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High-speed milling of light metals

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ABSTRACT

Purpose: of this paper: Introduction applicability of high-speed cutting of light metals is presented in this paper.
Design/methodology/approach: HSC is the result of numerous technical advances ensuring that milling has become faster than conventional milling and has gained importance as a cutting process. The advantages of the HSC milling are higher productivity owing to the reduction of machining times increase of the flow time of production, reduction of the number of technological operations, increase of the surface quality and longer service life of tools. The machining conditions for execution of the HSC (36000min^{-1} and feeding 20m/min) require modernly built machine tools to meet those machining conditions.
Findings: Continuous development of new materials is more and more dynamical, particularly, in the automobile, aircraft and electronic industry and in the manufacture of various mechanical parts. Also the achievements in the area of building of machines and tools, ensuring high cutting speeds (highly efficient machining) have contributed to development of the process.
Research limitations/implications: High quality of the surfaces, the quality of this so-called HSC milling can be compared to grinding.
Practical implications: High-speed milling of light metals from aluminium and magnesium is more and more frequently used in practice. This result is high quality of the surface and shorter machining times. In some cases when machining by grinding is specified, the latter is omitted.
Originality/value: The applicability of high-speed milling has proved to be successful, when aluminum and magnesium alloying materials are machined.
Keywords: Machining; High-speed milling; Light metals

1. Introduction applicability of HSC in cutting of light metals

The advantage of HSC milling are higher productivity owing to reduction of manufacturing times, increased flow time of production, reduced number of technological operations, increase in surface quality and longer service time of tools [1]. The HSC milling differs from the conventional milling, particularly, in the manner of formation of the chip, and its removal and tool geometry [2].

The applicability of this machining has proved to be successful, when very exacting materials, the so-called new materials, are machined. One of such widely used materials is aluminium with various alloying elements. The parts to be built in must be appropriate for exacting shapes, easy machinability, small mass and must overcome extreme operating conditions. To ensure the material to satisfy the mentioned requirements the alloy must be alloyed with elements meeting all conditions, e.g. the example for thermal resistance AlZnMgCu1,5-F51 ($R_m \approx 540$ N/mm^2 , AlMg3-F18 ($R_m \approx$ 215 N/mm^2), AlMg4,5-Mn-F27 ($R_m \approx 305$ N/mm^2), AlCuMg1-F40 ($R_m \approx 5050$ N/mm^2).

AlCuMgPb-F37 (Rm ≈ 470 N/mm2) is used in the area of materials for machining on automation machines [3]. Aluminium, alloyed with cast steel GK - AlSi6Cu4 is used for cylinder heads on the internal combustion engines and GD-AlSi12Cu9 for various housings. One third of all materials are represented by light-weight materials, such as MgAl8Zn1 used for the manufacturing of car rims. The purpose of alloying materials is to reach better properties then the basic materials. The advantage of light metals is their machinability:

- Smaller specific cutting force and smaller required power.
- Shear strain with short chips.

The increase in the service life of tools depends very much on the cutting materials used. High quality of the surfaces, the quality of this so-called fine milling can be compared to grinding. The cutting speed and feeding can be very high in case of light metals so that economical effects of high speed milling is reached [4, 5]: it varies between 1000 and 7500m /min (see Figure 1).

2. Machining parameters

High values of the cutting force in high-speed milling have not been confirmed due to increased temperature according to physical laws. The findings show that the temperature increases with the chip thickness and cutting speed [6]. Precise defining of the HSC milling does not make sense, since high-speed milling is derives from milling, where the feeding speed for certain machining operation is so high that it prevents the passage of high temperatures to the workpiece or tool.

This is based on the findings about thermal conditioning and change in structure, when milling aluminium alloys with small chip thickness and/or feeding speed. The basic technological parameters for light metals are given in Table 1.

