WATERJET DISMANTLING OF END-OF-LIFE OVERSIZE DUMPER TYRES

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ABSTRACT

The huge amount of end-of-use oversize tyres represents a big problem in large surface mines due to their heavy weight and bulkiness that make stockpiling and disposal in lanfills technically, economically and environmentally unfeasible.
Therefore the alternative option of dismantling and possibly recycling and reusing both the rubber and the reinforcing wire-frame seems by far preferable.
Several technologies have hitherto been developed relying on purely mechanical processing of the tyres that however are not fully suitable for recycling the materials recovered (rubber, metals and textiles). Waterjet can be a successful technology for this to be achieved owing to its flexibility, selectivity and performance.
A series of tests have been made on conventional car tyres at the University of Cagliari using stationary or pulsed jets with the aim of obtaining useful correlations of rubber removal rate and steel cleaning, as a function of the relevant operational parameters (pressure and water flowrate, nozzle diameter, traverse velocity, stand-off distance).
The results can be extended to the case of big mine tyres by modifying the operation's strategy that will include the use of robot-driven cutting head issuing low pressure, high flowrate water jets for the disintegration of the thread having a composite structure, in combination with conventional mechanical shredding for the treatment of the parts consisting of rubber only, previously separated with suitably directed abrasive waterjet cuts through the tyre body.

1. INTRODUCTION

Over the years, end-of life tyres and rubber waste in general have been disposed of in landfills, stockpiles, illegally dumped or burned, creating severe impacts on the environment. In latter years, a variety of industrial plants for tyre shredding and crumbing have been designed and built in Europe and elsewhere in compliance with UE directives.
In this way the environmental problems can be overcome while deriving real benefits from the sale in the marked of the materials recovered from used tyres turning them into an "economic resource".
In particular, the high cost and dwindling availability of natural rubber has opened up the market for recycled rubber powder. The difference in cost and the decreasing supply of virgin rubber on the one hand and the increasing demand for rubber products on the other, highlight the huge potential for developing innovative technologies enabling recycling of used rubber in industrial processes (Ciccu, 2009).

2. DISINTEGRATION OF TYRES WITH WATERJET TECHNOLOGY

The potential of waterjet for cutting rubber and expansive materials is well known.
The suitability for destroying the scrap tyres has been demonstrated by a previous investigation concerning car tyres (Ciccu, 2008) and mining tyres (Ciccu, 2009). Interesting results can be found in reference 1 (Cornier, 2004). In this paper the past and recent experience gained at DIGITA's waterjet laboratories is summarised.

2.1. Properties of tyres

The composition of car tyres is different from truck tyres, not only as to size, steel or textiles contained in the structure, but also in terms of ingredients and their proportions in the blend.
The two tables below show the differences in weight and composition between various types of tyres.

Table 1. Characteristics of tyres

VEHICLE TYPE	**WEIGHT kg**
Touring cars	7.5/8.5
Family cars	11
Truck	50
Semi trailer	55/80
Farm vehicles	100
Mining dumpers	1000-5000

Table 2. Composition of tyres

COMPONENTS	Proportion %	
	Car	**Truck**
Rubber/elastomers	48	43
Carbon black	22	21
Steel	15	27
Textile	5	--
Zinc oxide	1	2
Sulphur	1	1
Chemical additives	8	6

The specifications and weight of tyres varies from one continent to another, depending on a number of criteria including national speed limits, climatic conditions and topography, road structure and surface.
Tyres used in mining equipment generally have a diameter of at least 1.4 m, reaching even 3 m in the biggest dumpers. The thread width is approximately 40% of the tyre diameter.
The scrap car tyres used in the experimental tests carried out at DIGITA's laboratories contained around 1,560 g metal, accounting for more than 20% of the total weight.

2.2. Experimental tests on car tyres

The experimental investigation was performed on hard rubber mixture tyres.
Two approaches have been followed:

- Cutting the tyre into pieces by working at high pressure and low flowrate (region 1);
- Disintegration of the rubber into fine particles by using larger nozzles issuing a fan jet under moderate pressure (region 2).

