OBSERVATIONS OF THE MAGNETIC ANISOTROPY AND THE MAGNETIZATION REVERSAL IN LOCAL REGIONS OF A PERMALLOY THIN FILM BY LORENTZ MICROSCOPY

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Abstract

One of the advantages of Lorentz microscopy is that this method gives the magnetization direction in local regions of a film. By the use of this advantage, observations of the anisotropy and the magnetization reversal in local regions were made on a Permalloy film having large anisotropy dispersion. The magnetization reversal mechanism was found different from that of the coherent rotation theory. The difference can be explained qualitatively by the micromagnetic theory for thin magnetic films.

1. Introduction

Many investigations have been made on anisotropy dispersion[1)2)], because dispersion is one of the dominating factors of the application of the Permalloy films to memory devices. Anisotropy dispersion has been generally measured by crossed hysteresis or torque methods. These methods usually give properties averaged over some areas of films. On the other hand, Lorentz microscopy gives local informations in films. In Lorentz micrographs an intensity texture caused by the magnetization ripple gives the local direction of the magnetization. The aim of this paper is to observe the local anisotropy and to study the behaviour of the magnetization in local regions by Lorentz microscopy, which is of great use in studying the magnetic inhomogeneities or the local change of the magnetic anisotropy in films.

2. Experimental Procedure

Films were prepared by vacuum deposition of 78% Ni-22% Fe onto carbon covered collodion films mounted on electron microscope grids. Deposition was done without the application of a magnetic field and at the pressure of 3×10^{-5} Torr. The substrate temperature was near room temperature.

Observations were made in a Hitachi 11 A electron microscope. The double condenser, the objective and the intermediate lenses were used to produce a small illuminating source, and the Lorentz images of the film set in a magnetizing apparatus mounted on a specimen holder for high resolution diffraction were magnified by the projector lens[3)]. The apparatus for applying the magnetic field to the film was constructed (Fig. 1). Independent excitation of 2 pairs of the pole pieces set perpendicularly each other produces fields with any magnitude and direction, without mechanical movements. Similar 2 pairs of the pole pieces located below are used for the correction of the beam deflection caused by the upper pole pieces. The distribution of the field produced by this apparatus was investigated by potential measurement method utilizing a carbon paper, and it was proved that the variation of the field within the sample area being observed (2 mm in diameter) is less than 2% in magnitude and less than 1×10^{-2} rad. in direction.

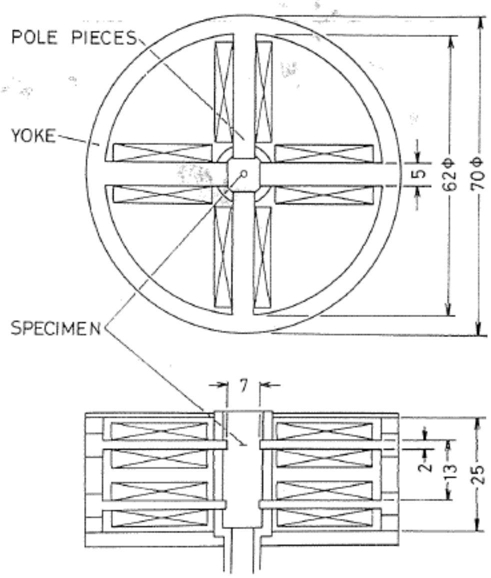


FIG. 1. Magnetizing apparatus.

