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# The mechanical energy loss in stressed and $\gamma$-irradiated polycrystalline aluminium

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**Abstract.** The mechanical energy loss in two very pure (99.9999%) deformed aluminium samples (strain, 2%; stress, 12.6 MPa) was studied using the pulse-echo technique at 10 MHz frequency. These two samples were given several $\gamma$-irradiation doses (up to $13 \times 10^8 \gamma$vt) at room temperature and liquid-nitrogen temperature. Two relaxation peaks $B_1$ and $B_2$, dislocation relaxation peaks, were found at temperatures from 179 to 169 K for peak $B_1$ and from 221 to 210 K for peak $B_2$, having relaxation strengths $Q_{max}^{-1}$ of $8.1 \times 10^{-4}$–$2.3 \times 10^{-5}$ and $1.5 \times 10^{-3}$–$1.2 \times 10^{-4}$, respectively. Both the peak heights and the peak temperatures decrease as the $\gamma$-irradiation dose increases. These variations are explained in terms of the kink-pair formation model.

## 1. Introduction

Bordoni (1949) discovered the existence of a strong relaxation phenomenon, i.e. internal-friction or mechanical spectrum, in various materials. Several years later, Niblett and Wilks (1960) observed another peak situated at a slightly lower temperature. It is generally admitted that the Niblett–Wilks peak ($B_1$) and the Bordoni peak ($B_2$) are due to the intrinsic properties of dislocations. Seeger (1971) had proposed a simple explanation of this phenomenon; screw dislocations and 60° dislocations can give rise to a relaxation due to formation of pair of kinks in a dislocation line to pass over the Peierls potential hills in the temperature domain of the Bordoni peak but not perfect edge dislocations because they are not parallel to the close-packed direction, $\langle 110 \rangle$. Several researchers have reported agreement between the experimental results and Seeger's theory (Fantozzi *et al* 1982).

Irradiation produces strong dislocation pinning which is expected to make $B_2$ and $B_1$ nearly disappear. This behaviour has been reported by several workers (Niblett and Wilks 1956, Chountas *et al* 1972, Mercier *et al* 1975, Lauzier *et al* 1975, Mizubayashi 1977, Boudraz and Gotthardt 1980, Guenin *et al* 1971, Fantozzi 1971, Zein and Alnaser 1991, Alnaser and Zein 1993, Alnaser *et al* 1991, Alnaser and Zein 1991, 1992).

The effect of $\gamma$-irradiation, at room temperature (300 K) and at a low temperature (77 K), on the temperature and the heights of $B_2$ and $B_1$ in aluminium after deformation has hardly been studied previously. However, a few studies were made (Routbort and Sack 1967) on the dislocation relaxation for pre-irradiated aluminium samples with neutrons followed by various amounts of deformation (Fantozzi *et al* 1972), and also on the internal-friction peaks in pure (99.999%) polycrystalline aluminium after $\alpha$-particle irradiation at 21.4 K (Riggauer *et al* 1969). This work will give better understanding of the behaviour of $B_1$ and $B_2$ in aluminium under the influence of $\gamma$-irradiation.

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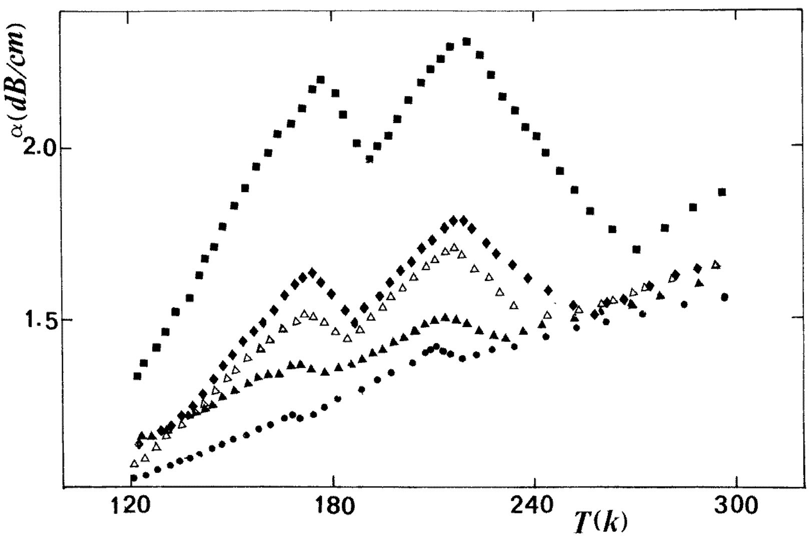