As shown in figure 1, jet conditions in the region 1 of the graph are more suitable for excavation, while conditions in region 3 are typical of cutting operations.
In fact mass removal of material depends chiefly on nozzle diameter and thence on water flowrate that controls the extent of the target area impacted by the jet, whereas jet penetration, increasing with pressure, is essential for cutting where material removal should be minimised for the sake of energy saving.
Actually as pressure increases water jet speed also increases thus concentrating more power in a smaller area as shown by the curve in the right side of figure 1.
The performance of each of the two options was checked experimentally at almost equal power in order to put into evidence the best solution for tyre dismantling.

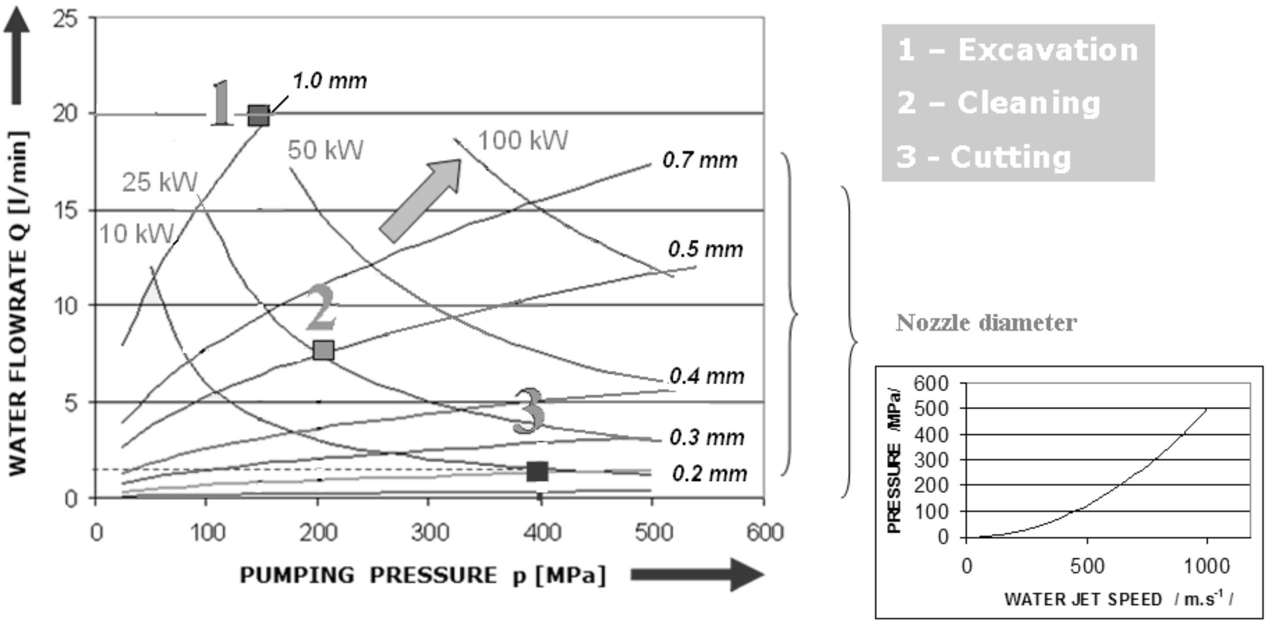


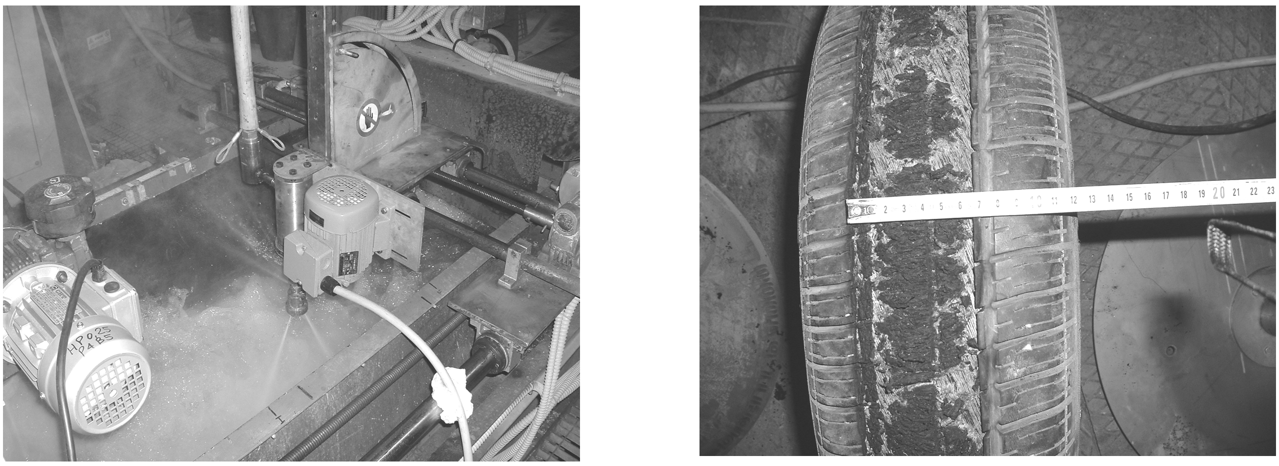
Figure 1. Fields of application of stationary water jets

