Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 14
ISSUE 1-2
January-February
2006

Concept of automatic programming of NC machine for metal plate cutting by genetic algorithm method

B. Vaupotic [a,*], M. Kovacic [b], M. Ficko [a], J. Balic [a]
[a] Laboratory for Intelligent Manufacturing Systems, Faculty of Mechanical Engineering, University of Maribor, Smetanova 17, SI-2000 Maribor, Slovenia
[b] ŠTORE STEEL d.o.o., Železarska cesta 3, 3220 Štore, Slovenia
* Corresponding author: E-mail address: bostjan.vaupotic@uni-mb.si

Received 15.11.2005; accepted in revised form 31.12.2005

Analysis and modelling

ABSTRACT

Purpose: In this paper the concept of automatic programs of the NC machine for metal plate cutting by genetic algorithm method has been presented.
Design/methodology/approach: The paper was limited to automatic creation of NC programs for two-dimensional cutting of material by means of adaptive heuristic search algorithms.
Findings: Automatic creation of NC programs in laser cutting of materials combines the CAD concepts, the recognition of features and creation and optimization of NC programs. The proposed intelligent system is capable to recognize automatically the nesting of products in the layout, to determine the incisions and sequences of cuts forming the laid out products. Position of incisions is determined at the relevant places on the cut. The system is capable to find the shortest path between individual cuts and to record the NC program.
Research limitations/implications: It would be appropriate to orient future researches towards conceiving an improved system for three-dimensional cutting with optional determination of positions of incisions, with the capability to sense collisions and with optimization of the speed and acceleration during cutting.
Practical implications: The proposed system assures automatic preparation of NC program without NC programer.
Originality/value: The proposed concept shows a high degree of universality, efficiency and reliability and it can be simply adapted to other NC-machines.
Keywords: Analysis and modeling; Artificial Intelligence Methods; Laser cutting; genetic algorithms; NC machines.

1. Genetic algorithms

Genetic algorithms (GA) are adaptive methods used for solving the search and optimization problems. They are based on the genetic process of biological organisms, since they imitate the evolution in nature, where the population of a species develops through generations according to the principle of natural selection and survival of the fittest. This was clearly recorded for the first time already by Charles Darwin. By imitating this process the genetic algorithms can "develop" the solution of a problem, if they are suitably programmed.

The bases of the genetic algorithms were presented for the first time by Holland in 1962. Since then, the genetic algorithms have been an interesting area of many relevant researches. The researches flourished particularly in 90ies, when many important articles and monographs were published, see e.g. [5]. The GA imitates the processes in nature, which are crucial for evolution. In the nature the individuals of a population mutually compete for the vital resources. Faster and cleverer representatives of the species have more and better resources for survival, whereas the slower and less claver ones get the resources more difficultly or not at all. Further, competition takes place when the partner for reproduction is searched for. The representatives of the species, who are more successful in survival and mating, will in all probability have a relatively greater number of descendants. Weaker individuals will have less descendants or none at all. It means that the genes of well adapted i.e. fit individuals will spread more intensively to future generations, whereas the weaker individuals will even die out. The combination of genes of two adequate parents can give birth to a super-fit descendant having better properties than both of the parents. In this way the species evolve and adapt themselves to their environment.

The GA act analogously with this natural process. They act over a population of subjects, each representing a possible solution of the problem. The estimate of success, adapted to the searched problem, is attributed to each chromosome. More adequate chromosomes - the ones with better estimate - have higher chances of reproduction than the others. Over the current population the simulated process of evolution is carried out. From our population the subset of procreating parents is selected. Thus, new descendants taking some properties from each parent are obtained for our population. Less adequate representatives will procreate with lesser probability and will die out.

By selecting the most adequate solutions (parents) through procreation, new solutions (descendants) replacing less adequate subjects are obtained. That new population of solution contains a higher average of properties of good solution of the previous population. In this way, good properties are spread into the next generations. By selecting more adequate chromosomes for procreation the most promising areas in the field of solutions are examined. If the GA has been well defined, the population will converge to optimal solution [8,10].

2. Structure of system

In general, the systems for automatic cutting of metal plates make the NC program on the basis of the previously made layout of products on the plate [4]. Two-dimensional products in the proposed system can be of any size and shapes. They can be nested (Figure 1) therefore they can contain internal and external boundaries which will be called cuts (Figure 2).

At the beginning, the system recognizes the characteristics on the basis of CAD drawing [9]. Automatically, the relations and the cuts are determined and then still the incisions are determined. The cuts can be nested or non-nested. If the nest contains only one cut, the latter is non-nested. The cuts can be open or closed (Figure 3).

The incisions are the points on the plate where the laser is ignited. Usually the cut during the laser ignition is rather inaccurate [1], therefore cutting is effected subsequently after a certain cut. Incisions are determined only in case of closed cuts. Further, the system creates and optimizes the NC program for cutting of plate. Figure 4 shows the algorithm of the system for programming the machine for cutting of plates in pseudo code [6].

