A Novel Technique for Characterizing the Influence of Refining Energy on the Mechanical Properties of TMP Fibres

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ABSTRACT

Mechanical fibres are commonly characterized by measuring their length distribution and freeness. These parameters, however, do not adequately characterize the influence of refining on their mechanical properties. In this work we conducted multiple compression on fibre mats prepared from different length fractions (Bauer McNet fractions) to generate stress-strain curves from which several quality parameters can be derived such as modulus, stress and toughness. We found that these characteristics of fibre are strongly influenced by the refining energy used to produce pulp; fibres of similar length exhibit different mechanical properties depending on the refining energy consumption.

INTRODUCTION

Mechanical pulp is usually characterized by fibre length distribution and freeness; the latter is principally determined by the amounts of fines (fibrous materials that pass through a 200-mesh screen). These measurements are often followed by physical tests to establish the bonding potential of pulp fibres, and do not, however, reveal the mechanical nature of the processed fibre's structure. The mechanical characteristics of the fibre structure can have significant impacts on the physical response of the fibrous network.

Mechanical properties of single wood pulp fibres such as tensile [1-5] had been reported. Testing single fibres is, however, tedious and time consuming. Additionally, evaluating single mechanical fibres could lead to extremely large variation in measurements because of the complexity in physical nature of these fibres in comparison with chemical fibres, due to the crudeness of mechanical pulping. For example, unlike the chemical counterpart, the mechanical fibres exhibit great variation in length, coarseness, cell wall thickness, cell wall splitting [6], cell wall dislocation [7] and surface fibrillation, etc. These defects induced by mechanical processing could greatly influence the measurements of the strength of individual mechanical fibres.

To overcome these difficulties fibre mats can be used instead of single fibres to characterize the mechanical nature of thermomechanical pulp (TMP) fibres in compression test. However, pressing wet fibre mat is a complicated process [8-20] and involves two main components, water and fibre [8, 11, 13, 16,19]. Within a wet fibre mat, the water presents in the interstices between fibres, in fibre lumens and in the fibre wall [21] can play an important role in compressive response of the wet fibre mat; they represent the hydraulic resistance during compression. To study the compressive response of the fibre structure resistance, the influences of these free waters, particularly the extra-fibre water and that in fibre lumens, have to be eliminated prior to compression. The water held in the cell wall, which represent a minor fraction of the total water in a wet web [22] is difficult to remove by pressing without resorting to heating. Additionally, removing this component would induce drastic modification of fibre properties [21, 23-25].

The fibre component includes fibre dimensions, fibre properties, and initial structure [9]. These aspects are of particular importance when mechanical fibres such TMP fibres are involved. It is well known that mechanical fibres exhibit a great variation in morphology and hence in physical and optical properties, making fibre property characterization complicated. To minimize these effects it is, therefore, necessary to fractionate the whole pulp into fractions of different lengths, and conduct compression test on each fraction.

The objective of the present study was to investigate the compressive response of the long fibre fractions of a TMP, viz. R14, R28 and R48 fractions. These fibres are more or less "intact", and their compressive behaviour could reveal the nature of the influence of refining on fibre's mechanical properties.

EXPERIMENTAL

Pulping

Thermomechanical pulping of black spruce (*Picea mariana*) was performed by means of a Sunds Defibrator 300CD pilot plant (Metso Paper). The primary pressurized stage of refining was done at 126°C yielding a pulp freeness of about 500 mL. The primary-stage pulp was further refined using the same refiner under atmospheric pressure to produce several pulps with freeness ranging from about 400 to 50 mL.

Pulp Fractionation

Four samples were selected from the pulps produced, representing a specific energy range of about 5 to 11 MJ/kg. They were fractionated using a Bauer McNett classifier. The fractionation provided us with homogenized test samples in terms of fibre length, and eliminated the influence of variation in fibre properties on compression responses. The long fibres retained on the 14- , 28- and 48-mesh screens were recovered and coded as R14, R28 and R48, respectively. The length weighted fibre length as determined by a Fiber Quality Analyzer, FQA (OpTest Equipment, Canada) were, respectively, 2.25 mm 1.45 mm for the R28 and R48 fractions. Due to a technical problem (clogging) the length of the longest fraction (R14) cannot be determined by the FQA. However, these fibres are usually intact and should have a length close to that of fibres in chip, i.e. approximately 3 mm. For the same difficulty fibre coarseness of the R14 was not measured.