**Figure 1.** The variation in the ultrasonic attenuation at 10 MHz with temperature in high-purity (99.9999%) polycrystalline aluminium subjected to successive $\gamma$-irradiation at room temperature: ■, 0; ♦, $2.13 \times 10^8 \gamma$vt; △, $3.46 \times 10^8 \gamma$vt; ▲, $6.45 \times 10^8 \gamma$vt; ●, $10.90 \times 10^8 \gamma$vt.

## 2. Experimental procedure

Two polycrystalline aluminium specimens of purity 99.9999% were used in this investigation. These were supplied by Metal Research Limited in the form of cylinders approximately 11 mm long and 13 mm in diameter. The specimens were lapped and polished. Afterwards, specimens AL1 and AL2 were annealed at a temperature of 550 °C for 5 h in argon gas. Both specimens were given a compressional force of 1 kN at room temperature using a Monsanto tensometer, resulting in a stress of 12.6 MPa (strain, about 2%). The mechanical loss spectra, i.e. ultrasonic attenuation at various temperatures from 80 to 300 K, were measured immediately. Specimen AL1 was given a successive $\gamma$-irradiation at room temperature using a $Co^{60}$ source with energy 1.3 MeV, while AL2 was given a successive $\gamma$-irradiation at liquid-nitrogen temperature (77 K). The pulse-echo technique, at frequency $f = 10$ MHz, was used to measure the ultrasonic attenuation $\alpha$ and to measure the speed $v$ of longitudinal sound waves in the metal. An $X$-cut quartz crystal gold plated on both sides and having a diameter nearly half the sample diameter (in order to minimize the ultrasonic attenuation due to diffractional loss) (Alnaser 1991) was used as a transducer. The two faces of the sample were made exactly parallel (greater than 99.95%) in order to reduce the ultrasonic attenuation due to non-parallelism. To minimize the ultrasonic attenuation due to acoustic bonding we used very thin layers (less than 0.1 mm thick) of Nonaq stopcock grease as an acoustic couple between the transducer and the sample for mechanical waves. The transducer acts as a transmitter and receiver for short pulses (1.5 $\mu$s duration) of the longitudinal waves introduced into the sample which were then displayed on an oscilloscope after amplification. The attenuation was measured from the average ratio of the amplitude of these successively reflected pulses (displayed on the oscilloscope). The maximum strain amplitude for this technique does not exceed $10^{-7}$.

The damping $Q^{-1}(= \delta/\pi;\ \delta$ is the decrement) was calculated by substituting the values of $\alpha$ (dB cm$^{-1}$), $v$ (cm s$^{-1}$) and $f$ (s$^{-1}$) in the relation $Q^{-1} = 0.036\alpha v/f$.

The peak height was calculated after subtracting the contribution of the ultrasonic attenuation resulting from non-parallelism, diffraction loss and acoustic bonding by the method described earlier (Alnaser 1986). The temperature measurements were made using two platinum sensors placed near the specimen and connected to a digital thermometer with a linear heating rate of nearly 0.7 K $min^{-1}$.

The stress given to the samples was intended to make the strain larger than 1% in order to eliminate the quartz-sample deformation (QSD) effect which arises from the difference between the thermal expansion of the quartz crystal (transducer) and that of the sample. This difference acts as stress applied to the sample when the acoustic bond between the quartz and the sample becomes solid and as a result a maximum is observed in the fully annealed or slightly deformed sample (less than 1%) at temperatures ranging from 140 to 170 K which is in the vicinity of the $B_1$ peak temperature in aluminium (Alnaser 1986).

The elapsed time between each $\gamma$-irradiation and ultrasonic attenuation measurement was made nearly constant (2 d) since the recovery in aluminium is high (Hassan and Niblett 1983, Baxter and Wilks 1963).