3. Experimental Results

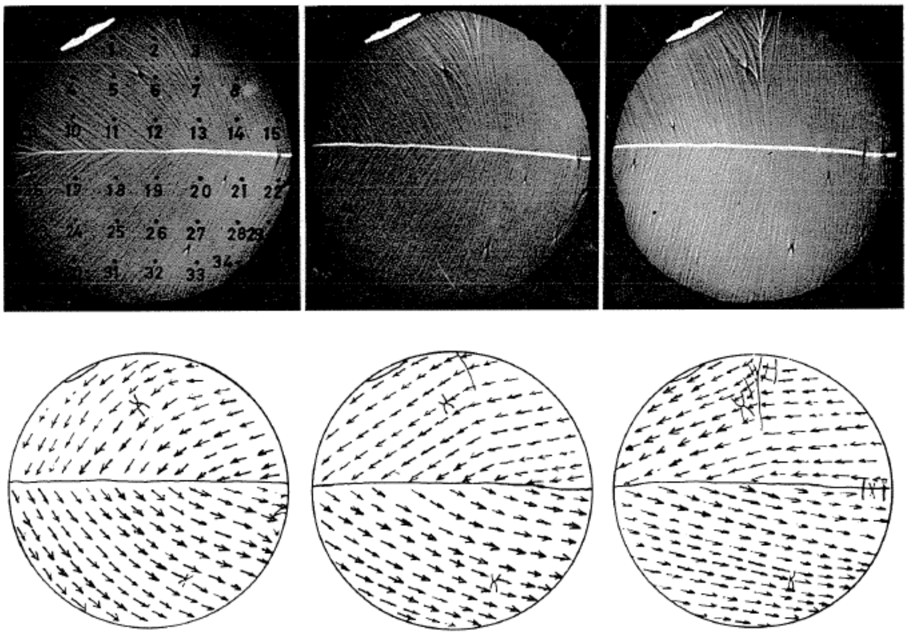
Fig. 2 shows a series of Lorentz micrographs and the magnetization configurations obtained from the micrographs, demonstrating the quasi-static magnetization reversal process. The film was first saturated parallel to the mean easy direction (downward on the micrographs) and the field was subsequently reduced to zero (Fig. 2 (1)). The field was reversed parallel to the mean easy direction (onward on the micrographs) and then increased (Figs. 2 (2)–2 (15)).

This film consists of two film regions with their different directions of the easy axis. A locking wall separating the two film regions does not move even when the applied field is increased to the coercive field. The wall is a counterclockwise Néel wall in Figs. 2 (1)–2 (3). When the field is increased to rotate the magnetization so that the angle between the orientations of the magnetization on both sides of the wall becomes more than 180°, Bloch lines nucleate and some parts of the counterclockwise Néel wall change to the clockwise wall so as to reduce the wall energy. With an increased field, the clockwise walls expand by the motions of the Bloch lines. The counterclockwise walls are indicated by thin lines and the clockwise walls are by thick lines in the magnetization distribution maps in Fig. 2.

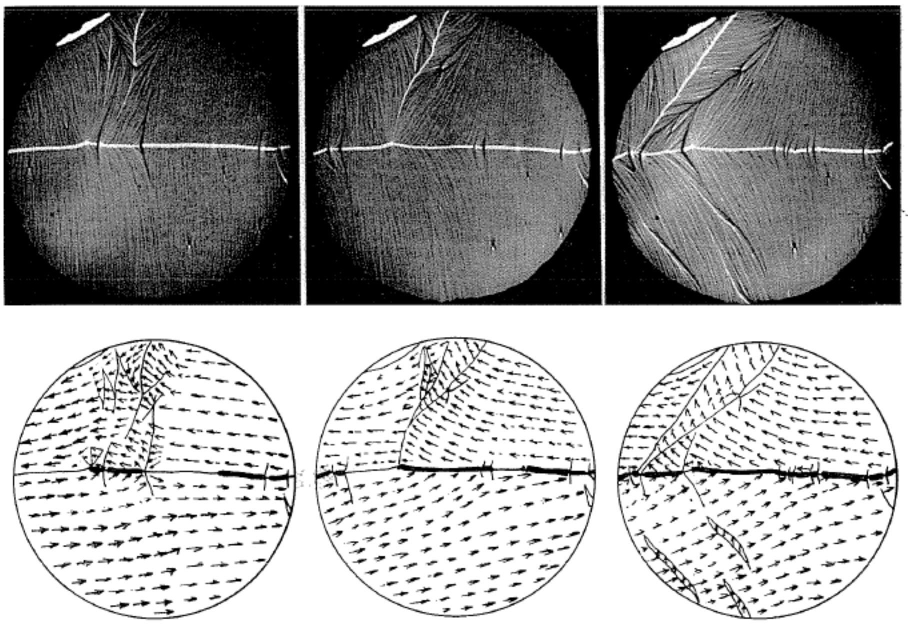
Although the field was applied to the mean easy direction, the magnetization reversal mechanism is completely different from that of the uniaxial film when the field is applied to its easy direction. The coherent rotation theory by Stoner and Wohlfarth[4] is used to determine the anisotropy field and to study the magnetization reversal process of the film shown in Fig. 2. The orientation of the magnetization M at the applied field H is given by minimization of the energy of Eq. (1).