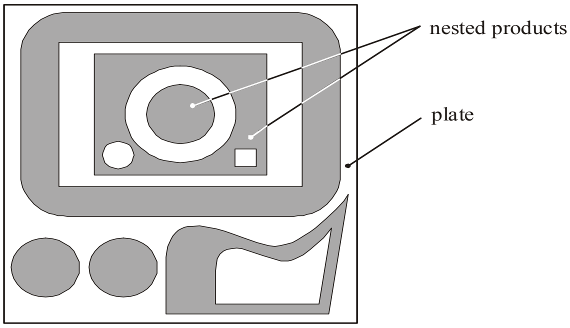

Fig. 1. Products and plate

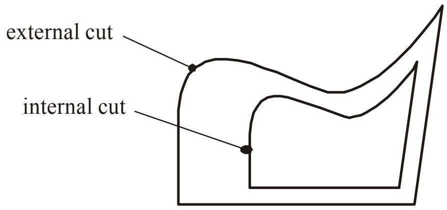

Fig. 2. External and internal boundaries

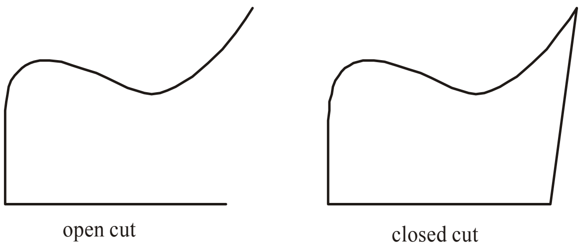

Fig. 3. Open and closed cut

```
start

input of data on blank, products, starting and
              final points
       recognition of characteristics
       determination of incisions
       start   t←0
          if NC program is known
          enter P(t)
          otherwise create P(t)
              evaluate P(t)
              until (stopping condition has been
                      fulfilled)
                     start
                            t→t+1
                     change P(t)
                            evaluate P(t)
                     end
       end
       print-out results
end
```

Fig. 4. Algorithm for programming the NC mach. in pseudo code

2.1. Recognition of characteristics

The product layout comprises nested and non-nested product [11]. Similarly as the products can be nested also the cuts can be nested. Figure 5 shows the nests and their depths for the example in Figure 1. The nests 2 and 3 consist only of cuts of product 3; therefore in this case, we can say that the two cuts of product 3 are non-nested. The nest 1 consists of cuts of product 4, 1 and 3. Products 4, 1 and 3 are nested similarly as their cuts. In case of nest 4 the product 2, contrarily to its cuts, is not nested. It is possible to determine also the depth of the nests. The nest 1 has the depth 5, the nest 2 and 3 are of depth 1, whereas the nest 4 is of depth 2. The system for recognition of characteristics is capable to recognize automatically the nesting of products and cuts and to determine the depth of nests.

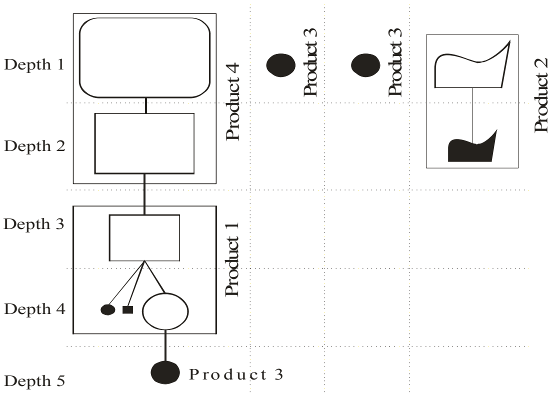

Fig. 5. Nests of cuts and depths of nests

For accuracy of manufacture it must be borne in mind that first the deeply nested cuts must be made in the nest [13]. As shown in Figure 5 only the cuts of products, marked in black, can be made in the beginning of cutting; thus, 6 possibilities can be selected. Consequently, the cuts from greater depths of nests up to shallow places (depth of nest 1) can be made. For greater clarity the Figure 6 shows gradual cutting from cuts of greater depths to shallow areas. Finally, the cut at depth 1 of nest 1 is made.

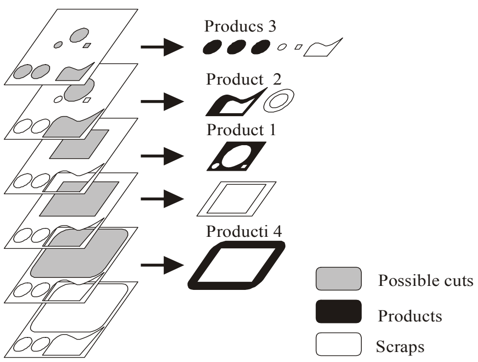

Fig. 6. Gradual cutting from cuts of greater depth of nests up to shallow places

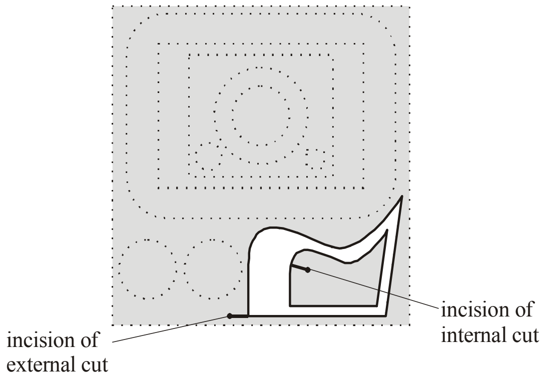

Fig. 7. Incisions, external and internal cuts

In Figure 5 it can be simply established which cuts are internal and which ones are external. Internal cuts are always located at paired depths of the nest (2, 4, 6 ...), whereas the external ones are located at odd parity depths of nests (1, 3, 5 ...). Accordingly, the incisions of external and internal cuts are determined.

2.2. Determination of incisions

The individual cuts may consist of lines, circles and circular curves. As already mentioned, the incisions are not determined for open cuts. The internal and external incisions are determined in the same way. Figure 8 shows the determination of the position of incision. Because of time demandingness of execution of the proposed system, the position of incisions cannot be determined at random. The positions of the incision are determined only at both ends of the lines and circular curves and at every 90°of the circle.

