22nd WORLD
MINING
CONGRESS & EXPO
11-16 SEPTEMBER
İSTANBUL-**2011**

Editor
Dr. Şinasi Eskikaya

VOLUME II

22nd WORLD MINING CONGRESS
TURKISH NATIONAL COMMITTEE

22nd WORLD MINING CONGRESS & EXPO
11-16 SEPTEMBER 2011 / ISTANBUL

Published by Aydoğdu Ofset, Ankara-Turkey
Phone: +90 (0312) 395 81 44, Fax: +90 (0312) 395 81 45

ISBN : 978-605-01-0146-1 (Takım)
978-605-01-0148-5 (2.Cilt)

Adress : The Chamber of Mining Engineers of Turkey
Selanik Cad. 19/4 06650 Kızılay-ANKARA-TURKEY
Phone : +90 (0312) 425 10 80 Fax: +90 (0312) 417 52 90
Web : www.maden.org.tr
E-Posta : maden@maden.org.tr

A DETERMINISTIC MODEL FOR PREDICTING AND OPTIMIZING PERFORMANCE OF CHAIN SAW MACHINES

[1]Assoc.Prof.Dr. H.Copur, *ITU Mining Eng. Department, Istanbul, Turkey*
[2]Assoc.Prof.Dr. C.Balci, *ITU Mining Eng. Department, Istanbul, Turkey*
[3]Prof. Dr. N.Bilgin, *ITU Mining Eng. Department, Istanbul, Turkey*
[4]Dr.Res.Assist. D.Tumac, *TU Mining Eng. Department, Istanbul, Turkey*
[5]Res.Assis. E.Avunduk, *ITU Mining Eng. Department, Istanbul, Turkey*
[6]M.A.Saracoglu, *Set Makina Co, Marble Machinery, Ankara, Turkey*
[7]A.Serter, *Basaranlar Marble and Travertine Co, Denizli, Turkey*

ABSTRACT

Some results of a project supported by TUBITAK (The Scientific and Technological Research Council of Turkey) are presented in this paper. A deterministic model used for predicting areal net cutting rates of chain saw machines is first presented. Field measurements in a stone quarry located in Turkey are performed to validate the model. A block of Beige Marble sample is obtained to perform a set of full-scale laboratory linear stone cutting tests for simulation of cutting action of chain saw machines, in addition to some physical and mechanical property tests. The block sample is cut using cutters with different sideways angles (0°, 15°, 30° and 45°) in the linear cutting test rig at different cutting conditions (depth of cut, cutter spacing, cutting pattern, etc). Linear stone cutting tests result in forces acting on the cutting tools and specific energy to cut a unit volume of rock. The results of linear cutting tests are used as input for the deterministic model.

The results indicate that the model is valid and reliable for predicting the areal net cutting rate of chain saw machines. The linear cutting tests make possible to deterministically simulate the cutting action of chain saw machines and develop optimum lacing designs for a given stone type, and predict and optimize machine performance.

Key words: Natural Stones, Chain Saw Machines, Linear Cutting Tests, Performance Prediction, Performance Optimization, Deterministic Modeling, Lacing Design.

1. INTRODUCTION

Natural stone production, consumption in parallel, has been growing gradually in all over the world. Chain saw machine has an important position among the machines which are used for production of stone blocks. They are used for cutting vertical or horizontal slots for production of large blocks in low to medium abrasive and soft to medium strength natural stones in both underground and surface quarrying operations, as well as for squaring purposes. They produce an excellent working environment, produce less waste material and dust (increasing recovery), eliminate collimation problems, reduce time and production losses to enter a new bench, and produce directly saleable blocks (Mancini et al., 2001; Copur et al., 2006; Primavori, 2006). They can not be used for cutting very hard and abrasive stones and frequently fractured deposits.