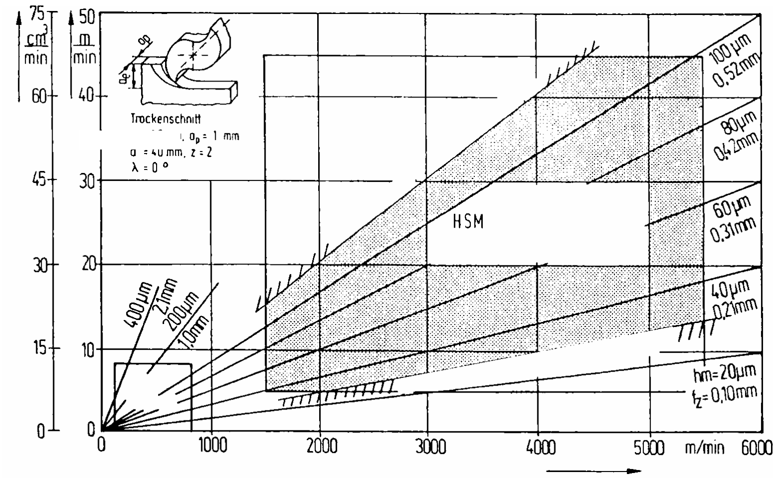

Fig. 1. Working area of high-speed milling

Table 1.
Machining values for light metals

	Aluminium			Magnesium
	Alloying casts		Wrought alloys	Alloying casts
	Si ≤ 12%	Si > 12%		
Circular milling				
v_c [m/min]	1300	1200	4700	1500 - 5500
f_z [mm]	0,43	0,47	0,04 - 0,2	0,16 - 0,23
v_f [mm/min]	9000	9000	2000 - 10000	13000 - 20000
Cutting material	KT - K 10	PKD	KT - K 20	KT - K 10
Boundary conditions	a_c = 1,5 mm D = 40 mm z = 2		a_c = 50 mm D = 50 mm z = 2	a_c = 1,5 mm D = 40 mm z =2
Face milling				
v_c [m/min]	1500 - 4500			1500 - 4500
f_z [mm]	0,02 - 0,15			0,02 - 0,15
v_f [mm/min]	3000 - 12000			3000 - 12000
Cutting material	KT - K 10			KT - K 10
Boundary conditions	a_p = 1,5 mm D = 40 mm z = 2			a_p = 1,5 mm D = 40 mm z = 2

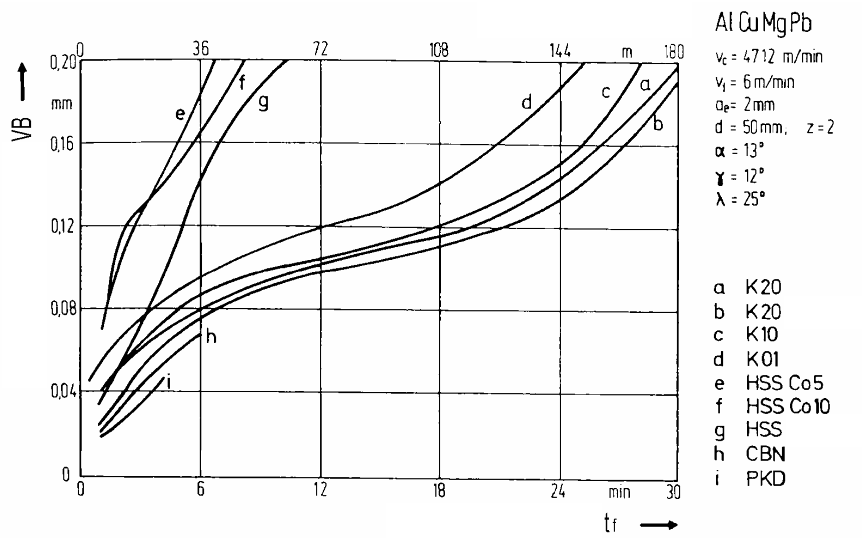

Fig. 2. Tool wear during milling of aluminium alloys

This is based on the findings about thermal conditioning and change in structure, when milling aluminium alloys with small chip thickness and/or feeding speed. The basic technological parameters for light metals are given in Table 1.