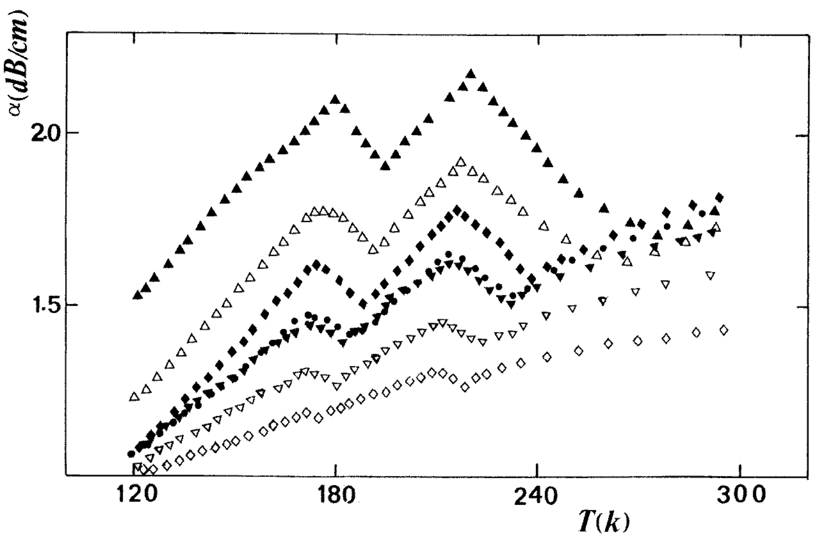


**Figure 2.** The variation in the ultrasonic attenuation at 10 MHz with temperature in high-purity (99.9999%) polycrystalline aluminium subjected to successive $\gamma$-irradiation at liquid-nitrogen temperature (77 K): ▲, 0; △, $2.15\times10^8\gamma$vt; ♦, $4.28\times10^8\gamma$vt; ●, $6.45\times10^8\gamma$vt; ▼, $8.6\times10^8\gamma$vt; ▽, $10.7\times10^8\gamma$vt; ◇, $12.58\times10^8\gamma$vt.

## 3. Results

The variation in the ultrasonic attenuation (in decibels per centimetre) at 10 MHz with the temperature for specimen AL1 given successive $\gamma$-irradiation doses at room temperature is presented in Figure 1. The height of and temperature for peak $B_2$ prior to irradiation were $15\times10^{-4}$ and 221 K, respectively, and for peak $B_1$ they were $8.1\times10^{-3}$ and 177 K, respectively. Figure 2 shows the variation in the ultrasonic attenuation with temperature for specimen AL2 given successive $\gamma$-irradiation at a low temperature (77 K). For this sample, the peak height of and temperature for peak $B_2$ prior to irradiation were $11.8\times10^{-4}$ and

220 K, respectively, while for peak $B_1$ they were $7 \times 10^{-4}$ and 179 K, respectively.

The difference between the values for peaks $B_2$ and $B_1$ in specimens AL1 and AL2 may be attributed to several effects such as different average grain sizes, slight change in thermomechanical treatment, fast recovery of aluminium and precision of measurements.

## 4. Discussion

### *4.1. Effect of $\gamma$-irradiation on the peak height*

According to most models of the Bordoni relaxation involving thermally activated pair-kink generation (Seeger 1956, 1971, Paré 1961, Engelke 1969, Schliff and Schindlmayr 1976, Esnouf and Fantozzi 1978) the relaxation strength $Q^{-1}_{max}$ ($B_2$) and the dislocation loop length are related to each other by the relation

$$Q^{-1}_{max} \propto \Lambda l^n \qquad (1)$$

where $\Lambda$ is the dislocation density and $n$ varies from 1 to 2. Figure 3 is a plot of log $Q^{-1}_{max}$ ($B_2$) and log $Q^{-1}_{max}$ ($B_1$) versus log $D_\gamma$ ($D_\gamma$ is the $\gamma$- irradiation dose). The following relations can be deduced from these plots.