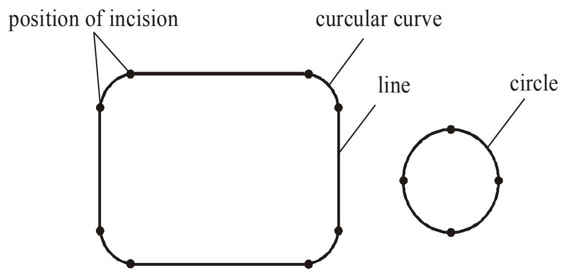

Fig. 8. Determination of position of incision

Subsequently, the orientation of the incision is determined; the orientation is different for the cut of equal form depending on the fact whether the cut is internal or external. On the basis of determined positions of the incisions the two coordinates of the gravity point of positions of incisions (X_t, Y_t) are calculated according to the generally known equations:

$$X_t = \frac{\sum_{i=1}^{n} x_i}{n} \qquad (1)$$

and

$$Y_t = \frac{\sum_{i=1}^{n} y_i}{n} \quad (2)$$

where:

n number of incisions,
i index of incision,
x_i x coordinate of position of incision
y_i y coordinate of position of incision.

Then the incisions are calculated on the basis of the calculated gravity point of their positions. They are oriented towards the gravity point in case of internal convex cuts and away from the gravity point in case of external cuts. Figure 9 shows the determination of incisions for internal and external cuts.

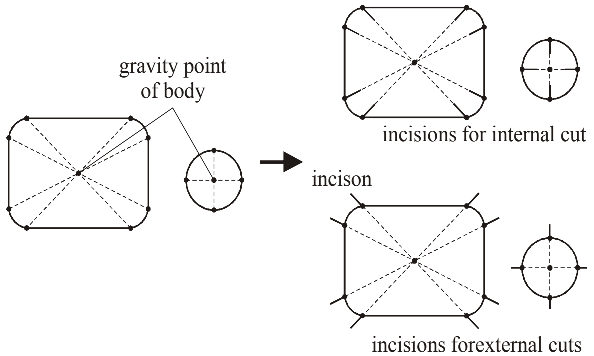

Fig. 9. Determination of incisions for internal and external cuts

Sometimes it may happen that the incision cannot be determined simply or even cannot be determined at all. Figure 10 shows the determination of external incisions, where the cuts are too close to each other. The incision in Figure, indicated enlarged, must be turned round the position of the incision for a certain angle due to proximity of the circular cut. The system automatically creates the incisions at each 15° from the original position of the incision. It selects the first possible incision. In the example, shown in Figure 10, even two incisions are possible. The system selects at random only one of them.

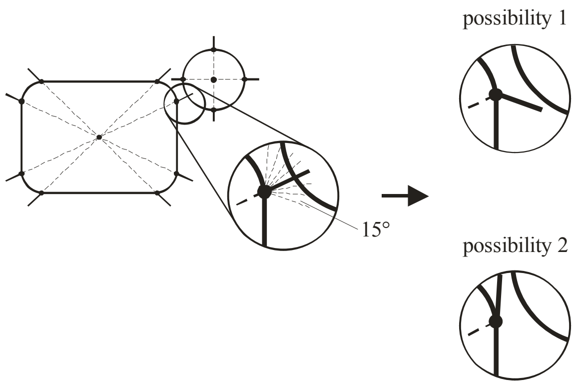

Fig. 10. Determination of incisions in case of adjacent cuts

Figure 11 shows the determination of incisions of internal and external concave cuts. The incisions, which pose problem, must be turned round the position of the incision for a certain angle. Figure 11 shows that one incision on the top right side had to be turned for 15° in anti clock direction round the incision position, the other for 60° in clock wise direction and the third for 15° in clock wise direction. In Figure 11 on the bottom side the incision posing problems, had to be turned for 155° in anti clock wise direction. The problematic incisions are indicated in Figure with a circle.

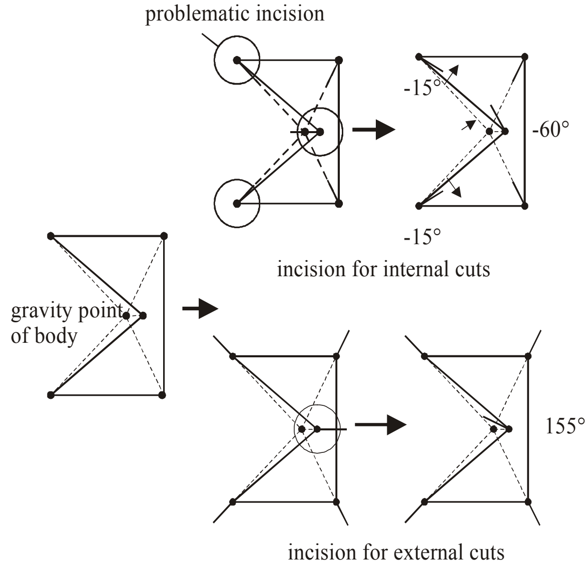

Fig. 11. Determination of incision of concave cuts

Figure 12 shows the example where the incision in the positions, indicated with circle, could not be determined. Irrespective of how the system turned the incision, the incision orientation was not possible; therefore the system did not determine the incision.