3. Cutting force and power

Calculation of cutting force according to DIN 6584

$$p_{cm} = \frac{a_p \cdot a_e \cdot v_f \cdot K_{cm}}{60 \cdot 10^6} \qquad (1)$$

- ap - chip width [mm]
- a_e - chip depth [mm]
- v_f - feeding speed [mm]
- K_{cm} – mean specific cutting force [N/mm^2]

$$v_f = f_z \cdot z \cdot n \qquad (2)$$

- f_z - feeding per tooth
- z -number of teeth
- n – number of revolutions
- Chip volume depending on time unit (Specific volume of chip)

4. Materials of cutting tools

High-speed steels as cutting materials are not suitable for high-speed milling of light metals. Alloys with different cutting materials and their wear are shown in Figure 2. With the case of the polycristal diamond or CBN the resistance of the cutting insert is strongly increased [7, 8] and it is shown in Figure 3.

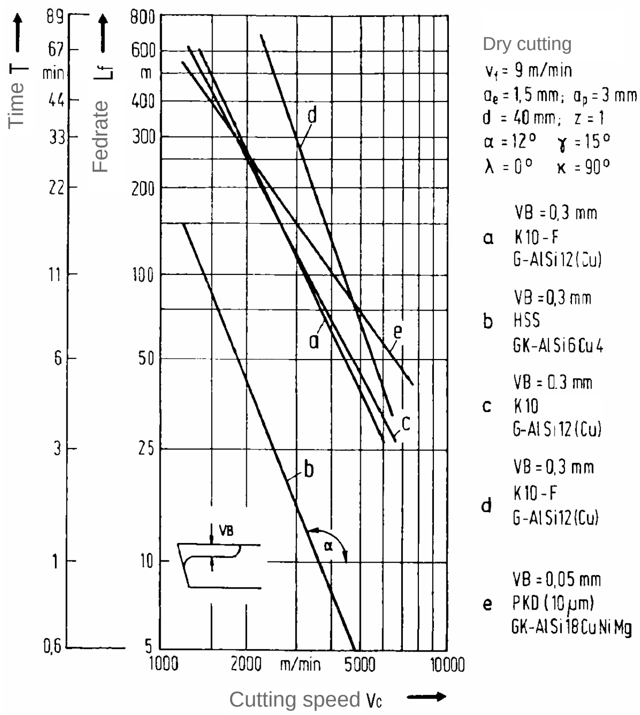

Fig. 3. Resistance of milling cutter in machining the aluminium alloyed with silicone

5. Tool geometry

As far as tool geometry is concerned it is desirable that it should have high resistance and optimal cutting capacity [9]. The makers offers end- milling cutters of up to 12mm diameter as shown in Figure 4.

For machining of light metals mainly the milling cutters with two cutting edges are used.

The number of revolutions must be very high so that a satisfactory surface quality is reached and adhering of chips to the shear surface is avoided [10].

6. Efficient HSM by using off-line cutting parameter optimization and force control

A remaining drawback of modern CNC systems is that the machining parameters, such as feedrate, cutting speed and depth of cut, are still programmed off-line. The machining parameters are usually selected before machining according to programmer's experience and machining handbooks. To prevent damage and to avoid machining failure the operating conditions are usually set extremely conservative. As a result, many CNC systems are inefficient and run under the operating conditions that are far from optimal criteria. Even if the machining parameters are optimised off-line by an optimisation algorithm [11] they cannot be adjusted during the HSC machining process.

To ensure the quality of machining products, to reduce the machining costs and increase the machining efficiency, it is necessary to adjust the machining parameters in real-time, to satisfy the optimal machining criteria. For this reason, adaptive control (AC), which provides on-line adjustment of the operating conditions, is being studied with interest [12]. In AC systems, the feedrate is adjusted on-line in order to maintain a constant cutting force in spite of variations in cutting conditions.

Force control algorithms have been developed and evaluated by numerous researchers. Among the most common is the fixed gain proportional integral (PI) controller, adjustable gain PI controller and adaptive model reference adaptive controller (MRAC). Unfortunately, adaptive control alone cannot effectively control cutting forces. Therefore, on-line adaptive control in conjunction with off-line optimization was implemented.

