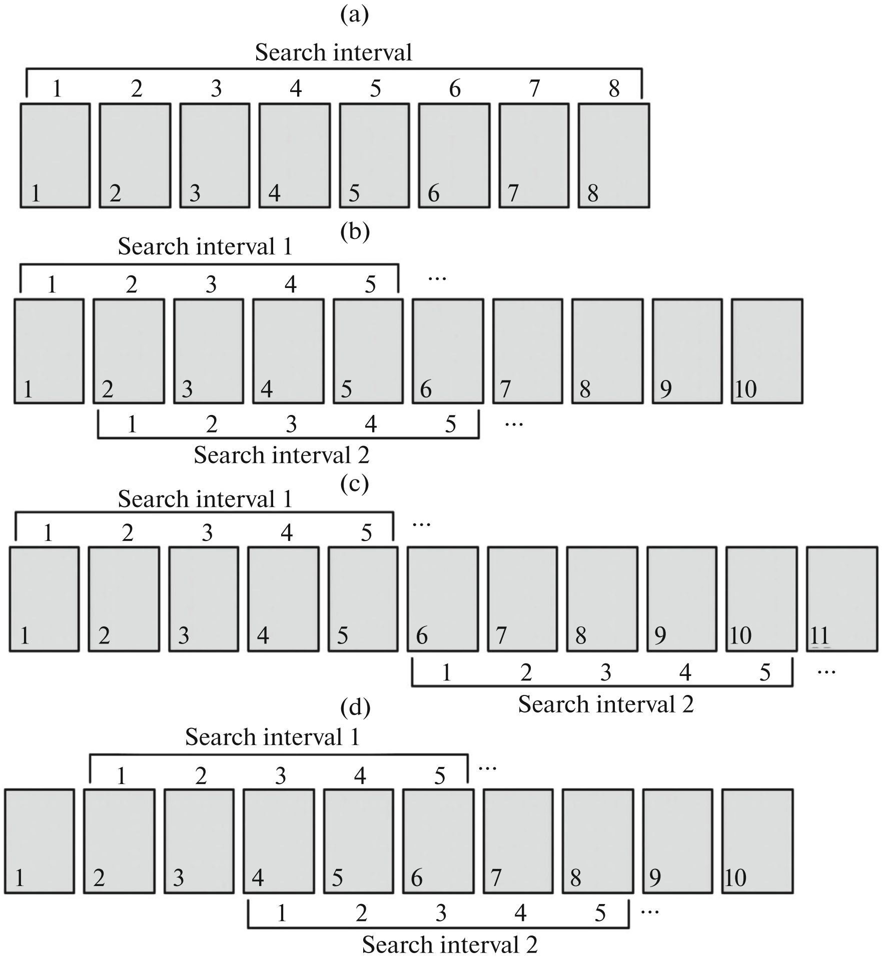

Fig. 4. Intervallic-search variants: (a) exhaustive search, (b) intervallic search with a step of 1, (c) intervallic search by interval size, and (d) random intervallic search.