Performance of a chain saw machine depends basically on geological and geotechnical features of the stone deposit, specifications and design of the machine, and operational conditions. Geological parameters include rock mass properties such as joint set number and frequency, dip and direction of the deposit, and intact rock properties such as uniaxial compressive strength, tensile strength, elastic properties, texture and petrographic properties. Machine related parameters include torque-power-thrust capacities, arm length, lacing design of the cutting tools and cutting tool properties. Operational parameters include arm cutting angle, chain rotation speed, and water feeding when cutting, cutting vertical or horizontal, arm cutting angle, quality of labor, material availability.

Chisel type cutting tools (also called wedge type and/or radial type cutting tools) made of tungsten carbide having rectangular prism geometry are the most widely used tools with a design of different sideways angles on chain saw machines. Tool (line) spacing and angular positions (sideways angle) and levels of striking points of each tool vary along the cutting profile (Copur et al., 2010). Cutting action of a sequence of cutting tools is repeated by the following sequences having exactly the same lacing design and cutting profile.

This study summarizes some of the results of a research project supported by the Scientific and Technological Research Council of Turkey (TUBITAK) (Copur et al., 2008a). A deterministic model for predicting areal net cutting rates of chain saw machines, which can also be used for machine design and optimization purposes, is suggested (Copur et al., 2008b; Copur, 2010). Model requires forces acting on cutting tools as input. Different quarries in Turkey are visited for collecting natural stone samples and measuring the field performance of chain saw machines. Samples are subjected to linear stone cutting tests in laboratory for providing input and validating the model.

2. SUGGESTED DETERMINISTIC MODEL

Upcutting mode of chain saw machines is considered for modeling as in Figure 1 (Mellor, 1976). Details of the suggested deterministic model are also found in Copur at al. (2008b) and Copur (2010).

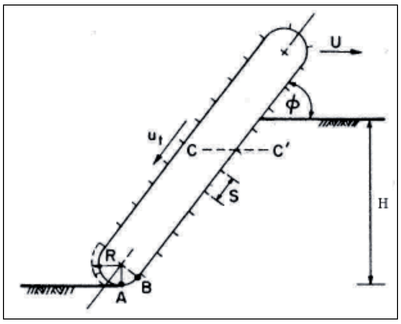

Figure 1. Kinematic parameters of chain saws in upcutting mode (Mellor, 1976)

Each tool enters the work at point A with a depth of cut (chipping depth) being close to 0, then, increases steadily through the curved portion of the nose *AB*, until it reaches a steady maximum value (*d*) which would be maintained throughout the rest of the working sweep. However, the change of depth of cut in this transition region can be ignored, since it is only a small portion of an arm.

The effective depth of cut (*d*) (normal to the face of the arm or of the stone surface being cut) is estimated by Equation (1) (Mellor, 1976):

$$d = \frac{U}{u_t} S \sin\phi \tag{1}$$

where, (*U*) is the forward movement speed of the machine, (u_t) is tangential (lineal) speed of tool, (*S*) is the longitudinal tool spacing, and (ϕ) is the arm angle (cutting angle).

Areal net cutting rate of the machine per unit time (*ANCR*) can be estimated by:

$$ANCR = H.U \tag{2}$$

where, (*H*) is the sumping depth of the arm measured perpendicular to the traverse direction

Length of the chain in contact with the stone (H_C), ignoring the nose section (*A-B*), can be estimated by:

$$H_C = \frac{H}{\sin\phi} \tag{3}$$

Number of sequences in contact with the stone (S_C) can be estimated by:

$$S_C = \frac{H_C}{S} \tag{4}$$

Number of tools in contact with the stone (T_C) can be estimated by:

$$T_C = S_C T_S \tag{5}$$

where, (T_S) is the number of tools on a sequence.