Fibre Mat Formation

Circular fibre mats having a basis weight of 240 g/m^2 were formed using a standard British handsheet former in which six stainless steel rings (2.8 cm diameter, 1.5 cm height) were placed onto the screen before the pulp suspension was introduced. After formation the rings were removed and then the sheet was manually couched with blotters and a steel plate. The couched mat was removed from the screen. To minimize the influence of hydraulic resistance in the wet web during compression, the water in the mat was further removed using blotters to yield a consistency of about 40%. With this high consistency it was believed that there was no free water in the interstices between fibres and little water remaining in the fibre lumen. Thereafter, the circular mats were separated from the rest of the sheet and placed in a plastic bag which was then sealed and stored in a cold chamber (4 °C) until further use.

Compression Test

Prior to the compression test, the sample disks were conditioned to 22 °C. Two disks were placed one on top of the other and pressed together by means of an Instron machine (model 4200). The compression conditions were: loading speed 1 mm/min, data collection 2 points per second, maximum strain 95%, 10 cycles with 5 s intervals.

RESULTS AND DISCUSSION

Physical Characteristics of Fibre

Coarseness

The coarseness of fibre having the same length (R28 and R48) decreased when the refining energy augmented, Fig. 1 shows. This finding suggests that the papermaking potential of a particular length fraction is dependent on the specific energy consumption used in refining. Fig. 1 also reveals that refining is a complex operation; it not only shortens fibres but also peel the fibre wall, among other actions and that the papermaking properties of a given length fraction would vary depending the consumption of refining energy.

Mat density

The density of uncompressed mats increased very gradually with increasing refining energy, but the difference between the fractions was relatively small, as seen in Fig. 2. However, after compression, the mat density increased more rapidly and the difference between the fractions was definite. The density of fibre mat after compression for the three fibre fractions in decreasing order was: R48 > R28 > R14. The trend was in contrast to that for fibre coarseness.

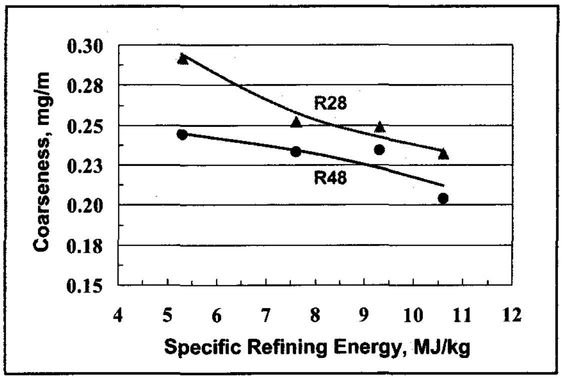

Fig. 1. Effect of refining energy on fibre coarseness

Property Parameters

Fig. 3 shows the typical multiple compression stress-strain curves which are partially illustrated up to 80% strain, permitting us to see more clearly the tendency of stress variation, the magnitude of which decreased with increasing number of compression cycle. The most substantial drop in stress occurred with the first cycle. In the figure, modulus I is defined as the tangent to the inflection point of the stress-strain curve before the sharp rise in stress. Modulus I is used to characterize the fibres' mechanical response (fibre bending and collapse) prior to web densification.

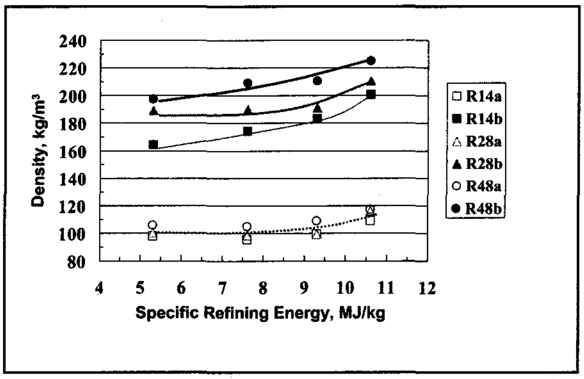

Fig. 2. Effect of refining energy on fibre mat density.
a: before compression; b: after 10 compression cycles