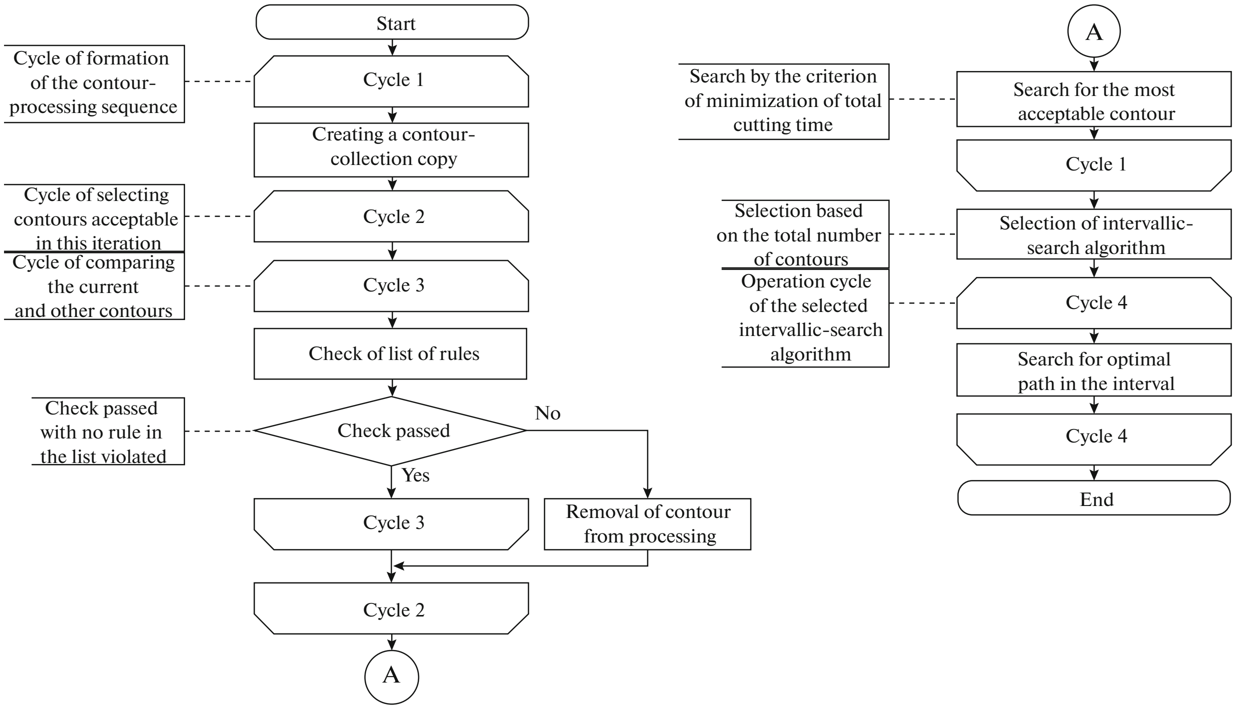

Fig. 5. CT routing algorithm chart.

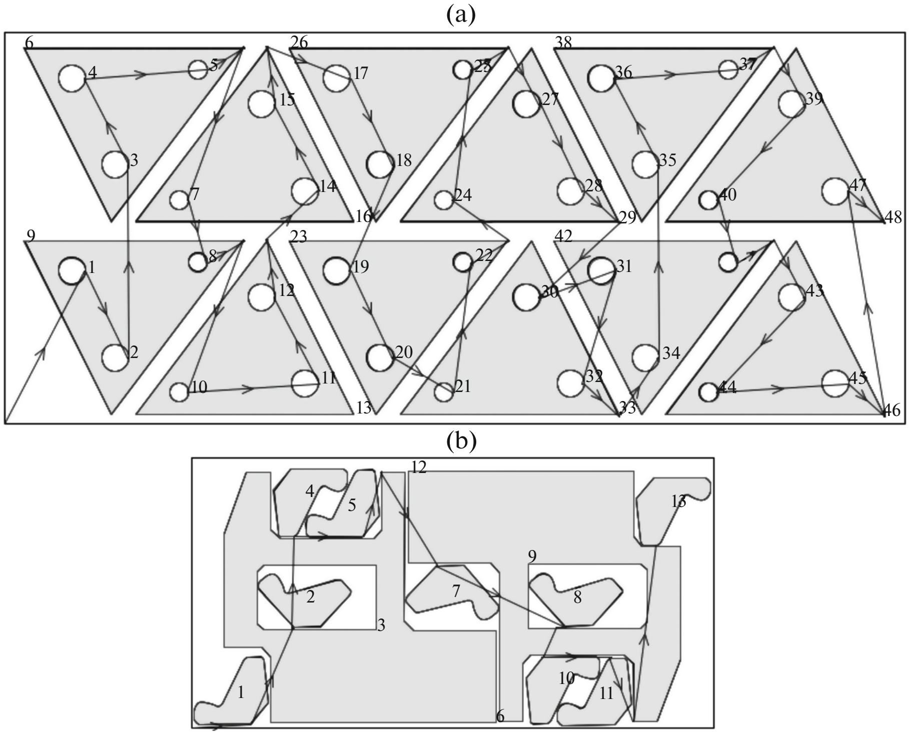

Fig. 6. CT routing algorithm test: (a) simple cutting chart; (b) complex cutting chart.

technological restrictions into account and prevents the formation of pockets with parts because it uses a list of rules that formalizes ambiguous cutting situations the consideration of which makes it possible to diminish the role of the human factor in drawing a path on cutting charts with many parts of complex shape.

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