Forces acting on the tools of a sequence and specific energy are estimated based on results of linear cutting experiments by using the relationships between effective depth of cut (*d*) and tool forces and specific energy:

$$FN_i \ (or\ FC_i) = A_i d^{B_i} \tag{6}$$

$$SE_i = C_i e^{D_i d} \tag{7}$$

where, (*FN*) is average normal force, (*FC*) is average cutting force, (*SE*) is specific energy, (*i*) is the subscript of tool number on a sequence, which defines the position, sideways angle and cutting pattern of the tools starting from 1 up to (T_S), (*e*) is the base of natural logarithm, (A_i) and (B_i) are experimental constants for tool forces and (C_i) and (D_i) are the experimental constants for specific energy. Side forces can be assumed to be neutralizing each other on a sequence since a sequence is laced symmetrically. On the other hand, it should be noted that sideways forces are usually less than 20% of cutting force for wedge type tools (Roxborough, Phillips, 1981).

Total forces ($\sum FN$ and $\sum FC$) acting on the arm can be estimated by:

$$\sum FN \ (or\ FC) = t.S_C.\sum_{i=1}^{T_S} FN_i \ (or\ FC_i) \tag{8}$$

where, (*t*) is a coefficient to take into account different cutting conditions. The value of (*t*) can be estimated by:

$$t = t_1 \cdot t_2 \cdot t_3 \tag{9}$$

(t_1) is the multiplier for wearing (dullness) of tools. Field studies (Copur et al., 2008a) indicated that (t_1) can be taken as 1.3 for average wear conditions.

(t_2) is the multiplier for groove deepening (incremental cutting) action of the tools. A literature survey (Roxborough, 1988; Morrel, Wilson, 1983) indicated that (t_2) can be assumed to be 3.0 for both normal and cutting forces for lower rake angles such as in chain saw machines.

(t_3) is the multiplier for rake angle. This multiplier can be used for if results of the cutting experiments have to be adapted to a different rake angle. A literature survey (Whittaker, 1962; Pomeroy, 1964) the tool forces, for shallow depth of cut values, should be reduced around 10 to 20% for every 5° of rake angle increase, or vice versa. Therefore, for example, (t_3) can be assumed 0.85 for adaptation of tool forces from (-5°) to (0°) rake angle.

Torque requirement of the machine for only cutting the stone (***Torque***$_{Cutting}$) can be determined by:

$$Torque_{Cutting} = \frac{\sum FC}{\mathrm{Cos}(\lambda)} r \quad (10)$$

where, (r) is the radius of chain driving sprocket and (λ) is the chain rib (ridge) angle.

Total torque requirement of the machine ($Torque_{Total}$) can be estimated by:

$$Torque_{Total} = \left(f_L \sum FC + f_f \sum FN\right)\frac{r}{\mathrm{Cos}(\lambda)} \quad (11)$$

where, (f_L) is a frictional loss coefficient due to chain rotation with only pretension (without cutting, d = 0 mm) which can be taken to be 1.15 (Copur et al., 2008a), (f_f) is the frictional coefficient between chain and arm guide which can be taken as 0.05 for very well lubricated chains and 0.15 for poorly lubricated chains (Mancini et al., 1992, 1994).

Power consumption of the machine ($Power_{Cutting}$) for cutting the stone and overcoming the frictional losses can be determined by:

$$Power_{Cutting} = 2.\pi.N.Torque_{Total} \quad (12)$$

where, (N) is rotational speed of the chain sprocket wheel. This power estimation does not include the power consumption for cart movement and any efficiency factor for estimation of gross power requirement.

Total horizontal force acting on the machine body (F_H), which is balanced by the weight of the machine and determines the total thrust requirement of the machine, is estimated as the sum of the horizontal components of ($\sum FN$) and ($\sum FC$) by:

$$F_H = \sin\phi \sum FN + \cos\phi \sum FC \quad (13)$$

Total vertical force acting on the machine body (F_V) is estimated as the sum of the vertical components of ($\sum FN$) and ($\sum FC$) by:

$$F_V = \cos\phi \sum FN - \sin\phi \sum FC \quad (14)$$

Field observations and measurements indicated that (F_H) had to be equal to or less than the weight of the machine for a secure operation and breakage free machine components (Copur, 2010). This can be considered as a design and optimization criteria for chain saw machines. (F_H) and (F_V) values can also be used for structural design of chain saw machines.