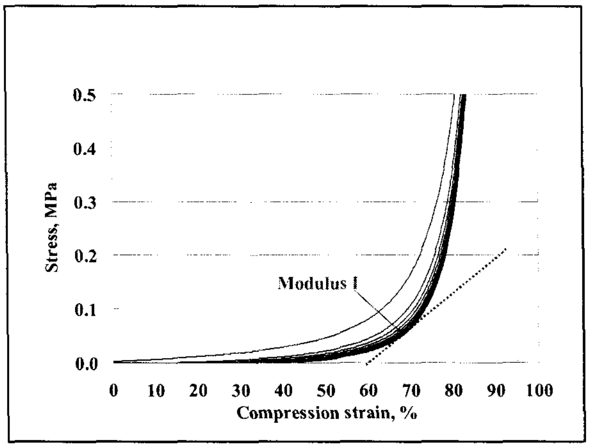

Fig. 3. Typical multiple compression curves showing the inflection point where modulus I is taken

Fig. 4 illustrates the typical complete stress-strain curves with a maximum strain of 95% strain. The relatively low stress up to about 70% strain reflects the possible fibre bending and repositioning in the mat structure. Thereafter, the stress rose rapidly, signifying fibre collapse and conformation within the fibre network. Following this point, the densification of fibre wet took place with little change in strain. The stress at 80% strain is used to express the structural resistance of the fibre mat prior to web densification, while modulus II, the tangent to the final linear part of the compression curve, represents that of the densified structure. The toughness, the ratio of energy (area under the compression curve up to 95% strain) to specimen volume, is employed to indicate the global response of the mat.

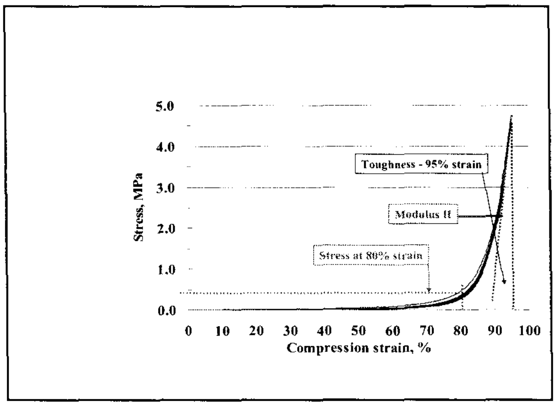

Fig. 4. Typical complete stress-strain curves showing the definitions of stress at 80%, modulus II and toughness

In our work, the fibre mats had a relatively high consistency, about 40%, which means that there was little free water in the network and the component of free water would have little influence on compression mechanism. The possible compression mechanisms of a fibre web were characterized by Han [9] as fibre bending, fibre repositioning and fibre conformation, while Amiri and Hofmann [19] suggested that a compressive stress-strain model curve includes three distinct compression mechanisms: a first region of fibre deflection in network pores, a second region of fibre collapse and a third region of network deformation through fibre collapse with a strain plateau. The first part of our stress-strain curves shown in Fig. 4, before the inflection point, is considered to include both the first and second regions of that model [19]. In reality, the compression mechanism of fibrous mat made of mechanical fibres is rather complex due to the extreme variation in fibre morphology ranging from intact long fibres to fines. The fines may consist of brick-like ray cells, flack-like outer layers of fibre wall and fibrils peeled from the secondary cell wall. To minimize the influence of fibre morphology we classified our sample pulps into fractions based on length and performed compression tests on each fraction, excluding the short and fine elements.

Modulus I

Fig. 5 shows the modulus I of the three fibre fractions. There was no clear trend of the influence of refining energy on the modulus I of R14. These fibres were the longest and the most intact in comparison with other shorter fractions, and they were presumed to receive lesser mechanical action during refining. Therefore, the modulus I of these fibres did not exhibit any definite relation with the total refining energy.

The influence of refining energy on the modulus I became increasingly more evident in the R28 and R48 fractions. This implies that fibres were cut as they received increasing mechanical energy, and that the structural modifications in the cell wall of fibres of the same length fraction were associated with the consumption of refining energy. That is, their mechanical response was energy dependent. Generally, the modulus I decreased with increasing refining energy.