6.1. System for off-line optimization and adaptive control

The basic idea of this approach is to merge the off-line cutting
condition optimization algorithm and adaptive force control (Figure 5). When spindle loads are low, the system increases feeds above and beyond pre-programmed values, resulting in considerable reductions in machining time and production costs. When spindle loads are high the feed rates are lowered, safeguarding cutting tool from damage and breakage.

When system detects extreme forces, it automatically stops the machine to protect the cutting tool.

Sequence of steps for on-line optimization of the milling process is presented below.

1. The recommended cutting conditions are determined by ANfis (adaptive neuro-fuzzy inference system) models.
2. The pre-programmed feed rates determined by off-line optimization algorithm are sent to CNC controller of the milling machine
3. The measured cutting forces are sent to neural control scheme,
4. Neural control scheme adjusts the optimal feedrates and sends it back to the machine,
5. Steps 1 to 3 are repeated until termination of machining.

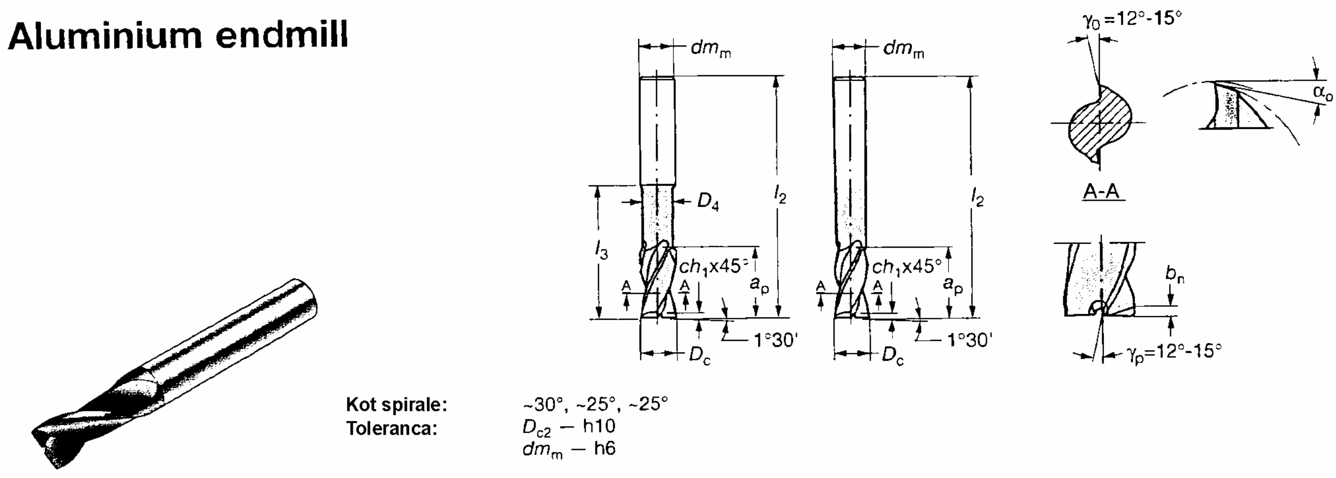

Fig. 4. End-milling cutters for machining light metals

6.2. System for simulating of high-speed machining

CNC milling simulator is used to evaluate the adaptive controller design before conducting experimental tests. The CNC milling simulator tests the system stability and tunes the adaptive controler parameters.

The simulator consists of a neural force model, a feed drive model and model of elasticity (Figure 6). The neural model predicts cutting forces based on cutting conditions and cut geometry as described by [13].

The feed drive model simulates the machine response to changes in desired feedrate. The elasticity model represents the deflection between the tool and the workpiece.The feed drive model is determined experimentally by examining responses of the system to step changes in the desired feed velocity. The best model fit is a second-order system with a natural frequency of 3 Hz and a settling time of 0.4sec.

The feed drive model, neural force model and elasticity model are combined to form the CNC milling simulator. Simulator input is the desired feedrate and the output is the X, Y resultant cutting force. The cut geometry is defined in the neural force model.