A limitation for chain saw machines is the available haulage volume of the chain. The loose volume of material cut (v_c) by one tool along the arm, neglecting the nose section, for unit width of the chain can be approximated as (Mellor, 1976):

$$v_c = \frac{U}{u_t} SHK_b \quad (7)$$

where, (K_b) is bulking factor, with the value of 1.85. For one complete interval between tracking tools, the space available per unit width (v_a) is estimated as (Mellor, 1976):

$$v_a = Sh_t - v_t \quad (8)$$

where, (h_t) is the height of the tool holder above the chain surface and (v_t) is the volume of the tool holder itself. Therefore, a design criterion can be given as ($v_a \geq v_c$).

The suggested model can be coded into a worksheet computer program such that any parameter can be varied for a performance prediction and optimization process; and also, it can be applied or adopted to other types of continuous belt type of mechanical miners.

3. VALIDATION OF THE MODEL

Different quarries in Turkey were visited for collecting stone samples and measuring the field performance of chain saw machines. Samples are subjected to linear stone cutting tests in laboratory for providing input and validating the model. The results for only the samples taken from a Beige Marble Quarry are presented in this study.

3.1. Field Studies

Field studies were performed in a Beige Marble Quarry (Figure 2) located at Yesilova-Burdur, of Basaranlar Marble and Travertine Co in Denizli.

Garrone MCRH 340 chain saw machine is used in the quarry for cutting horizontal bottom surface of the marble blocks (Figure 3, Table 1). Lacing pattern of cutting tools was defined as in Figure 4.

Figure 2. Beige Marble Quarry in Yesilova-Burdur (Basaranlar Marble and Travertine Co)

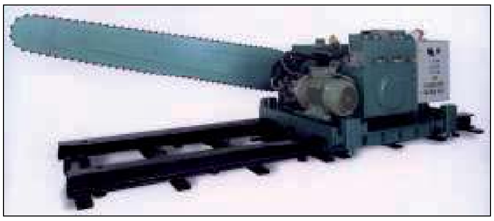

Figure 3. Garrone MCRH 340 chain saw machine

Table 1. Technical features of Garrone MCRH 340

Weight	5.5 tonnes
Electric Voltage	380 V
Total Installed Power	50 kW
Maximum Reach	340 cm
Chain Speed	0 to 1.8 m/s
Feed Motion Speed	0 to 20 cm/min
Cutting Width	42 mm
Oil Tank Capacity	220 liters
Chain Pressure	350 bar
Load Pump Pressure	25 bar
Cart Move Pump	50 bar
Arm Rotation Pressure	70 bar
Arm Rotation	360°

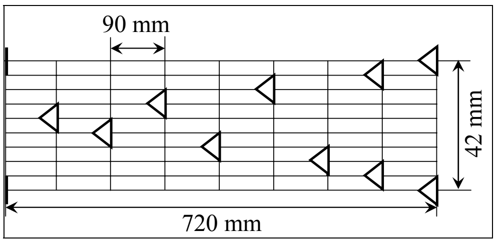

Figure 4. Lacing design of a cutting sequence used for performance prediction (Copur et al., 2008a)

Data acquisition system (Figure 5) for field measurements includes optic tachometer for chain speed, power and ampere meters, hydraulic pressure transducers for cart movement and chain rotation motors, portable computer for recording pressures, and stopwatch and tape measure.

Figure 5. Field measurement equipment

An experimental cut is applied in the field for cutting horizontal bottom surface of Beige Marble and the realized operational parameters of the machine are recorded (Table 2) and used as input to the suggested model (Copur et al., 2008a). First, the chain speed is arranged to be around maximum, and then, the cart movement speed is increased up to a safe limit. Operator arranges this value based on his ampere readings on the control panel of the machine (around 45 A in this case) and pressure readings (around 120 bars for chain rotation).