Repeated compression densified the fibre mat and, as a result, augmented the modulus I. The increase was particularly sharp during the first 4 cycles, after which the rate became relatively gradual. Further, after the 10th compression cycle the modulus I tended to increased somewhat from R14 to R48 fraction, which was related to the mat density; the mat density of shorter fibres was greater than that of longer ones.

Modulus II

The refining energy had a definite and clear effect on the modulus II of the three fibre fractions, as revealed in Fig. 6; the modulus decreased when the refining energy increased. This clearly confirms our observations on modulus I: the mechanical properties of a given length fraction are associated with the total energy consumption by the pulp produced. The augmentation of modulus II as a function of compression cycle was rather gradual, which was in contrast to that of modulus I. This may be explained by the fact that the former characterizes the densified web while the latter indicates the mechanical properties of the web before being densified.

Stress at 80% strain

The stress at 80% compression strain is presumed to indicate the combined mechanical resistance of fibre deflection and most importantly the fibre collapse. Its magnitude for the three fibre fractions dropped with rising refining energy (Fig. 7). It fell with increasing compression cycle, which was particularly sharp during the first four cycles. Thereafter, the drop was relatively gradual. Again, this property for a given length fraction was also dependent on the global energy consumption received by the pulp. The R48 fraction, which had greater mat density, exhibited higher stress than the longer fractions, R14 and R28.

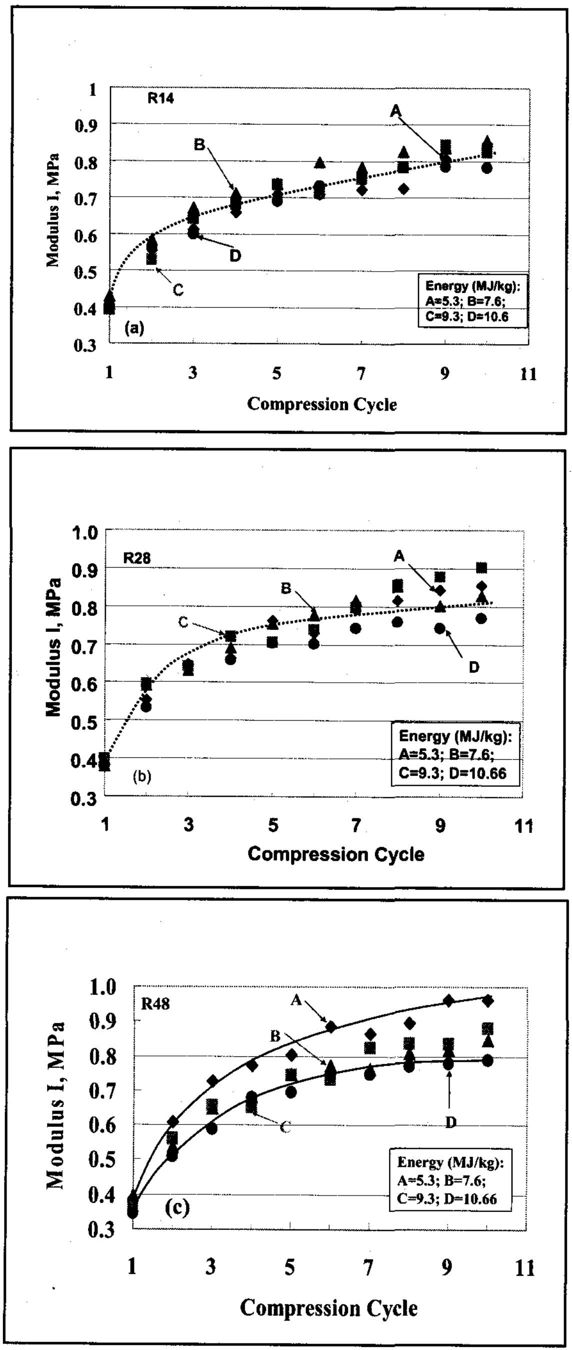

Fig. 5. Effect of refining energy on modulus I as a function of compression cycle