2.2.1. Tests at high pressure

This subject has been dealt with in a previous research, the main results of which are here recalled (Ciccu 2009).

In this case the cutting head consisted of a fast rotating lance ending with a nozzle holder through which two angled jets were issued, as shown by the image at the left side of figure 2. The jets were directed against the tyre surface impacting the target over a width of about 7 cm while the tyre was rotated along its axis.

The trajectories were roughly two phase-shifted epicycloids crossing each other with fair angles resulting in the detachment of fusiform stripes of rubber with small proportion of fine powder.



Water jet feature *Strip of tread treated in two minutes*

Figure 2. Details of the experimental setup for waterjet cutting experiments at high pressure

With a single two-nozzled head, the part of the tread impacted by the waterjet was a strip roughly 7.5 cm wide (figure 2 right side). Consequently, to destroy the entire tread in two minutes requires two heads to be used. Once the tread has been destroyed, the two sides devoid of metal reinforcement can be shredded using a conventional blade chopper.
The data obtained with several series of systematic tests were analysed in order to obtain the amount of tyre destroyed (% of original weight less metal reinforcement) as a function of the two most important hydraulic parameters:

1. Water pressure
2. Hydraulic power of the two jets

The hydraulic power (cutting output) and pressure required to completely destroy in two minutes a 7.5 m wide strip of tread can then be extrapolated from the trend lines. Once the power carried by each jet has been determined, the number of nozzles required to destroy the whole tyre in the same time can be obtained.
The graphs of figure 3 show that to destroy the whole tyre in two minutes requires a waterjet pressure of about 260 MPa using 0.6 mm nozzles. Decreasing nozzle diameter to 0.5 mm, a pressure of almost 290 MPa would be required to achieve the same result.

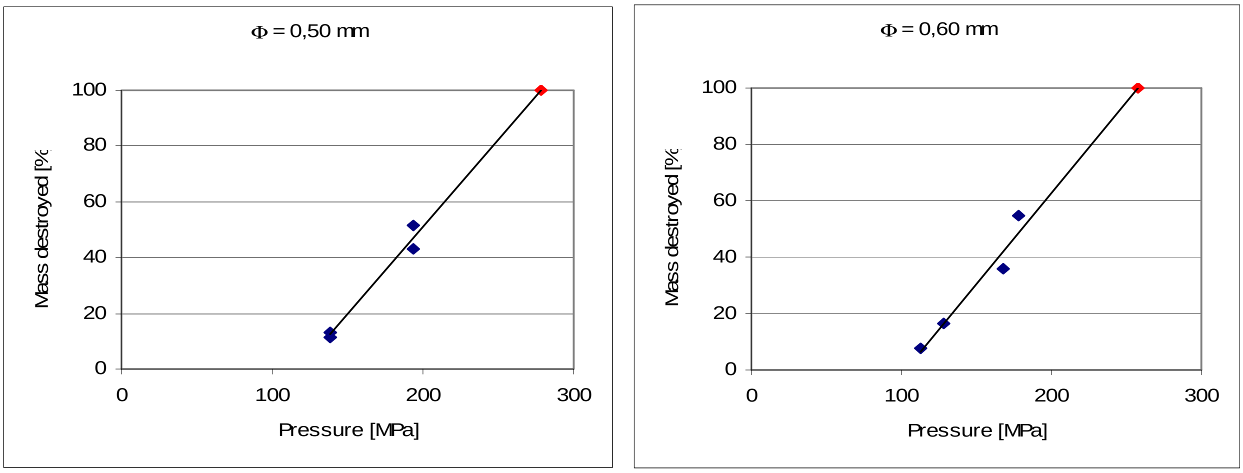


Figure 3. Influence of pressure and nozzle size on cutting performance.