6.3. Data acquisition system

The data acquisition equipment consists of dynamometer, fixture and software module as shown in Figure 5. The cutting forces were measured with a piezoelectric dynamometer (mounted between the workpiece and the machining table.

The interface hardware module consists of a connecting plan block, analogue signal conditioning modules and a A/D interface board (PC-MIO-16E-4).

In the A/D board, the analogue signal will be transformed into a digital signal so that the LabVIEW software is able to read and receive the data.

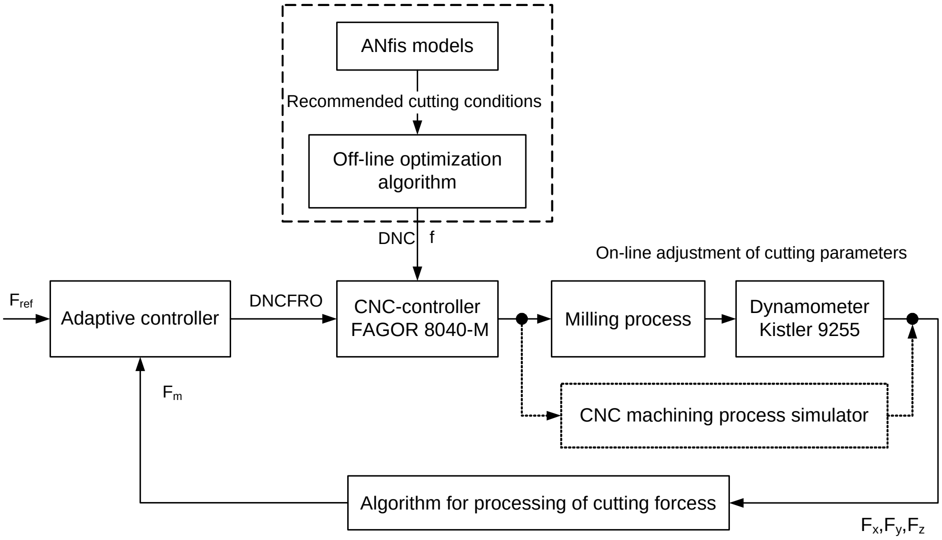

Fig. 5. System for off-line optimization and adaptive control

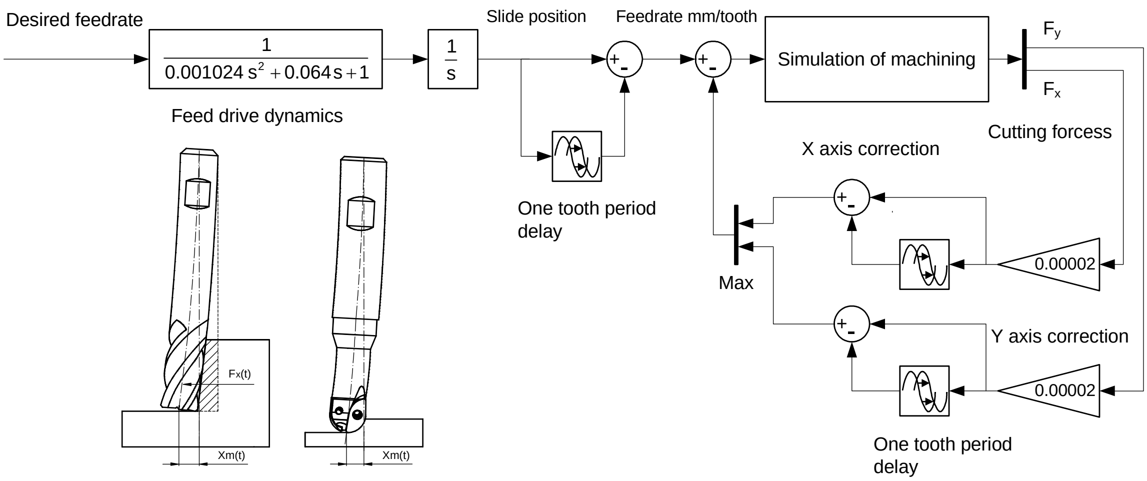

Fig. 6. HSC simulator

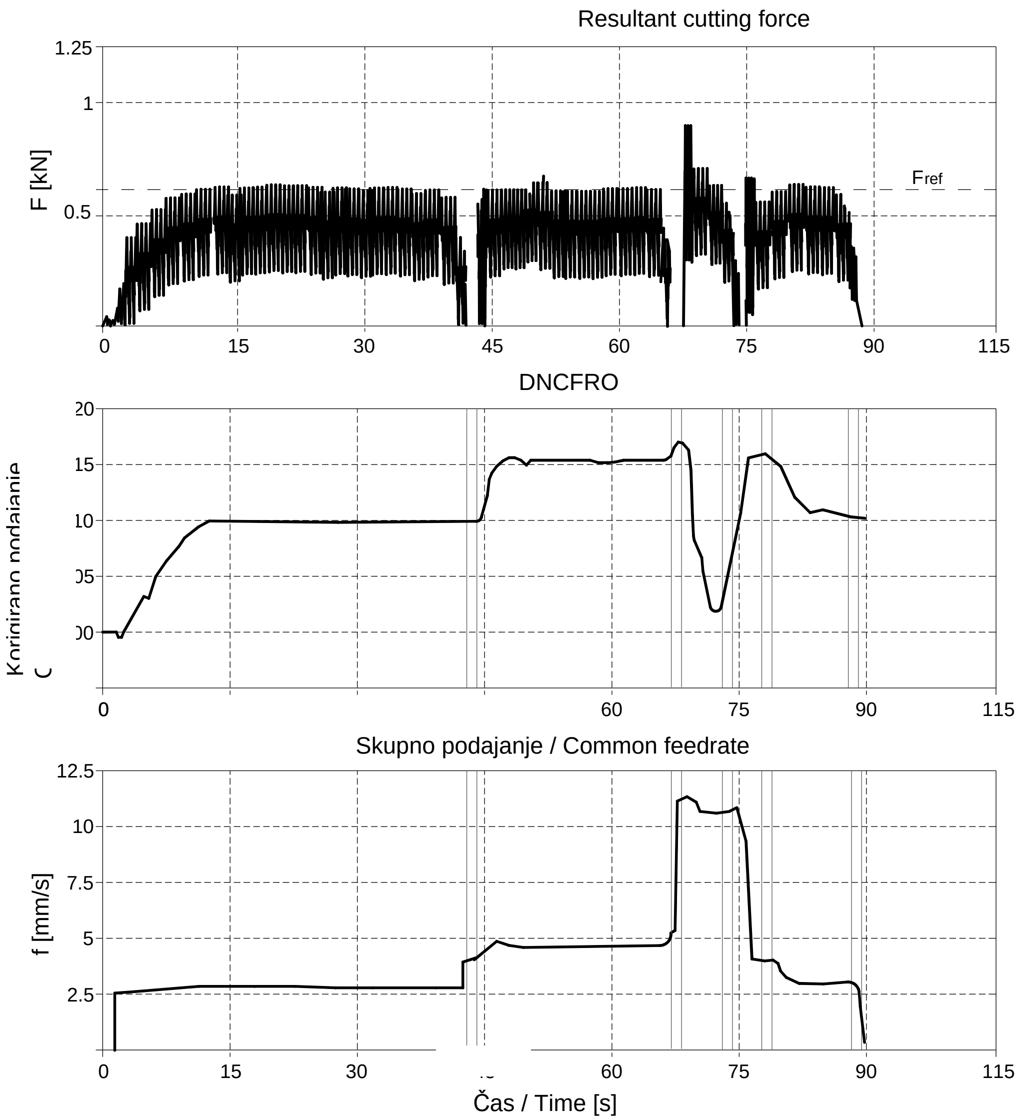

Fig. 7. Experiment; Testing of adaptive controller during high-speed maching

With this program, the three axis force components can be obtained simultaneously, and can be displayed on the screen for further analysis. Communication between the control system and the CNC machine controller is accomplished over RS-232 protocol.