Table 2. Field measurements (Copur et al., 2008a)

Surface being cut	Bottom surface
Useful arm cutting depth, (*H*)	2.60 m
Arm angle, ϕ	78°
Average net cutting rate, (*ANCR*)	4.630 m^2/hour
Average cart motion feed, (*U*)	1.78 m/h (0.5 mm/s)
Ave. chain rotation speed (linear), (u_t)	1.15 m/second
Effective depth of cut of a tool, (*d*)	0.30 mm
Water feeding	8 – 10 liters/minute
Cutting tools	4-edge chisel
Tool rake and clearance angles	0° and 8°
Lubricator (Grease) consumption	0.5 kg/m^2
Cart motion speed pressure (cutting)	20.7 bar
Cart motion speed pressure (not cutting, moving empty, frictional)	3.28 bar
Chain rotation pressure (cutting)	117.0 bar
Chain rotation pressure (rotating without cutting, pretension friction)	21.9 bar
Rotational speed of the chain driving sprocket, (*N*)	110 rpm
Power consumption (including 3 kW for cart movement)	18.9 kW
Power consumption for cutting and frictional loses ($Power_{Cutting}$)	15.9 kW

3.2. Experimental Studies

Samples are subjected to full-scale linear stone cutting tests in laboratory, in addition to physical and mechanical property tests. Linear cutting tests (Figure 6) were performed based on the lacing pattern (Figure 4) and cutting patterns (Figure 7) defined in the field.

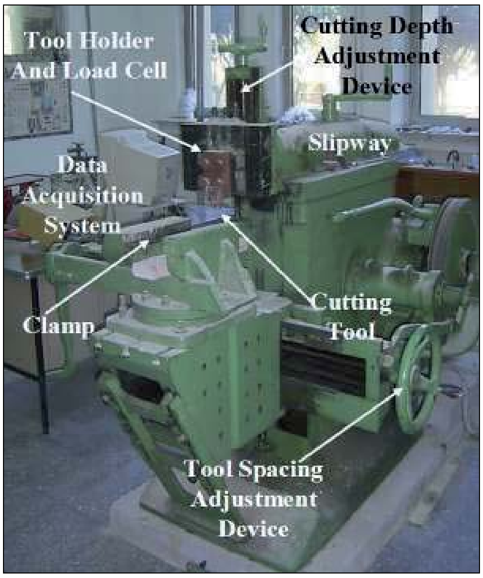

Figure 6. Linear cutting test rig of ITU Mining Engineering Department

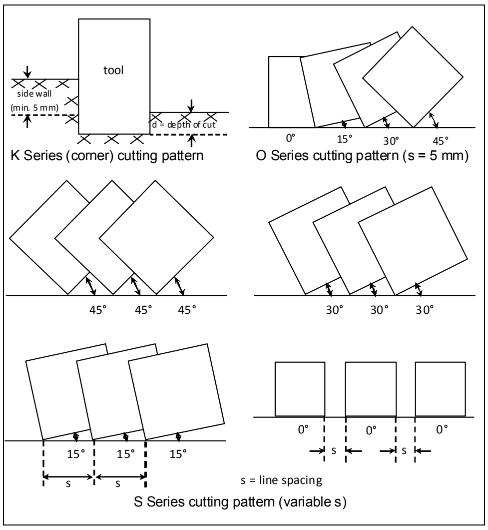

Figure 7. Cutting patterns of chain saw machines (Copur et al., 2008a, 2010; Copur, 2010)

Details about linear cutting test rig can be found elsewhere (Balci, 2004; Copur et al., 2007). Details of cutting patterns can be found elsewhere (Copur, 2010; Copur et al., 2010).

Some of the physical and mechanical properties of Beige Marble are presented in Table 3.

Table 3. Physical-mechanical properties of Beige Marble (micritic limestone), (Copur et al., 2008a)

Natural unit weight	2.70 g/cm^3
Uniaxial compressive strength	83.7 MPa
Brazilian tensile strength	8.5 MPa
Cerchar abrasivity index	1.1
Static elasticity modulus	17.17 GPa
Static Poisson's ratio	0.20
Dynamic elasticity modulus	82.8 GPa
Dynamic Poisson's ratio	0.38
Cone indenter hardness	2.72

The relationships between effective depth of cut and tool forces (normal and cutting) and specific energy are found by linear cutting tests (Figure 8). Results of linear cutting tests are summarized in Figure 9 as a force balance diagram of a cutting sequence.