$$E = K\sin^2\theta - MH\cos(\alpha-\theta), \quad (1)$$

where K is the anisotropy energy, α is the angle between the easy axis and the direction of the applied field, and θ is the angle between the easy axis and the magnetization direction. Minimization of Eq. (1) produces

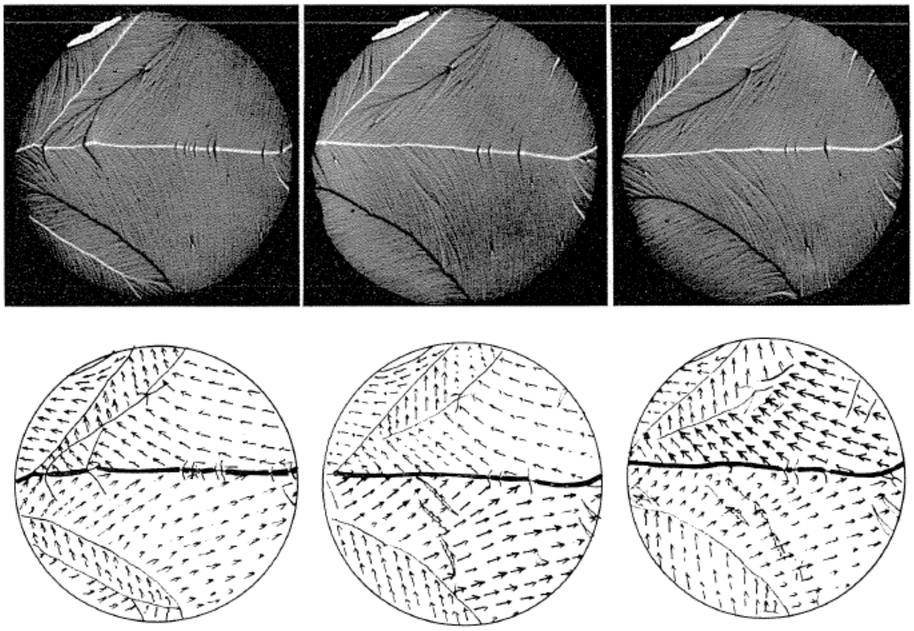


(1) ↓ $H=0$　　(2) ↑ $H=2.2$ Oe　　(3) $H=4.2$ Oe

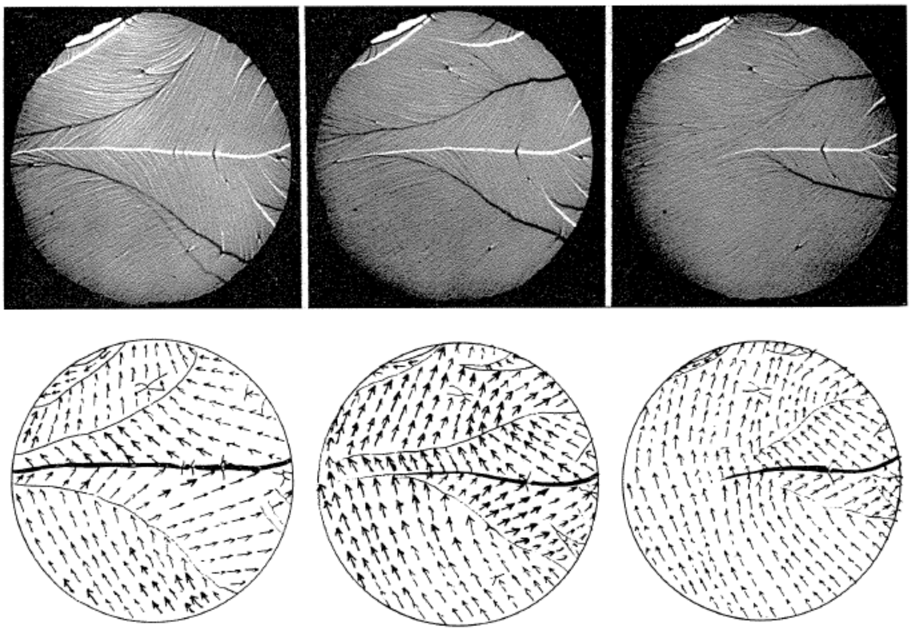


(4) $H=5.3$ Oe　　(5) $H=6.0$ Oe　　(6) $H=6.3$ Oe

FIG. 2

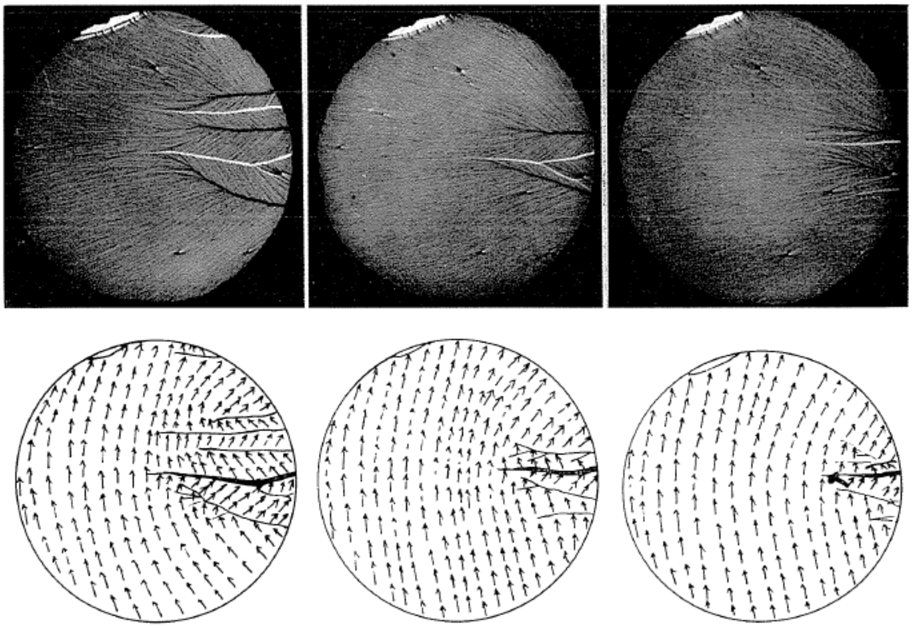


(7) $H=6.7$ Oe (8) $H=7.3$ Oe (9) $H=8.1$ Oe



(10) $H=8.5$ Oe (11) $H=9.0$ Oe (12) $H=10.5$ Oe

FIG. 2.



(13) $H=11.7$ Oe (14) $H=14.0$ Oe (15) $H=16.0$ Oe

FIG. 2.

FIG. 2. Lorentz micrographs and the magnetization configurations demonstrating the quasistatic magnetization reversal of a Permalloy film. The film was saturated parallel to the mean easy direction (downward on the micrographs) and the field was reduced