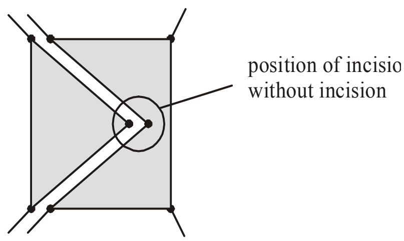

Fig. 12. Determination of incisions of concave cuts

2.3. Coding of NC program

The NC programs, created at random, can be represented again by a weighted graph [12]. The points in the graph are working motions (cuts) and the connections between the points are feeding motions. Each point in the graph is connected with the other points in the graph. The points and connections in the graph are weighted. The weights at the connections from cut i to cut i+1 can be differently weighted. The value of the weight between cuts i and i+1 depends on the previously made cut i-1 (i-1'). Figure 13 shows the change of length of path between cuts i and i+1 depending on the previously made cut. During the motion of the cutter from cut i to cut i+1 the system selects the nearest incision of cut i+1; consequently the cutter moves from the incision of cut i, which is nearest to the incision of cut i-1 (i-1'), to the incision nearest to cut i+1. For the sake of clarity the Figure does not show the incisions. Only the incision positions are shown.

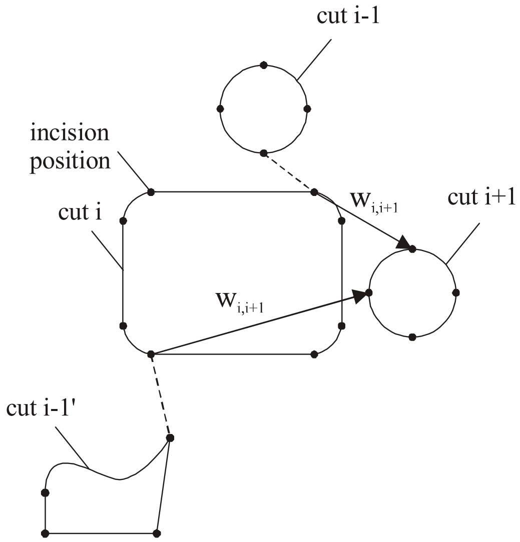

Fig. 13. Differently weighted weights from cut i to cut i+1

The sequence of genes (cuts) represents again the successive motion of the cutter from cut to cut. The first and the last gene of the list represent the initial and the final point of motion of the cutter. The intermediate links illustrate the sequence of cuts to be made. The blade first moves with the feeding motion from the initial point to the first cut in the list. Then it performs the working motion up to the first cut, makes it, proceeds with the feeding motion up to the next cut, and makes it, and so on until all cuts have been made. In the end, it reached the final point with the feeding motion. The NC programs, created at random, mutually differ in length of the path covered by the cutter and in the number of skipped depths in the nest K. Figure 14 shows different numbers of skipped depths of nest 1 from Figure 5. For example, 3 cuts are selected in nest 1: cut 1 which is at the depth 1, cut 2 which is at depth 4 and cut 3 which is at the depth 5. The depth of nest 1 is 5. If the cut 1 is cut out from the whole plate fixed on the machine, the plate will look like shown in Figure 14 on the top right side after removal of the cut out piece. Now from the fixed plate cutting of cut 2 and cut 3 cannot be continued. The number of skipped depths of the nest amounts to 5 (depth of the nest) reduced for 1 (depth of cut 1 in nest 1), i.e. K=5-1=4. If from the entire fixed plate the cut 2 is cut out (Figure 14 on the right side in the middle), the number of skipped depths of nest 1 will be 5-4=1, while, if from the entire fixed plate the cut 3 (Figure 14 on the bottom right side) is cut out, the number of skipped depths of nest 1 will be equal to 0.

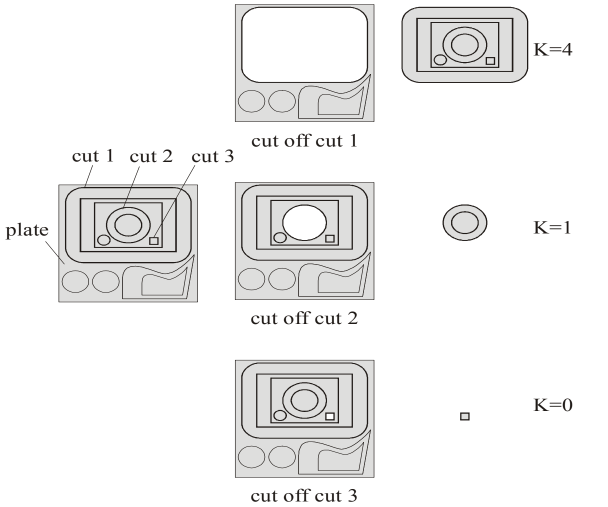

Fig. 14. Number of skipped depths in nest

2.4. Evolution of population

When evaluating the NC program [7] the length of cuts and feeding motions (tool motions between individual cuts) and the number of skipped depths K are taken into consideration. The function for evolution can be written as follows:

$$= w_{1,s} + \sum_{i=1}^{n-1} w_{i,i+1} + \sum_{i=1}^{n} r_i + w_{n,c} + f \cdot K \,, \tag{3}$$

where:

- $w_{i,i+1}$ *length of feeding motion between cuts i and i+1 depending on the preceding cut i-1,*
- $w_{s,1}$ *length of feeding motion between initial point s and the first cut,*
- $w_{n,c}$ *length of feeding motion from the cut n to final point c,*
- r_i *length of cut i,*
- f *factor of influence*
- K *number of skipped depths*

2.5. Genetic operations

We used the genetic operators of reproduction (selection), crossover and permutation [2]. For selection of chromosomes participating in operations of selection and changes we used tournament selection [15].

3. Example 1

To present operation of the system for programming the plate cutting machine we selected two examples, the first of them is shown in Figure 15.