The graph of figure 4 shows the data obtained for the two series of tests conducted (with nozzle diameters of 0.5 and 0.6 mm). To destroy the whole tyre in two minutes would require a cutting output of at least 55 kW. Consequently, specific energy resulted to be 0.94 kJ/g, although this figure might have been underestimated being it roughly calculated by linear extrapolation of few scattered and distant data, not taking into account the curbing trend normally observed at increasing power.

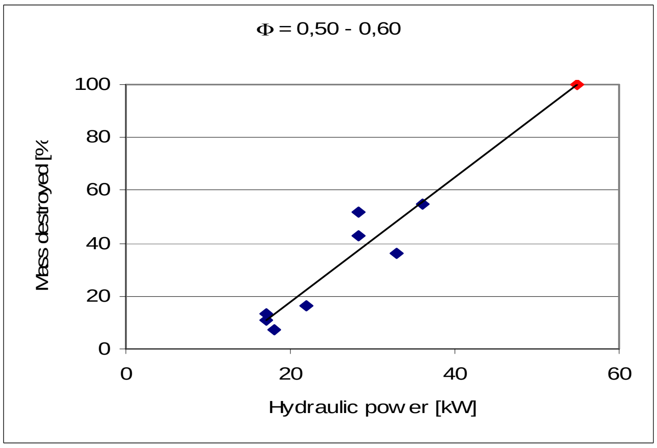


Figure 4. Influence of hydraulic power on cutting performance.

2.2.2. Tests at moderate pressure

Instead of destroying the whole tyre, only the threads previously cut out by means of separation cuts were treated with waterjet, while the shoulders containing no metal could be shredded by means of conventional machines.
Aiming at possibly reducing the specific energy that is the most significant parameter for the economic feasibility of the technology, a fan jet nozzle was traversed sideways with alternate motion across the thead, laying flat onto a supporting metal grid while advancing by discrete steps.
The tests were carried out at moderate pressures, below 100 MPa with or without pulsation obtained by means of a piezoelectric device capable of modulating the jet at a frequency of about 15 kHz (Bortolussi, 2006).
The expected advantages achievable with the industrial application of this concept are:

- Lower capital expenditures for the waterjet system
- Better long-term reliability
- Good treatment capacity
- Expected higher performance
- Improved product quality
- Higher capacity of the plant owing to the parallel treatment of threads and shoulders.

On the other side water requirement when working at moderate pressures is much larger (although almost entirely amenable to recycling back to the pumps after filtering).
The best results have been obtained using single fan jets 3.00 and 2.08 mm in diameter generated at a pressure of 80 MPa.
For all the configurations the cutting rate was 600 cm^2/min.
The results reported in table 3 show that the stationary fan jet issued by the 2.08 mm nozzle at a 30 mm stand-off distance from the workpiece seems the most energy efficient.

Table 3. Results of the tests at equal cutting rate

Nozzle diameter [mm]	Pressure [MPa]	Water Flowrate [l/min]	Hydraulic power [kW]	Stand-off distance [mm]	Traverse velocity [mm/min]	Advance step [mm]	Cutting rate [cm2/min]	Specific energy [kJ/cm2]	Pulsation
3,00	75	108	135	60	6000	10	600	13.5	YES
3,00	90	120	180	60	6000	10	600	18.0	YES
2,08	75	55	69	30	6000	10	600	6.9	NO

In a further series of tests the lance manipulation system was modified in order to explore the possibility of maximising the cutting rate and thence the throughput capacity of the industrial plant that has a capital importance for the economic feasibility of the technology.
As shown in figure 5 the lance was guided by a forth/back linear manipulator while the thread was fed forward by a conveyor belt beneath the fan jet nozzle. The disintegration products were collected in the vessel below together with the water and pumped to a vibrating circular screen for size classification before final drying.
The concept is sketched in figure 5.