to zero (1). The field was reversed parallel to the mean easy direction (onward on the micrographs) and then increased (2)-(15). The micrographs show an area of 100 μ in diameter.

$$h = \sin 2\theta / 2 \sin (\alpha - \theta), \tag{2}$$

in which

$$h = MH/2K = H/H_k. \quad (H_k: \text{ anisotropy field}) \tag{3}$$

The easy direction was determined from the magnetization direction in Fig. 2 (1) ($H=0$) on 34 points in the film. The magnitude of the anisotropy field was determined from the slope of the relation of H versus h, where h was obtained from Eq. (2) by measurements of the magnetization direction. Some relations of H versus h on typical points are shown in Fig. 3. The direction of the easy axis and the magnitude of the anisotropy field are given in Table 1. If α_{90} and Δ_{90}[2] (90% of the local easy axes

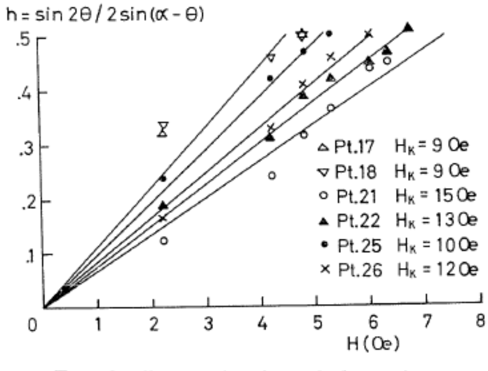


FIG. 3. Determination of the anisortopy field H_k.