6.4. Neural cutting force model

To realise modelling of cutting forces, a standard BP neural network (UNM) is used based on the popular back propagation learning rule.

During preliminary experiments it proved to be sufficiently capable of extracting the force dynamics model directly from experimental machining data. It is used to simulate the dynamics of cutting process. The UNM for modelling needs eight input neurons: for federate (f), cutting speed (v_c), radial and axial depth of cut (A_D / R_D), type of machined material, hardness of the machined material, cutting tool diameter (D), and tool geometry.

The geometry of the cutter is indicated with an 8-digit systematization code containing the data on the cutting edge shape, rake angle, free angle, tip radius, base material, cutting coating and length of the cutting edge.

The output from the UNM are cutting force components, therefore three output neurons are necessary.

During simulation most input vector parameters do not change (e.g. cutter diameter and geometry, material etc.). The detailed topology of the used UNM with optimal training parameters is shown in Figure 8.

6.5. Testing of HSM adaptive control system

To examine the stability and robustness of high-speed machining the system is first analysed by simulations. Then the system is verified by experiments on a CNC milling machine for workpieces with variation of cutting depth (Figure 7).

The experiments with small and large step changes are run to test system stability over a range of cutting conditions.

The experimental results show that the milling process with the adaptive controller has a high robustness, stability, and also higher machining efficiency than standard controllers.

Experiments have confirmed efficiency of the adaptive control system, which is reflected in improved surface quality and decreased tool wear. It is obvious that the system can be extended to other machines to improve cutting efficiency.

6.6. Neural network based optimisation of end milling parameters in HSC

Optimization of machining parameters is a non-linear optimization with constrains, so it is difficult for the conventional optimization algorithms to solve this problem because of problems of convergence speed or accuracy. For the process of the single objective optimization several different techniques have been proposed, such as genetic algorithms, linear programming geometric and stochastic programming and computer simulating. The new approach which ensures efficient and fast selection of the optimum cutting conditions and processing of available technological data are the artificial neural networks (UNM).

Required steps for optimization of cutting parameters:

1. Entering of input data; set-up time, tool change time, tool idle time, tool cost, labour cost, overheads, permissible range of cutting conditions, F_{max}, P_{max}).
2. Generation of random cutting conditions.
3. Preparation of data for training and testing of UNM. Uniting of cutting conditions and other calculated values into a data matrix. Breakdown of the data matrix into the input and output vector. Distribution of the input / output vector into the two sets for training and testing.
4. Use of UNM. The purpose of the neural network is to predict the manufacturer's value function (y) in case of randomly selected cutting conditions.
   - Procedure of training of the UNM by using the training set. Selection of the type and architecture of the UNM and searching for optimum training parameters.
   - Testing of trained UNM. The testing set is to be used to verify and validate the resultant neural network from supervised learning.
5. Optimization process; The cutting conditions where the function (y) has the maximum are the optimum cutting conditions. Since the function (y) is expressed with UNM, it means that the extreme of the neural network is searched for. The area in which the extreme is searched for is defined with limitation equations.
6. Calculation of the other variables in case of optimum cutting conditions.