For $B_2$ and room-temperature $\gamma$-irradiation (AL1),

$$\log Q^{-1}_{max}(B_2) = 7.059 - 1.212 \log D_\gamma \qquad r = -0.9920. \qquad (2)$$

For $B_2$ and low-temperature $\gamma$-irradiation (AL2),

$$\log Q^{-1}_{max}(B_2) = 5.289 - 0.989 \log D_\gamma \qquad r = -0.9106. \qquad (3)$$

For $B_1$ and room-temperature $\gamma$-irradiation (AL1),

$$\log Q^{-1}_{max}(B_1) = 13.308 - 1.971 \log D_\gamma \qquad r = -0.967. \qquad (4)$$

For $B_1$ and low-temperature $\gamma$-irradiation (AL2),

$$\log Q^{-1}_{max}(B_1) = 6.670 - 1.174 \log D_\gamma \qquad r = -0.884. \qquad (5)$$

The high values of the correlation coefficient $r$ indicate that $Q^{-1}_{max}(B_2)$ and $Q^{-1}_{max}$ ($B_1$) are greatly linearly affected by $D_\gamma$ and the general form of the above relationship is

$$\log Q^{-1}_{max} = A - n \log D_\gamma. \qquad (6)$$

Here $A$ is a constant. Equation (6) may be written as $Q^{-1}_{max} \propto \Lambda D_\gamma^{-n}$. Since $D_\gamma$ is proportional to the concentration $C$ of the defect (vacancies or interstitial) (Lawley and Gaigher 1964, Taylor and Christian 1967) and $l$ is inversely proportional to $C$, $l \propto C^{-1}$ (Fleischer 1961, Labuch 1970); therefore, $Q^{-1}_{max} \propto \Lambda l^{+n}$. The values of $n$ in equations (2)–(5) vary from 0.989 to 1.212 for peak $B_2$ and from 1.174 to 1.971 for peak $B_1$.

We can conclude here that room-temperature $\gamma$-irradiation cases have larger reduction for the relaxation strength than do low-temperature $\gamma$-irradiation cases. Peak $B_1$ is more sensitive to irradiation than peak $B_2$ in both cases (room-temperature or low-temperature radiation). Since the deformation was carried out at room temperature, therefore long screw dislocations were expected to be more available than edge dislocations (Rieu 1978). The broadening of the peaks may be attributed to the reorientation of clusters (three or more interstitials) which occurs by a number of jumps over different equivalent sites (Riggauer *et al* 1969).

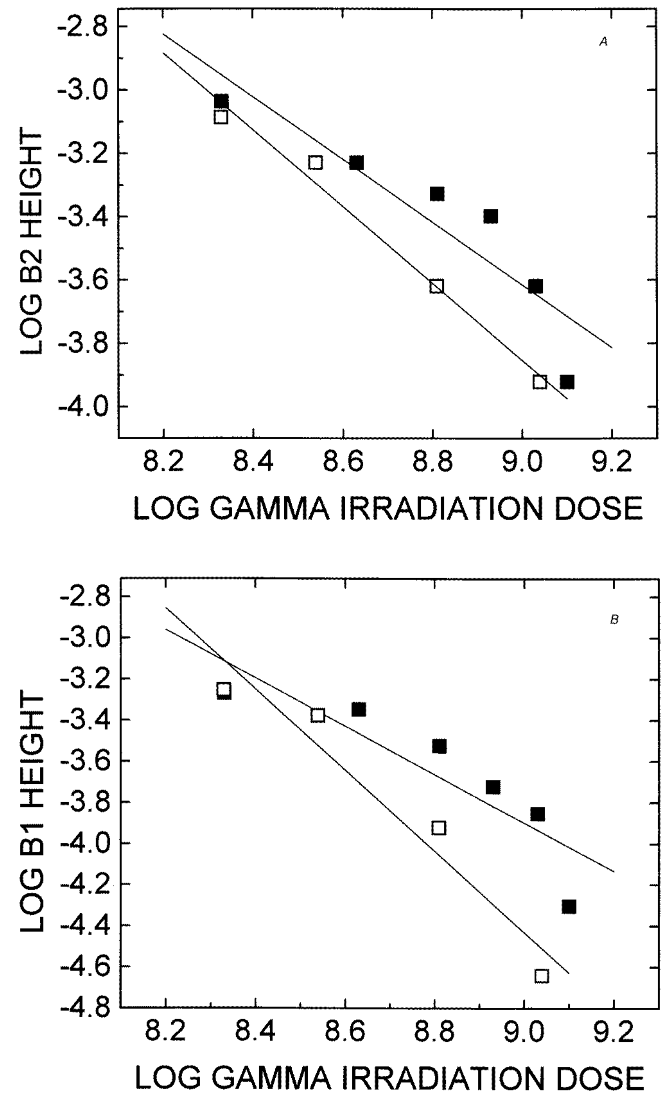


**Figure 3.** The relation between the logarithm of the dislocation relaxation peak height and the logarithm of the $\gamma$-irradiation dose for (a) peak $B_2$ and (b) peak $B_1$: □, room-temperature irradiation, AL1; ■, low-temperature irradiation, AL2.