The metal plate is of dimensions 1000×1000 mm. In the layout there are 6 products of four different types.

They include single products of type 1, 2, and 3, and three products of type 4. The greatest depth of cuts of the individual nest is 5. In the Figure the deepest nest is indicated in grey. The deepest cut of the deepest nest is the external cut of type 4 product. We selected also the initial and final point of the cutter. Total length of all cuts is 14007.5 mm.

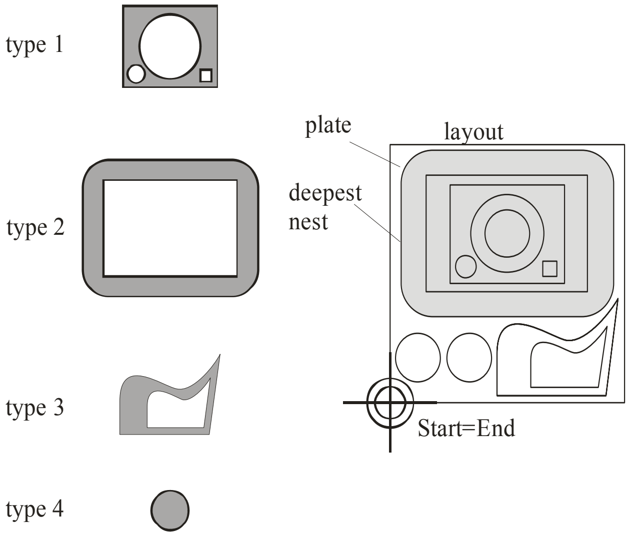

Fig. 15. Example 1

The system for programming the plate cutting machine was run 100 times. For all starts the same evolution parameters were used, namely the population size 1000, the maximum number of generation 30, the reproduction probability 0.1, the crossover probability 0.6 and the permutation probability 0.3. The tournament selection of organisms with tournament size 7 was used.

The average length of the best paths of each start amounted to 16542.18 mm. The best path out of the 100 starts of the system is of 16093.99 mm length.

As a matter of interest one of the independent starts of the system is presented.

Of course the result of random creation of NC programs of the plate cutting machine is bad (Figure 16). The best organism in the initial population 0 has the length of 17180.6 mm. The length of feeding paths of the cutter in relation to the total length is 18.46%. The position of incision of the cut, where errors due to skipping of the cut depths in the nest appear, is encircled in grey.

To show the variety of organisms in the initial generation still the worst NC program in generation 0 is presented (Figure 17). That program has the length 4200.43 mm and causes as much as K=8 skips of depths. The number of wrongly cut out cuts is 4. The length of feeding paths of the cutter in relation to the total length is 23.07%.

In generation 2 the first NC program without depth skips appears (Figure 18). The NC program has the length 16515.01 mm. The length of feeding paths in relation to the total length amounts to 15.18%.

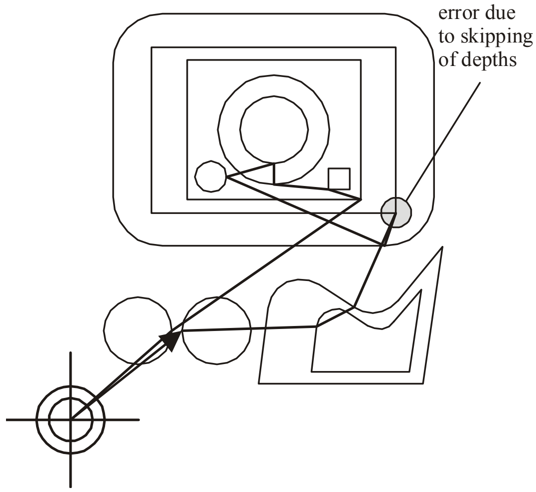

Fig. 16. The best NC program in initial generation 0

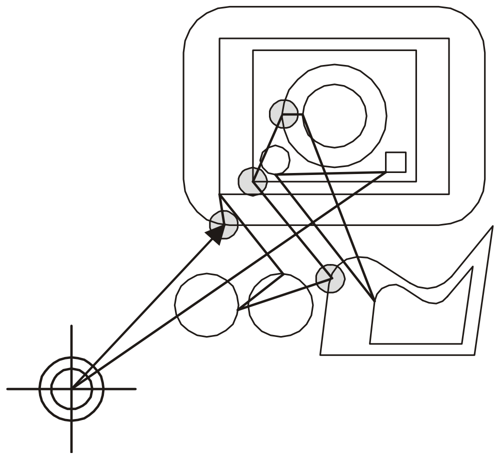

Fig. 17. Worst NC program in generation

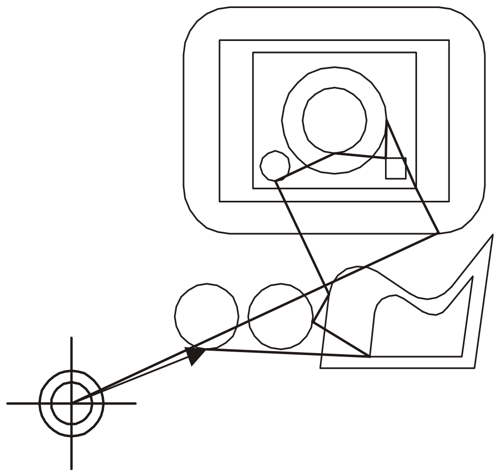

Fig. 18. The best NC program in generation 2

The evolution develops already to generation 5 the best NC program of the civilization (start of system) with 16093.99 mm (Figure 19). The length of feeding paths in relation to total path length amounts to 12.9%.