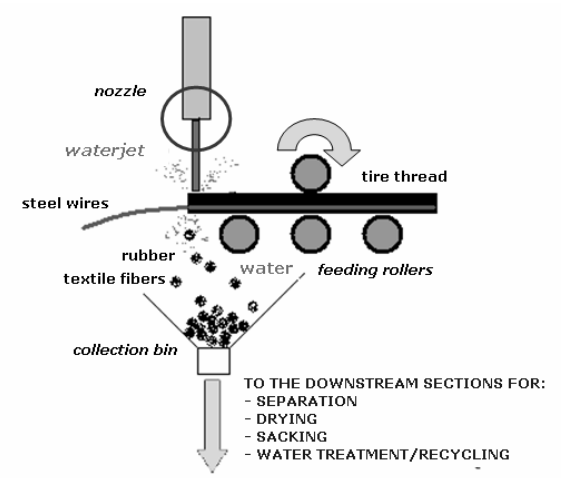


Figure 5. Concept and experimental apparatus for the tests at moderate pressure

Results reported in Table 4 show that cutting rate can be raised to beyond 1,000 cm^2/min with a corresponding energy consumption around 6 kJ/cm^2, (about 3 kJ/g, assuming an average thickness of 2 cm and a volumic mass of the rubber around 1g/cm^3).
Compared to the figure given for the high pressure tests, this one is about 3 times higher. However the comparison is not fully consistent since the size of the rubber particles obtained when working with fan jets is much finer at the expense of additional energy.
The experimental results obtained at moderate pressure are much more reliable, owing to the fact that specific energy has been determined after the complete disintegration of the thread and not simply inferred from partial data like in the case of high pressure tests.
Accordingly, the preliminary performance evaluation assumed in the design of an industrial plant has been based on a conservative value of 8 MJ/kg.
The mass removal rate can be estimated at about 120 kg/h per 100 kW of power involved.

Table 4. Results of the tests at variable cutting rate

Nozzle diameter [mm]	Pressure [MPa]	Water Flowrate [l/min]	Hydraulic power [kW]	Stand-off distance [mm]	Traverse velocity [mm/min]	Advance rate [mm/min]	Cutting rate [cm2/min]	Specific energy [kJ/cm2]	Processing quality
2.08	80	56	75	40	1200	230	445	10.1	Fair
2.08	80	56	75	25	1200	230	480	9.4	Fair
2.08	100	62	103	25	3000	410	778	7.9	Good
2,08	100	62	103	40	3000	470	1,037	6.0	Fair

Disintegration of tyres with water jets, either continuous or pulsating, is always very selective, allowing to obtain a clean metal product (with less than 5% residual rubber) and a rubber product with very fine size distribution (typically 60%<1mm) well appreciated by the market (figure 6).
Textile fibers can be separated by dry ventilation.

Figure 6. Typical quality of disintegration products

2.3. Plant design

An industrial plant based on waterjet disintegration of the tyre threads previously separated from the shoulders by means of a cutting machine provided with sharp blades can consist in a number of parallel lines according to a concept matching operational flexibility, better reliability in continuous operation and economic advantages.
The two shoulders of each tyre (containing no steel) can be disintegrated with mechanical shredding and granulation machines in a separate section of the plant having a capacity of about 3,000 tpy.
The expected plant performance based on the experimental results having an industrial significance so far obtained is summarized here below:

- Total processing capacity (nominal): 7,000 tpy (about 1,000,000 car tyres)
- Number of parallel lines: 6 (threads) + 1 (shoulders)
- Working shifts: 2 (16 production hours per day)
- Working days: 250 per year (28 tpd = 4,000 tyres)
- Feed rate of each individual waterjet lines: about 180 kg per hour
- Pumping pressure: 50-70 MPa (30-50MPa with pulsed jets)
- Flowrate of each pump: 160-200 l/min
- Total hydraulic power issued by the pumps: 1,200 kW
- Amount of water required: <70 m^3/h (80% recycled)
- Cutting rate: about 800 cm^2/min (standard car tyre)
- Average processing time for each tyre: 60s

2.4. Discussion

With the experimental waterjet facility for tyre destruction described here it was possible to separate the rubber from the steel cords, No hazardous substances are generated during the process as the working fluid is plain water.
The rubber can be readily recovered with a cyclone in which the water is separated from the rubber. The millimetre size rubber cuttings are then dried and placed in suitable containers. The steel wires are totally rubber free and can be readily reused.
Recent advances in waterjet technology will no doubt further enhance performance of this type of plant.