Figure 8. Sample surface after a set of cutting tests

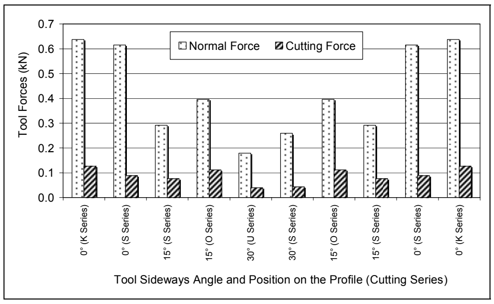

Figure 9. Force balance diagram on chain profile for Beige Marble at 0.3 mm of effective depth of cut (U Series of cutting pattern indicates unrelieved/non-interactive/single cutting mode), (Copur et al., 2010)

3.3. Evaluation of the results

Total forces acting on the arm are estimated to be 49.3 kN (5024 kgf) for normal force and 9.2 kN (934 kgf) for cutting force. Total horizontal (F_H) and vertical (F_V) components of tool forces acting on the machine are 50.1 kN (5109 kgf) and 1.3 kN (131 kgf), respectively. The estimated thrust, 50.1 kN (5109 kgf), should be balanced by the machine mass of 5.5 tonne-force (excluding the rails) showing that the machine works close to its thrust capacity in this case (Copur, 2010).

Estimations based on the proposed deterministic model indicates that the chain saw machine modeled in this study becomes thrust limited after reaching 4.63 m^2/h areal net cutting rate, which is normal for cutting very hard (around 84 MPa) Beige Marble by chain saw machines. The field studies also indicated that the same chain saw machine can reach at up to 15 m^2/h areal cutting rate for cutting Travertine having 12-15 MPa uniaxial compressive strength (Copur et al., 2006).

The suggested model was run for other types of natural stones, as well. And, the results indicates that the model gives reasonable results for predicting areal net cutting rates of chain saw machines. All cases indicate that the chain saw machines are thrust limited machines.

4. PERFORMANCE OPTIMIZATION AND SUGGESTION OF A NEW LACING DESIGN

It is known that the machine is not operated at optimum conditions for the example given above. Optimum tool spacing to depth of cut ratio (s/d) value is around 3.0 for Beige Marble; therefore, the depth of cut value should be kept around 1.7 mm for providing an interaction (chipping) between tool lines being average 5 mm. If the machine is operated at 1.7 mm depth of cut value for the same lacing design by only setting the cart movement speed as 4.0 m/s and chain rotational speed as 0.5 m/s, the areal net cutting rate increases from 4.63 m^2/h up to 10.4 m^2/h and the thrust requirement reduces to around 30.8 kN (3140 kgf) since the incremental groove deepening effect diminishes at optimum cutting condition by taking t_2 of 1.0 (Copur, 2010). This improvement / optimization on performance would also reduce the tool consumption rate per square meter of cut.

The performance of this machine could also be improved by applying new lacing designs. For example, a second sequence could be introduced to cut the ridges produced by the first. However, since no experimental data is available on this type of sequencing of the chisel tools, any simulation by using the suggested deterministic model could not be run for the time being.

5. CONCLUSIONS

A deterministic model is suggested based on kinematics of continuous belt type machines. The model uses the results of linear cutting tests as input parameters. The model is verified by the field measurements and experimental studies performed on Beige Marble and proven to be a useful and reliable tool for performance prediction, optimization and lacing design of chain saw machines.

ACKNOWLEDGEMENTS

The authors would like to convey their appreciation to The Scientific and Technological Research Council of Turkey (TUBITAK) for their support on the Project 105M017.

REFERENCES

Balci, C., 2004. Comparison of Small and Full Scale Rock Cutting Test to Select Mechanized Excavation Machines. PhD Thesis, Istanbul Technical University, Mining Eng Dept. (in Turkish with English abstract).