### *4.2. Effect of $\gamma$-irradiation on the peak temperature*

Fantozzi *et al* (1973), on the basis of their study of the secondary features of the Bordoni relaxation in aluminium, suggested that the peak temperature $T_{max}$ varies in a similar way to the peak height because of pinning of active dislocations by the point defects created during the deformation (or in this case $\gamma$-irradiation). They derived the following relation:

$$T_{max}^{-1} = \text{constant} - \frac{mk}{2W} \ln \ Q_{max}^{-1} \tag{7}$$

where $m$ is a constant, $k$ is the Boltzmann constant and $W$ is the activation energy. According to equation (7) there is a linear variation in $T_{\max}^{-1}$ with $\log Q_{\max}^{-1}$, assuming $\Lambda$ to be constant. Since we found that $\log Q_{\max}^{-1} = A - n \log D_\gamma$ (equation (6)), then we can write equation (7) as follows:

$$T_{\max}^{-1} = \text{constant} - \frac{mk}{2W} \log(A - n \log D_\gamma). \tag{8}$$

Equation (8) indicates that an increase in the $\gamma$-irradiation dose (or impurities) in the sample would affect only the dislocation loop length and leave the sample with its dislocation density, which is a result of pre-strain introduced by plastic deformation. This means that, as $D_\gamma$ increases, the peak temperature will decrease linearly accordingly. To support this conclusion we plotted the effect of increasing the $\gamma$-irradiation dose on the peak temperature of $B_2$ and $B_1$ (figure 4). The following relations were found.

For $B_2$ and room-temperature $\gamma$-irradiation (AL1),

$$T_{\max} = 297.25 - 9.563 \log D_\gamma \qquad r = -0.9933. \tag{9}$$

For $B_2$ and low-temperature $\gamma$-irradiation (AL2),

$$T_{\max} = 292.76 - 9.059 \log D_\gamma \qquad r = -0.9942. \tag{10}$$

For $B_1$ and room-temperature $\gamma$-irradiation (AL1),

$$T_{\max} = 228.14 - 6.584 \log D_\gamma \qquad r = -0.9452. \tag{11}$$

For $B_1$ and low-temperature $\gamma$-irradiation (AL2),

$$T_{\max} = 245.59 - 8.338 \log D_\gamma \qquad r = -0.9938. \tag{12}$$

The correlation coefficient $r$ in equations (9)–(12) are larger than those from equations (2)–(5). This means that the drop in the peak temperature is more systematic and obvious than the drop in the peak height as $\gamma$-irradiation increases. Equations (9)–(12) can be written in the following form:

$$T_{\max} = \text{constant} - b \log D_\gamma \tag{13}$$

where $b$ varies from 9 to 10 for $B_2$ and from 6.5 to 8.5 for $B_1$. This equation gives a similar meaning to equation (8), i.e. the $\gamma$-irradiation dose increases as the peak temperature decreases linearly.

We can conclude here that the $B_2$ temperature is more sensitive to $\gamma$-irradiation than is the $B_1$ temperature. Also room-temperature $\gamma$-irradiation affects the peak temperature of $B_2$ more than low-temperature $\gamma$-irradiation does and the opposite is true for $B_1$.

## 5. General conclusion

From the general behaviour of $B_2$ and $B_1$ under the influence of deformation and irradiation, i.e. shortening the dislocation loop lengths, the temperature of the peaks at 10 MHz frequency compared with the position at kilohertz (Fanti and Nuovo 1965, Hassan and Niblett 1983) and hertz (Volkl *et al* 1965, Deterre *et al* 1979) frequencies, one can conclude that these peaks are dislocation relaxation peaks. Since equations (1) and (7) were in agreement with our results and these two equations emerged from the theories based on the kink-pair formation model, one can conclude that kink-pair formation in dislocations parallel to Burger vectors and at 60 °C are responsible for $B_2$ and $B_1$, respectively.