Owing to the high selectivity achievable, all the products resulting from waterjet disintegration of end-of-life car tyres can be employed in a variety of applications, such as (Ciccu, 2010):

- Manufacturing of new tyres (with preliminary de-vulcanization)
- Rubber objects for wheels, rollers, vibration dampening elements
- Rubber components in buildings, floors and school furniture
- Industrial carpets
- Road cover with bituminous binders
- Noise barriers
- Light insulation panels
- Row material for pyrolysis processes
- Filtering beds for water decontamination
- High quality metal products
- Plastic containers

3. DESTRUCTION OF MINE TYRES WITH COMBINED TECHNOLOGIES

Over the years, mining operations and equipment have become greater in efficiency and scale, reducing unit costs. As a result, mining productivity is now evaluated more on an exploitation efficiency basis than the conventional cost per hour basis.
With total operating costs calculated according to mined tonnage, super-large big payload trucks are employed by mine owners everywhere. As the market evolves in this new millennium, global mining requires bigger, higher-efficiency machines with payload capacity of of up to 350 t.
The fact that larger dump trucks need larger tyres to accommodate the greater load and stress applied means promising prospects for tyre manufacturers, although tyre shortage is faced by many companies forcing them to buy used tyres, sharing between mines and smoothing open-pit floors to reduce wear.

3.1. Tyre Life Cycle

The tyre life cycle can be affected by some conditions concerning the manufacturer, the distribution system and the end user (Ciccu 2009). In particular:

1) Product development and innovation increase tyre life, number of replacements, consumer safety, and reduce tyre waste.
2) Proper manufacturing and quality of delivery reduces waste at production.
3) Direct distribution through retailers, reduces inventory time and ensures that the tyres are properly and safely used by the customers.
4) Consumers use and maintenance choices like tyre rotation, the application of protection chains and a good quality of road surface affect tyre wear and safety of operation.
5) Manufacturers and retailers set policies on return, re-thread, and replacement to reduce the waste generated from tyres and assume responsibility for taking the ‘tyre to its grave’ as later as possible.
6) Recycling end-of-life tyres by developing strategies that combust or process waste into new products, creates viable businesses, thus fulfilling public policies.

If the above measures are adopted the overall technical life of truck tyres under moderately severe conditions can be less than 6 months of working.

3.2. Tyre destruction strategy

The results of a previous investigation (Ciccu 2009) indicated that in the case of largest tyres the most convenient strategy is the following (figure 7):
Separation cut with premixed abrasive waterjet (AWSJ) followed by shredding of the part free from metal in conventional mechanical blade choppers while destroying the remaining carcass by plain waterjet (WJ) until complete cleaning of the wire-fabric reinforcing.
Direct shredding is practically impossible for large mining tyres.

Abrasive waterjet is a widely used technology applicable to a variety of materials and its cutting performance has been improved in the recent years (Bloomfield, E.J. e Yeomans, M., 1991; Guo N.S.et al., 1991; A. Bortolussi et al. 2006)
According to this strategy a separation cut cylindrical in shape is made as shown in figure 8 for removing the shoulders and the tread i.e. the thick rubber, or rubber/composite compound formulated to provide an appropriate level of traction, whose pattern is characterized by the geometrical shape of the grooves, lugs, voids and sipes. The cut surface is πD x W.
After the separation cut is made it is assumed that the residual part of the tyre that contains the reinforcement steel represents about 40% of the original mass.

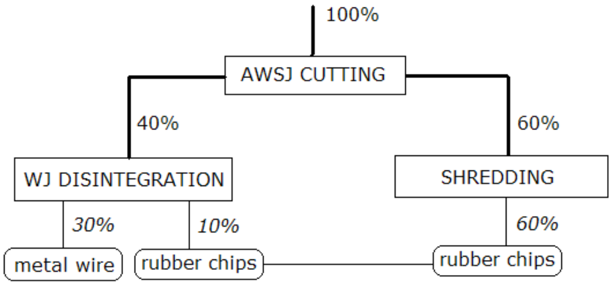


Figure 7. lowsheet of dumper tyre processing with combined technologies

Figure 8 Pattern of separation cut with abrasive waterjet

Concerning the jet configuration most suitable for the treatment of oversize tyres it is clear that a sigle nozzle lance is not the best solution since the power generated would be insufficient for disintegrating the whole tyre in a reasonably short time.
Therefore a rotating head provided with multiple nozzles (up to 8) placed along two arms could be used. This cutting head at the end of a robot-driven articulated arm can be moved around the tyre's carcass laying onto a supporting platform.
Tests have been started and the first results obtained appear promising. Assuming that the specific energy is the same, this rotating head could replace 4 lances equipped with single fan jets.