Copur, H., 2010. Linear stone cutting tests with chisel tools for identification of cutting principles and predicting performance of chain saw machines. Int J Rock Mech & Min Sci, Vol. 47, Issue: 1, pp. 104-120.

Copur, H., Bilgin, N., Balci, C., Tumac, D., 2008a. Optimization of Cutting Performance of Chain Saw Machines Used for Natural Stone Quarrying. Report Submitted to TUBITAK, No: 105M017. Istanbul Technical University, Mining Engineering Department.

Copur, H., Balci, C., Bilgin, N., Tumac, D., 2008b. Laboratory cutting tests for performance prediction of chain saw machines. Proceedings of the 21st World Mining Congress and Expo 2008, Krakow-Katowice-Sosnowiec, Poland, 7-12 Sept., ISBN: 978-83-88519-81-9, pp. 97-107.

Copur, H., Balci, C., Bilgin, N., Tumac, D., Duzyol, I. 2007. Full-scale linear cutting tests towards performance prediction of chain saw machines. In: C. Karpuz, et al., Eds., Proceedings of the 20th International Mining Congress and Exhibition of Turkey, Ankara, 6-8 June, pp. 161-169.

Copur, H., Balci, C., Bilgin, N., Tumac, D., Feridunoglu, C., Dincer, T., Serter, A., 2006. Cutting performance of chain saws in quarries and laboratory. In: M. Cardu, et al., Eds., Proceedings of the 15th International Symposium on Mine Planning and Equipment Selection, Torino-Italy, 20-22 Sept., pp. 1324-1329.

Copur, H., Balci, C., Tumac, D., Bilgin, N., Avunduk, E., 2010. Field and laboratory studies on performance of chain saw machines. In: J.

Zhao et al., Eds., Proceedings of EUROCK 2010, Lausanne-Switzerland, 15-18 June, pp. 823-826.

Garrone, Product Catalogues

Mancini, R., Cardu, M., Fornaro, M. and Toma, C.M., 2001. The current status of marble chain cutting. In: R.K. Singhal and B.P. Singh, Eds., Proceedings of the 9th International Symposium on Mine Planning and Equipment Selection, New Delhi, 19-21 Nov., p. 151-158.

Mancini, R., Cardu, M., Fornaro, M., Linares, M., Peila, D., 1992. Analysis and simulation of stone cutting with microtools. In: Proceedings of the 3rd Geoengineering Congress, Rock Excavation: The Future and Beyond, 1-2 Dec., pp. 227-236.

Mancini, R., Linares, M., Cardu, M., Fornaro, M., Bobbio, M., 1994. Simulation of the operation of a rock chain cutter on statistical models of inhomogenous rocks. In: G. Pasamehmetoglu et al., Eds., Proceedings of Mine Planning and Equipment Selection, pp. 461-468.

Mellor, M., 1976. Mechanics of Cutting and Boring, Part 3: Kinematics of Continuous Belt Machines. CRREL (US Army, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire), Special Report, No: 76-17.

Morrell, R.J., Wilson, R.J., 1983. Toward Development of a Hard-Rock Mining Machine – Drag Cutter Experiments in Hard, Abrasive Rocks. USBM, RI 8784.

Pomeroy, C.D., Breakage of coal by wedge action – Factors affecting tool design - 2. Colliery Guardian, July 24, pp. 115-121.

Primavori, P., 2006. Uses for the chain saw. Marmo Macchine International 53:80-102.

Roxborough, F.F., 1988. Multiple pass sub-interactive rock cutting with picks and discs. In: Proceedings of CARE '88 (Conference on Applied Rock Engineering), pp. 183-191.

Roxborough, F.F., Phillips, H.R., 1981. Applied Rock and Coal Cutting Mechanics. Workshop Course, Australian Mineral Foundation, Adelaide, 11-15 May, 1981.

Whittaker, D., 1962. Effect of pick shape on cutting forces. Colliery Guardian, Aug. 23, pp. 242-244.