TABLE 1. Direction of the easy axis and the magnitude of the anisotropy field on the points shown in Fig. 2 (1).

Point No.	H_k(Oe)	α (degree)	Point No.	H_k(Oe)	α (degree)
1	13.5	−142	18	9	138
2	8.5	−137	19	9.5	129
3	15	−110	20	11	124
4	16.5	−130	21	15	114
5	8.5	−140	22	13	109
6	9.5	−135	23	8.5	136
7	13.5	−100	24	9	136
8	16	−112	25	10	138
9	10	−149	26	12	129
10	9	−142	27	12	115
11	9	−140	28	13	115
12	10	−134	29	10.5	127
13	11	−107	30	10	130
14	14	−105	31	9.5	130
15	17	−103	32	10	126
16	9	135	33	14.5	111
17	9	141	34	14	118

lie with $\pm\alpha_{90}$ of the mean easy direction and 90% of the magnitudes of the local anisotropy fields range within Δ_{90} times the mean value around the mean value) are used for the expression of angular and magnitude dispersion of the anisotropy field, the dispersion is $\alpha_{90}=15°$ and $\Delta_{90}=0.2$. Although an attempt to study this film by torque method failed because of a small volume of the film, the values obtained here are close to those obtained by torque method with films deposited on glass substrate having large dispersion.

The magnetization reversal process was investigated and some typical examples are shown in Fig. 4. The curves show the relations expected from the

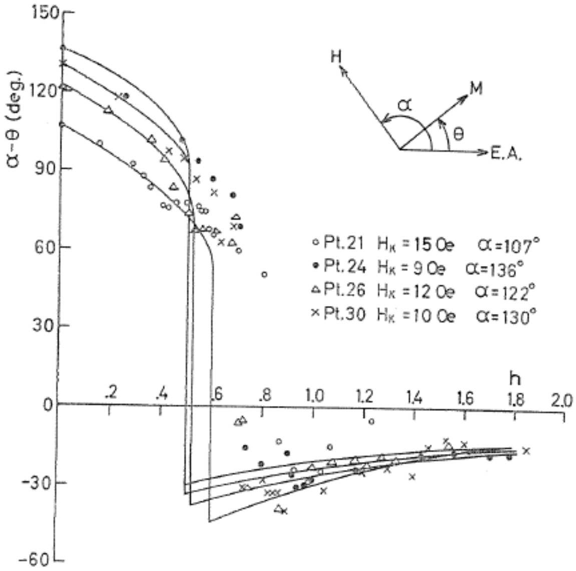


FIG. 4. (a)

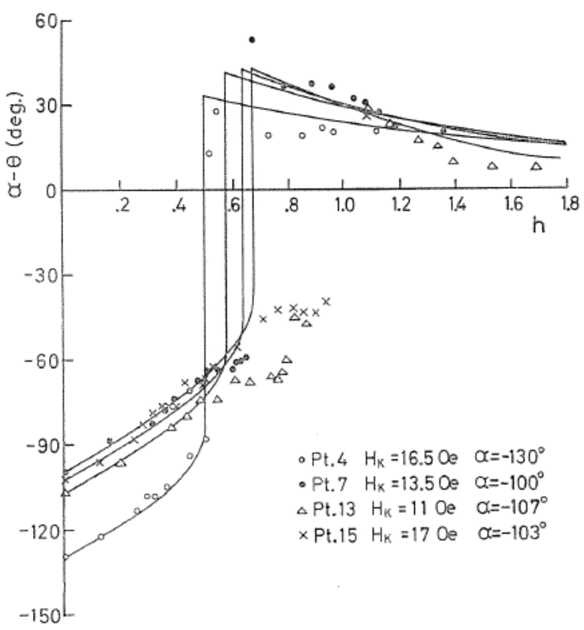


FIG. 4. (b)

FIG. 4. Magnetization direction as a function of the field h. The curves were calculated from the coherent rotation theory.

coherent rotation theory (Eq. (2)). The points are obtained from the measurements of the magnetization direction and Eq. (3). Deviations of the measured magnetization direction from the coherent rotation theory are discussed in the next section.