3.6 . Economic feasibility

On the basis of the results obtained with the tests using 4 fan jet nozzles bearing a total hydraulic power of 400 kW, the cost of disintegrating a giant dumper's scrap tyre (with 30% steel; mass: 4,000kg (2,800kg rubber); D: 3,000mm; R: 1,200mm; W: 1,200 mm) according to the above devised strategy is represented in the bar diagram of figure 9.

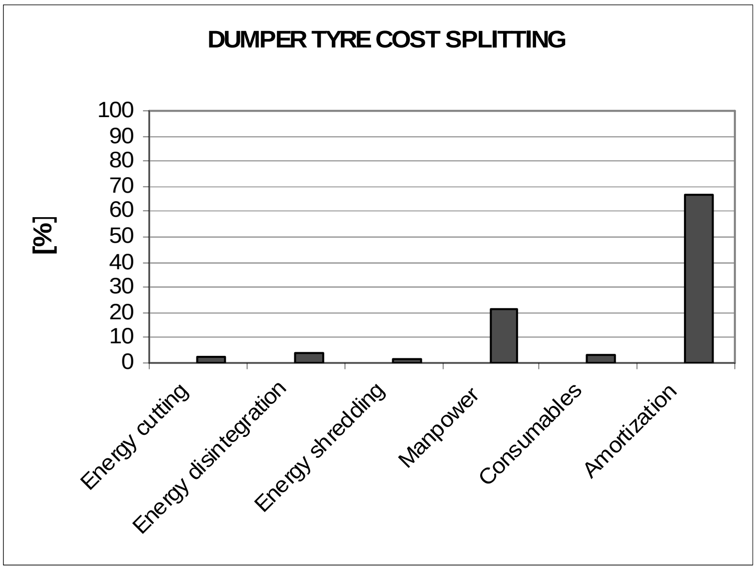


Figure 9. Cost splitting for disintegrationg a dumper tyre

Total operational cost (not including overhead expenses), assuming the price of productive factors (energy, manpower, consumables) typical of European situation, slightly exceeds 1,000 € per each tyre of which more than 60% is represented by amortization calculated over a period of 10 years.
This cost can be totally covered by the market value of products obtained (rubber and metal) leaving a considerable profit.

4. CONCLUSIONS

The results achieved with the experimental research have shown that waterjet technology can be readily applied for the destruction of end-of-life tyres.
Moreover, the simple-to-use equipment employed, the robustness, great flexibility, exceptional operating comfort and high level of automation that this technology offers all suggest that before long it will become a major success for tyre destruction and be able to rival traditional techniques.
Advances in waterjet technology such as the development of waterjet facilities, study of nozzle design and cutting head motion, improvement of feed systems, perfection of automation systems will all contribute to reducing production costs and hence to enhancing performance and competitiveness.
Lastly, the investigation should be extended to multiple rotating waterjet heads (two-nozzled). A waterjet facility equipped with several multiple rotating heads offers in our opinion enormous potential. Considering that by increasing the number of two-nozzled rotating waterjet heads, the rate of tyre destroyed and thus the number of tyres destroyed (and hence productivity) increase proportionally, while the capital and operating costs (for pumps of increasing output as a function of number of nozzles) increase less than proportionally, a waterjet facility of this type would deliver high productivity adopting an economically efficient process to yield good quality products.
Clearly, a rigorous analysis of strong and aggressive production and marketing strategies will be required, not on the part of the business itself but of the system as a whole in order to face up to the competitiveness challenge. This can be achieved by improving the technology and production and organizational efficiency also with a view to opening up the market, resulting in a positive impact on the regional economic system.
Concerning mine tyres, the recycling option can even be more attractive than for car tyres because it would provide a solution to the disposal problem that is much more difficult-to-solve while offering an interesting contribution to the company's profit.
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Moreover, the simple-to-use equipment employed, the robustness, great flexibility, exceptional operating comfort and high level of automation that this technology offers all suggest that before long it will become a major success for tyre destruction and be able to rival traditional techniques.
The good selectivity of the operation allows full recycling of disintegration products meeting the market requirements for a variety of uses, some of them offering a very attractive economic return.

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