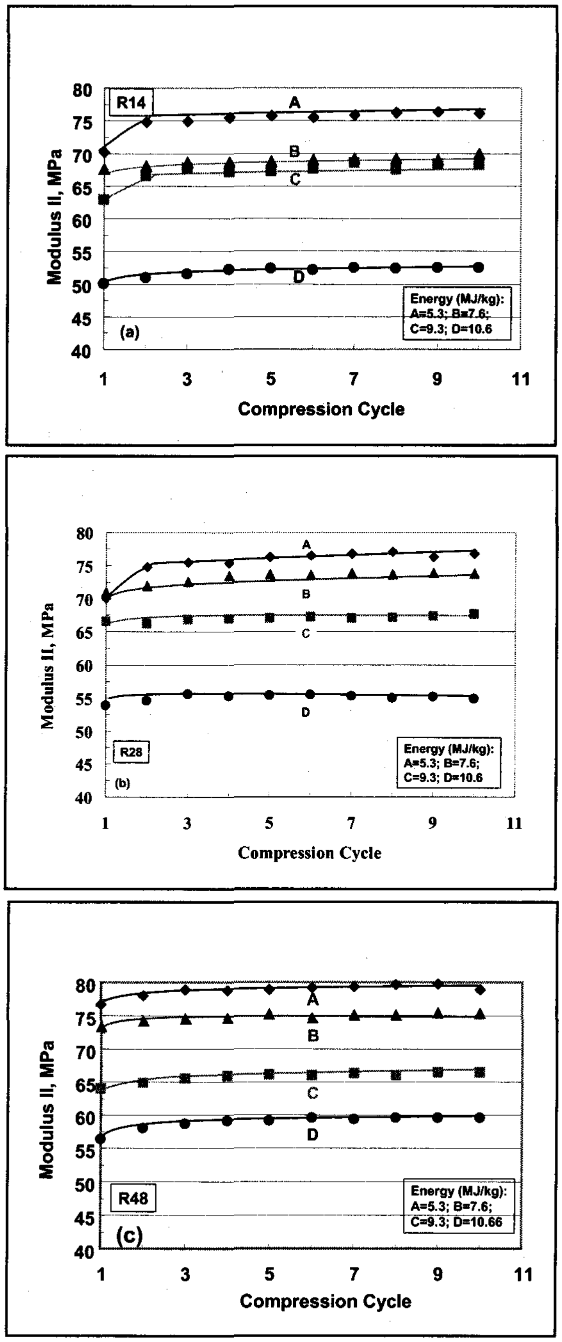

Fig. 6. Effect of refining energy on modulus II as a function of compression cycle.

Toughness

The toughness, ratio of compression energy to specimen volume, for a given fibre fraction was also significantly affected by the total energy consumption during refining; it fell with increasing refining energy (Fig. 8). It also decreased gradually with repeated compression, indicating the effect of flexibilization of the fibre structure. It was noted that the R14 fraction which consisted of the longest fibres exhibited higher toughness than the shorted fractions, R28 and R48,
meaning that this fraction was more resistant to compression.

CONCLUSION

Compression of high consistency pulp mats made from long fibre fractions of TMP yields important information on the influence of refining on mechanical characteristics of fibres. The compression parameters used in this study are useful for characterizing the effect of refining on fibre properties.

The mechanical properties such as modulus I, modulus II, stress at 80% strain and toughness for a given fibre fraction are closely related to the total refining energy received by the pulp produced; they decrease with increasing refining energy. The moduli I and II increase when the compression cycle increases, while the stress at 80% compression strain and the toughness decrease.