According to Lomer and Niblett (1962), in order to produce a change in decrement comparable with that obtained at room temperature in electron-irradiated copper, a 50 times

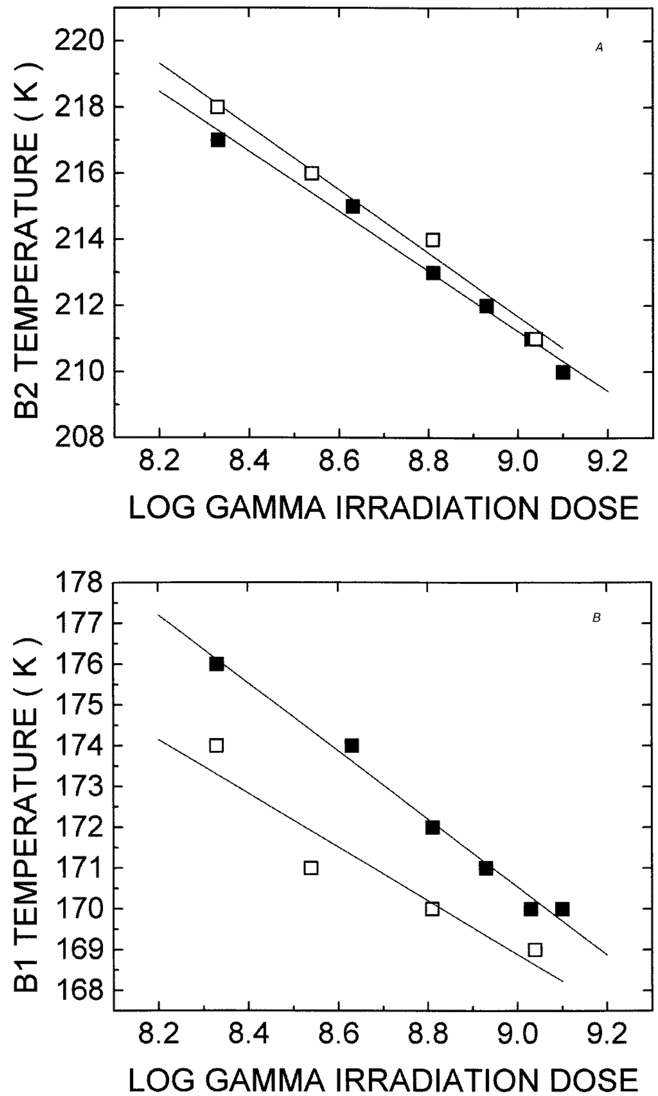


**Figure 4.** The relation between the dislocation relaxation peak temperature and the logarithm of the $\gamma$-irradiation dose for (a) peak $B_2$ and (b) peak $B_1$: □, room-temperature irradiation, AL1; ■, low-temperature irradiation, AL2.

greater dose was required. This arises because the defects introduced by the irradiation are less mobile at 80 K than at room temperature, which may explain why the heights of $B_2$ and $B_1$ and their temperatures decrease more on room-temperature $\gamma$-irradiation.

Our results agree with the work of Routbort and Sack (1967) who found that $\gamma$-irradiation at 80 K has a slight effect on the $B_1$ and $B_2$ peak shapes (figure 3 in their paper). The peak heights and their temperatures change slightly (the $B_2$ height and temperature decrease while the $B_1$ height decreases and its temperature slightly increases after $\gamma$-irradiation). This slight change, relative to our work, is believed to be due to a shorter loop length of dislocation (because of entanglement or because the internal stress produces bowed-out arrangements with short effective lengths) even though the dose used in their work was high ($10^{17}\gamma$ cm$^2$ at 80 K) which corresponds to $10^{15}$ Frenkel pairs cm$^{-3}$. The purity of their specimen was only 99.999% and underwent a similar strain to ours (2%); therefore shorter dislocation loop lengths were expected to be produced in comparison to ours (Hassan 1985).

In conclusion, $\gamma$-irradiation affects the $B_2$ and $B_1$ relaxation peak heights and their temperatures whether irradiation was made at room temperature or liquid-nitrogen temperature. However, the former has more effect on $B_2$ and $B_1$ than the latter does.

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