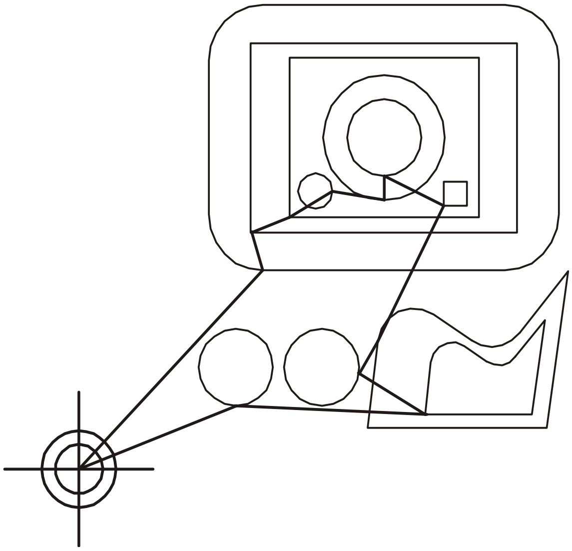

Fig. 19. The best NC program of civilization

Figure 20 shows the gradual development of the best solutions through generations in relation to their length. The Figure shows that the shortest NC program developed already in generation 5 and was maintained as long as up to the last generation 50.

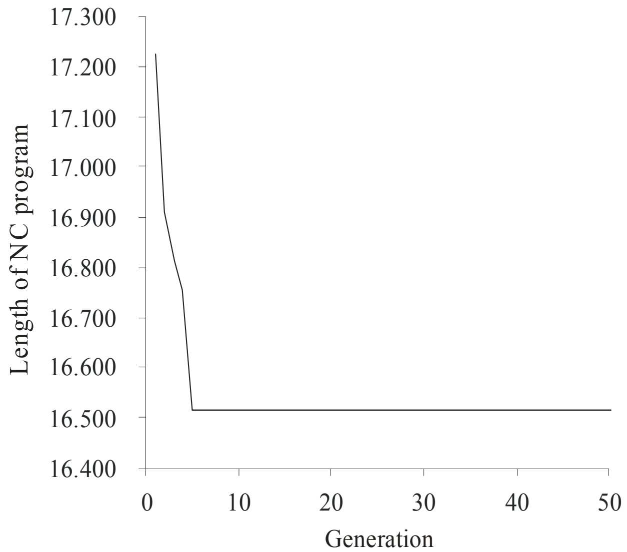

Fig. 20. Length of the best NC programs in the individual generation

The resulting best program was verified in program environment hyper VIEW 4.5 [14] (Figure 21).

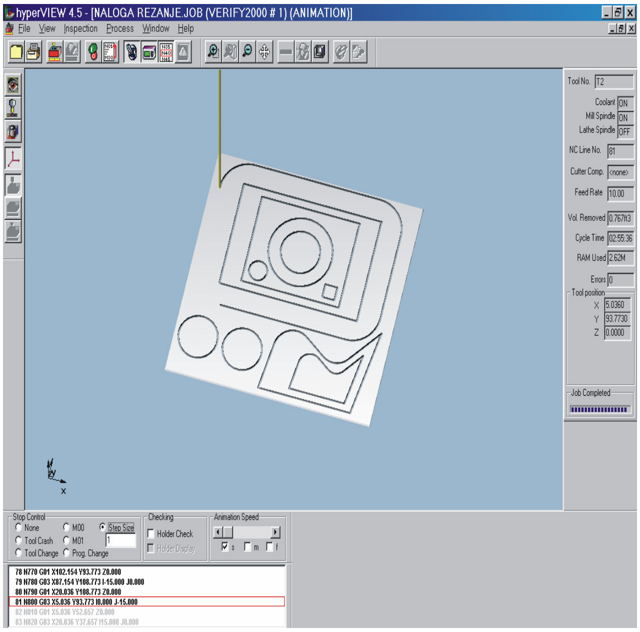

Fig. 21. Verification of the best NC program of the civilization in program environment hyper VIEW 4.5

4. Example 2

For the example 2 the layout with a great number of products was selected (Figure 22). The plate was of dimensions 1600×1600 mm. The layout (Figure 22) comprised 19 products of four different types. All internal and external cuts amounted to 48. 3 products are of type 1, 9 products of type 2, 5 products of type 3 and 2 products of type 4. The greatest depth of cuts of the individual nest is 4. In the Figure the deepest nest is indicated in grey. The deepest cut of the deepest nest is the internal cut of type 4 product. Also the initial and final point of the cutter was selected. The total length of all cuts was 32167.4 mm.

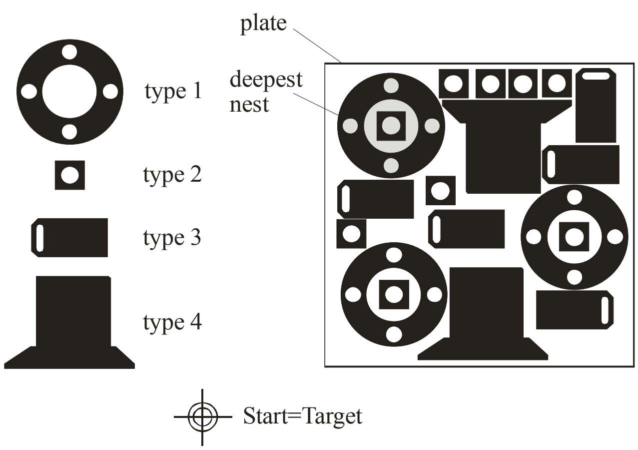

Fig. 22. Example 2

The system for programming the plate cutting machine was run again 100 times. For all starts the same evolution parameters were used, namely the population size 1000, the maximum number of generation 100, the reproduction probability 0.1, the crossover probability 0.6 and the permutation probability 0.3. The tournament selection of organisms with tournament size 7 was used.