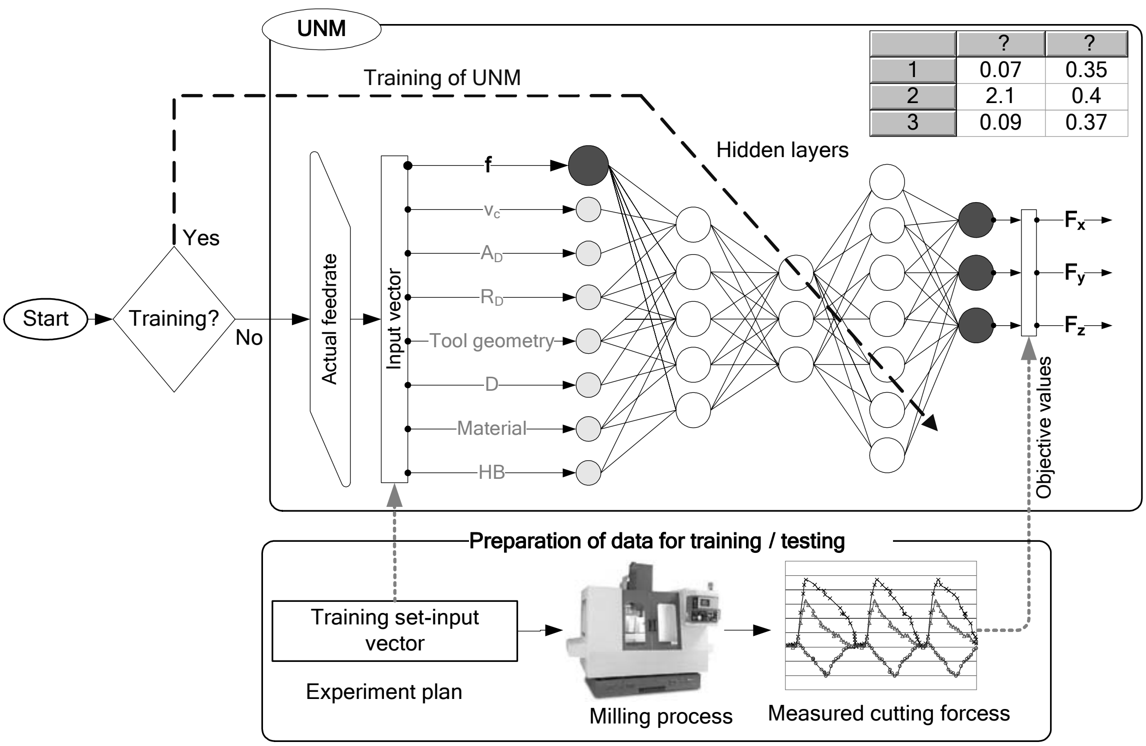

Fig. 8. System for prediction of cutting forces in HSM

6.7. Optimization of cutting conditions with Genetic Algorithms (GA)

In a GA approach to solve combinatorial optimization problems, a population of candidate solutions is maintained. To generate a new population, candidate solutions are randomly paired.

For each pair of solutions, a crossover operator is first applied with a moderate probability (crossover rate) to generate two new solutions. Each new solution is then modified using a mutation operator with a small probability (mutation rate).

The resulting two new solutions replace their parents in the old population to form a temporary new population. Each solution in the temporary population is ranked against other solutions based on a fitness criterion. A roulette wheel process is then used to determine a new population identical in size to the previous population, such that higher-ranked candidates are allowed to assume higher priority in the new population.

GA iterates over a large number of generations and, in general, as the algorithm executes, solutions in the population become fitter, resulting in better candidate solutions. Last but not least, GA is a search strategy that is well suited for parallel computing.

7. Area of application oh HSM

High- speed milling is suitable for:

- Mounting parts in aircraft and automobile industry and in building the engines from aluminium alloys with the volume of up to 95%.
- Small parts to be machined with tools of small diameters.
- Machining of beams from aluminium alloys.
- Various housing for additional machining
- Various parts whose surface must be of high quality.
- The basic rule, when deciding on high-speed milling, is the cost-effectiveness of the prices expressed in time savings.
- Racionalization is possible where the machine tools allow it; in particular the machine rigidity and the number of spindle revolutions are important.
- High-speed milling is particularly suitable for machining the parts previously manufactured according to another machining process.

8. Conclusions

HSC is the result of numerous technical advances ensuring that milling has become faster than conventional milling and has gained importance as a cutting process.

The advantages of the HSC milling are higher productivity owing to the reduction of machining times increase of the flow time of production, reduction of the number of technological operations, increase of the surface quality and longer service life of tools. High-speed milling of light metals from aluminium and magnesium is more and more frequently used in practice.

This result is high quality of the surface and shorter machining times. In some cases when machining by grinding is specified, the latter is omitted.

The machining conditions for execution of the HSC ($36000 min^{-1}$ and feeding 20m/min) require modernly built machine tools to meet those machining conditions.

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