4. Discussions and Conclusion

Some examples showing the difference between the measured magnetization direction and the direction expected from the coherent rotation theory are plotted as a function of $h(\alpha)$ in Fig. 5. $h(\alpha)$ was defined by Hoffmann[5] (he termed it *the real effective single domain field*), and

$$h(\alpha) = h\cos(\alpha-\theta) + \cos 2\theta. \tag{4}$$

In all cases $\Delta(\alpha-\theta)$ goes to negative first when $h(\alpha)$ is decreased from 1 (which is equivalent to increasing h from zero). Then $\Delta(\alpha-\theta)$ increases and changes its sign. After reaching a maximum, $\Delta(\alpha-\theta)$ decreases again to negative value, which is followed by switching. A non-linear torque[6] $h\sin(\alpha-\theta)-0.5\sin 2\theta$ was also evaluated for some points (Fig. 6). $\Delta(\alpha-\theta)$ and the non-linear torque measured at the points of the film show the tendency quite similar to those measured over some area of the film by Hoffmann[6] by means of the Kerr magneto optic effect. A quantitative discussion of these deviations from the coherent rotation theory is difficult at this moment because accurate knowledge of the properties of the film structure and of the ripple is required.

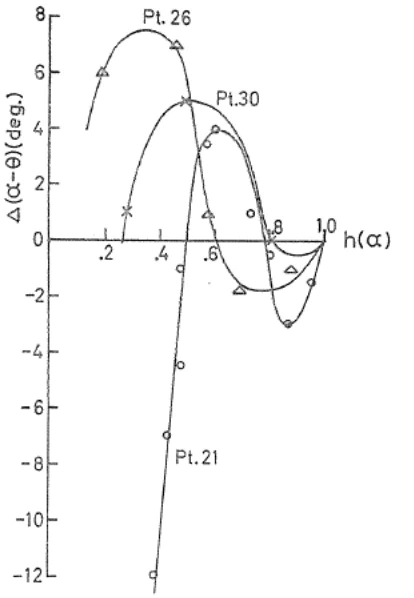


FIG. 5. Difference angle $\Delta(\alpha-\theta)$ as a function of the effective single domain field $h(\alpha)$.

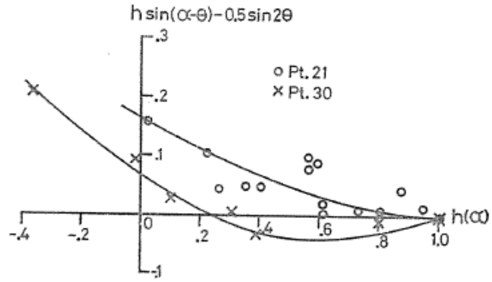


FIG. 6. Non-linear torque calculated from $h\sin(\alpha-\theta)-0.5\sin 2\theta$ as a function of the effective single domain field $h(\alpha)$.

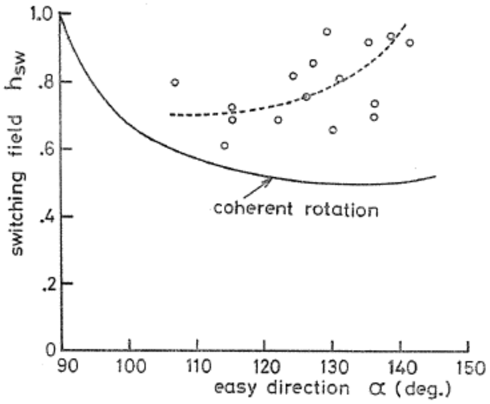


FIG. 7. Field when switching occurred (h_{sw}) plotted as a function of the easy direction α.

Fig. 4 shows clear delay of switching behind the coherent rotation theory and the magnetization rotates continuously toward the field direction even after the field passed the value at which switching is expected by coherent rotation theory. In Fig. 7, the value of h when switching ocurred (h_{sw}) is plotted as a function of the easy direction α. Although the measured points are scattered, they indicate a tendency that the deviation of h_{sw} from the coherent rotation theory is large when α is large.

The local anisotropy, the anisotropy dispersion and the magnetization reversal process of a Permalloy film having large dispersion were investigated by Lorentz microscopy. The magnetization reversal mechanism of local regions of the film deviates from the coherent rotation theory. This deviation qualitatively agrees with the non-linear ripple theory developed by Hoffmann.

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