Herebelow, the development of the NC program of one independent start is described. Only the length of working motions of the NC program is discussed and not the entire length.

The result of the random creation of NC programs of the plate cutting machine at the beginning of the evolution of one independent civilization is bad, of course. The best organism in the initial generation 0 (Figure 23) has 36495.4 mm length of feeding paths representing 113.45% of cutting path of the NC program and as much as 68.02% of the whole path of the cutter. The position of incision of the cut, where errors due to skipping of cut depths in the nest appear, is encircled in grey. The number of skipped depths K=9, whereas the number of wrongly cut out cuts is 6.

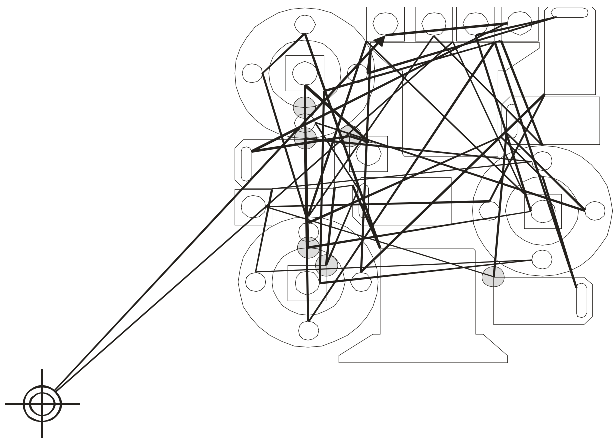

Fig. 23. The best NC program in generation 0

In the generation 7 the first NC program without depth skips emerges (Figure 24). The length of feeding paths amounts to 35179.8 mm which is equal to 109.36% in relation to the cutting path and to 52.23% in relation to the entire path of the cutter.

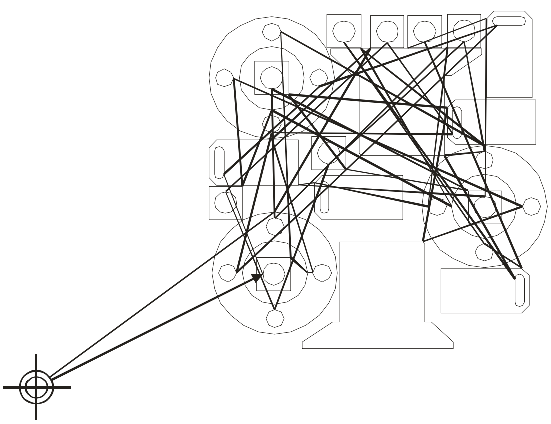

Fig. 24. The best NC program in generation 7

The best program of the generation 20 (Figure 25) has 21489.7 mm length of feeding paths which is equal to 66.80% of the cutting path and to 40.05% of the entire path of the cutter.

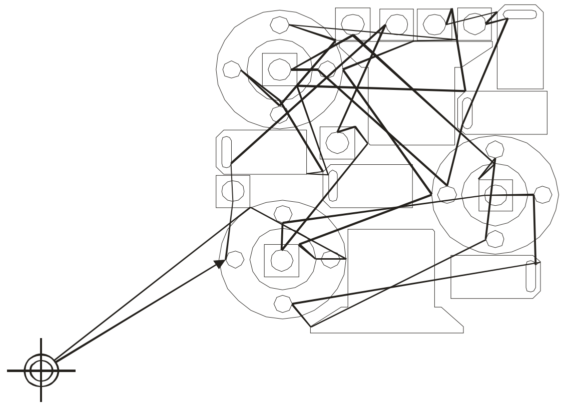

Fig. 25. The best program in generation 20

The appearance of NC programs developed throughout evolution. The paths are less and less entangled. A significant progress in comparison with the NC programs in the previously presented generations 0, 7 and 20 can be noticed in case of NC program created in generation 50 (Figure 26). The length of the feeding paths amounts to 14885.5 mm which is equal to 46.28% in relation to the cutting path and 31.36% in relation to the entire path of the cutter.

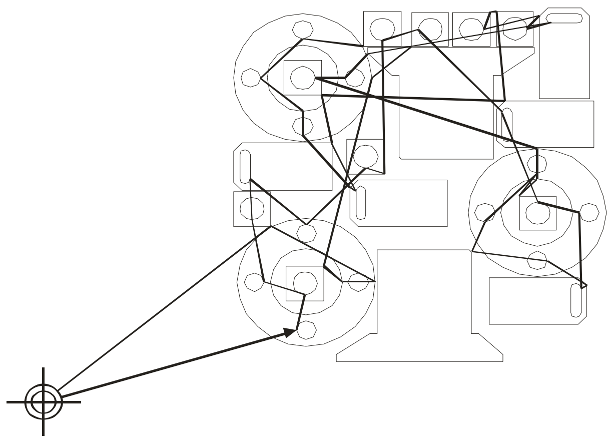

Fig. 26. The best NC program in generation 50

In the generation 95 the best NC program of the civilization independent start of the system) (Figure 27) was created. The length of the shortest feeding path amounts to 12453.2 mm which is equal to 38.71% of the cutting path and to 27.90% of the entire path of the cutter.

Figure 28 shows the gradual development of the best NC programs through generations with respect to their length of feeding paths.