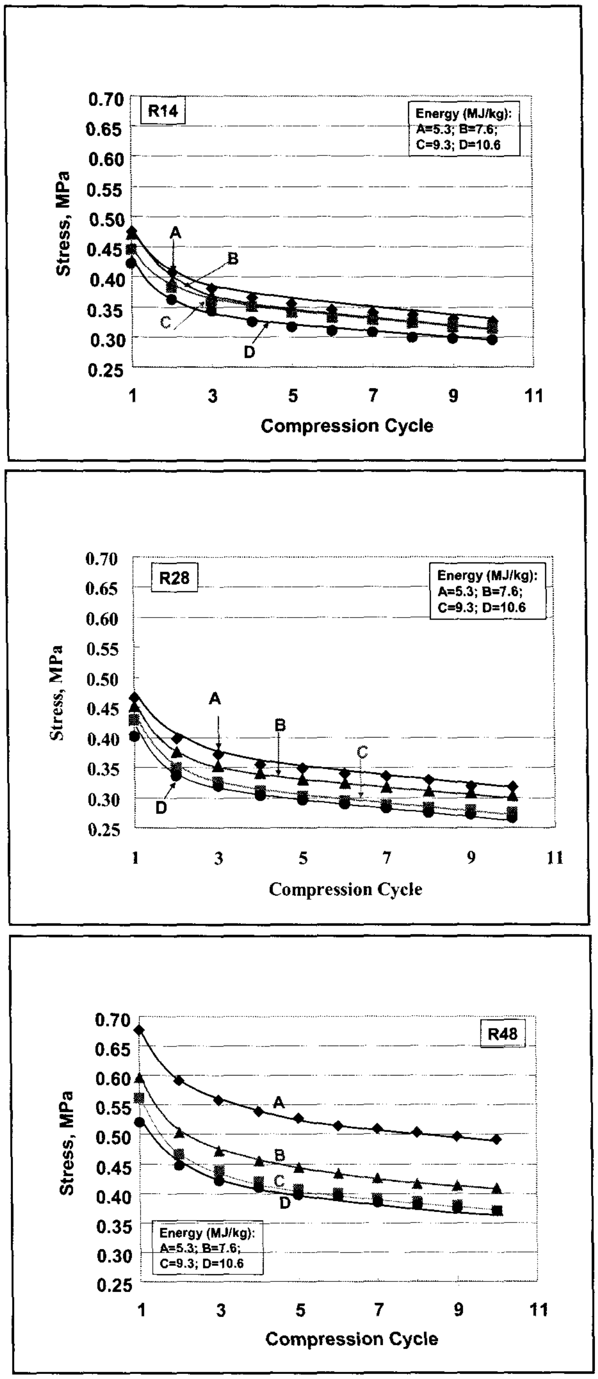

Fig. 7. Effection of refining energy on stress at 80% strain as a function of compression cycle

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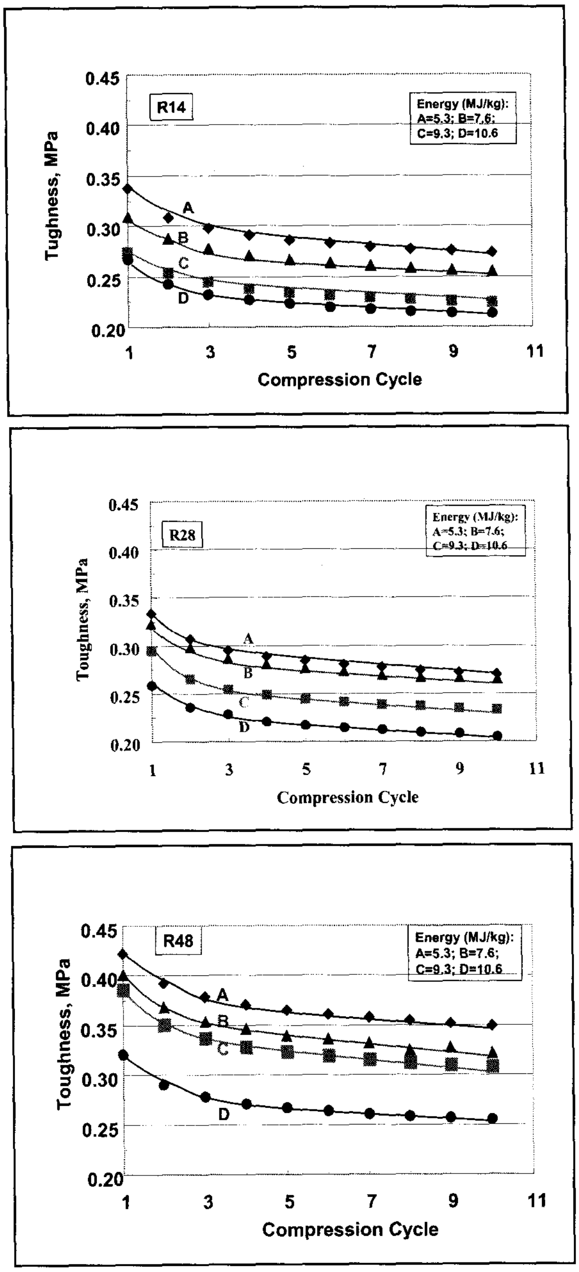

Fig. 8. Effect of refining energy on toughness as a function of compression cycle

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