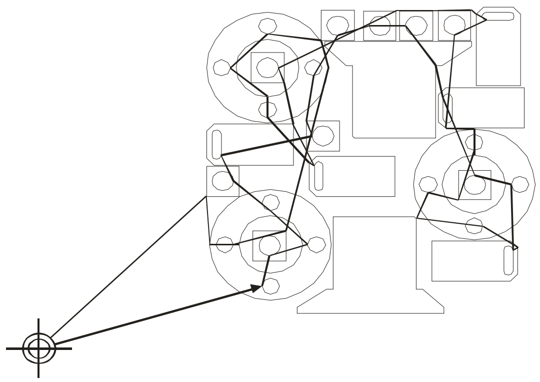

Fig. 27. The best NC program in generation 95

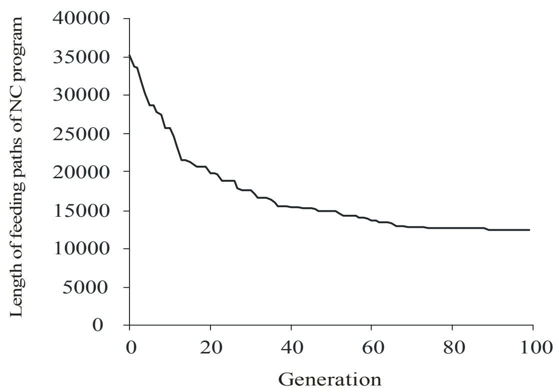

Fig. 28. Length of feeding paths of the best NC programs in the individual generation

5. Conclusions

In this paper the concept of automatic programs of the NC machine for metal plate cutting by genetic algorithm method has been presented. In the proposed system the products comprise internal and external cuts. The cuts are of any shapes; they consist of lines, semi-circles and circles. The proposed intelligent system is capable to recognize automatically the nesting of products in the layout, to determine the incisions and sequences of cuts forming the laid out products. Position of incisions is determined at the relevant places on the cut.

By the genetic algorithm method the system is capable to find the shortest path between individual cuts and to record the NC program. With minor corrections, adapted to the user, the system can be quite practically used.

It would be appropriate to orient future researches towards conceiving an improved system for three-dimensional cutting with optional determination of positions of incisions, with the capability to sense collisions and with optimization of the speed and acceleration during cutting.

References

[1] R. Aloke, V. Girish, R.F. Scrutton, P.A. Mollian, A model for prediction of dimensional tolerances of laser cut holes in mild steel thin plates, International Journal of Machine Tools and Manufacture, Vol. 37, No. 8 (1997), 1069-1078.

[2] D. E. Goldberg, , Genetic algorithms in search, optimization, and machine learning, Addison-Wesley, Reading, 1989.

[3] S. D. Jackson, O.R. Mittal, Automatic generation of 2-axis laser-cutter NC machine program and path planning from CAD, Computers in Industry, Vol 21, No.2 (1993), 223.

[4] M. Kovačič, J. Balič, Evolutionary programming of a CNC cutting machine. Int. j. adv. manuf. technol., vol. 22, No. 1/2, str. (2003) 118-124.

[5] Z. Michalewicz, Genetic algorithms + data structures = evolution programs, Springer - Verlag, New York, 1999

[6] M. Brezočnik, M. Kovačič, M. Ficko, Prediction of surface roughness with genetic programming. J. mater. process. technol., [Print ed.], 20.dec.2004, vol.157/158, pp.28-36.

[7] I. Drstvenšek, M. Ficko, J. Balič, Relational database as a cogitative part of an intelligent manufacturing system. J. mater. process. technol., [Print ed.], Dec.2004, vol.157/158, pp.114-122.

[8] M. Ficko, M. Brezočnik, J. Balič, Designing the layout of single- and multiple-rows flexible manufacturing system by genetic algorithms. J. mater. process. technol., [Print ed.], Dec. 2004, vol. 157/158, pp. 150-158.

[9] M. Ficko, I. DrstvenšeK, M. Brezočnik, J. Balič, B. Vaupotič, Prediction of total manufacturing costs for stamping tool on the basis of CAD-model of finished product. J. mater. process. technol., [Print ed.], 15. maj 2005, vol. 164-165, str. 1327-1335.

[10] M. Brezočnik, J. Balič, Z. Kampuš, Modeling of forming efficiency using genetic programming. J. mater. process. technol., [Print ed.], 2001, vol. 109, no. 1/2, special issue "AMME'97", pp. 20-29.

[11] M. Kovačič, J. Balič, M. Brezočnik, Evolutionary approach for cutting forces prediction in milling. J. mater. process. technol., [Print ed.], Nov. 2004, vol.155/156, pp.1647-1652.

[12] M. Kovačič, M. Brezočnik, I. Pahole, J. Balič, B. Kecelj, Evolutionary programming of CNC machines. J. mater. process. technol., [Print ed.], 15. maj 2005, vol. 164-165, pp. 1379-1387.

[13] I. Drstvenšek, I. Pahole, J. Balič, A model of data flow in lower CIM levels. J. mater. process. technol., [Print ed.], Dec. 2004, vol. 157/158, str. 123-130.

[14] I. Drstvenšek, I. Pahole, M. Kovačič, J. Balič, Intelligent interface in a flexible production environment. J. mater. process. technol., [Print ed.], 15. maj 2005, vol. 164-165, pp. 1309-1316.

[15] M. Nastran, J. Balič, Prediction of metal wire behavior using genetic programming. J. mater. process. technol., [Print ed.], 2002, vol. 122, no. 2/3, pp. 368-373.